UNIVERSITA' DEGLI STUDI DI PADOVA
DEPARTMENT OF INDUSTRIAL ENGINEERING

Master Thesis in Energy Engineering

Optimal management of a virtual power plant with photovoltaic and power-to-gas to exploit the benefit of value stacking from cross-market arbitrage

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Alla mia cara nonna

Abstract

The energy sector is facing a transformation, the traditional business model for electricity generated by large, centralized plants with limited customer engagement and standardized supply contracts is fading away. The restyling of the electricity markets is a consequence of several factors: the liberalization of the electricity sector began around 20 years ago in Italy; the growth of intermittent and unpredictable renewable technologies thanks to lower costs and larger investments than fossil fuels ones; the spread of distributed generation that makes the consumer able to produce energy too, which makes him an active player in the market by becoming a so-called prosumer. In this context, given the dynamism to which the electricity market is subjected, it is interesting to study the economic feasibility of enhanced bidding strategies from the point of view of the manager of a plant consisting of photovoltaic and Power-to-Gas.

The starting point of this thesis is a code formulated by the research group from the Department of Industrial Engineering at the University of Padua which comprehends Jan Marc Schwidtal, Marco Agostini, Massimiliano Coppo, Fabio Bignucolo, and Arturo Lorenzoni. Specifically, the research work models the operation of a virtually aggregated plant by highlighting the opportunities arising from the value stacking in terms of progressive market penetration of this unit. It evaluates energy flows and financial results on annual basis, taking into account the technical constraints of photovoltaic generation and of the Power-to-gas specifications. In this thesis, changes have been introduced concerning only the description of the economic side of the model and not the technical one. The idea is to implement an enhanced optimization approach to formulate a combined bidding strategy across the energy markets and the auxiliary services markets, exploiting the concept of cross-market arbitrage: this method regards in particular the intraday and balancing markets and consists in buying and subsequently reselling the same type of energy in the same quantity at two different prices. Four different operating modes with a gradual and increasing integration in the markets are studied and the respective optimization problems are solved using the *Gurobi* solver through the *Yalmip* toolbox installed within the *Matlab* software. Lastly, considerations were drawn about

the risk management that could affect the manager of the unit by investigating how far it is possible to go in adopting this bidding strategy while operating the plant.

Sommario

Il contesto in cui è ambientata questa tesi è quello di un settore dell'energia in trasformazione. Il modello di business tradizionale basato fino ad ora su grandi impianti centralizzati, sul coinvolgimento limitato dei clienti e su contratti di fornitura standardizzati, sta svanendo. Il restyling del mercato elettrico è la conseguenza di diversi fattori: la liberalizzazione del settore elettrico; l'impiego massivo delle tecnologie rinnovabili intermittenti favorita da costi inferiori e investimenti maggiori rispetto a quelle fossili; la diffusione della generazione distribuita che rende il consumatore stesso in grado di produrre energia, e quindi attivo nel mercato (*prosumer*). In questo contesto, data la dinamicità a cui è sottoposto il mercato elettrico, è interessante studiare la fattibilità economica di strategie avanzate per la compravendita di energia, dal punto di vista del gestore di un impianto composto da fotovoltaico e Power-to-Gas.
Il punto di partenza di questa tesi è un codice formulato dal gruppo di ricerca del Dipartimento di Ingegneria Industriale dell'Università di Padova che comprende Jan Marc Schwidtal, Marco Agostini, Massimiliano Coppo, Fabio Bignucolo e Arturo Lorenzoni. Nello specifico, il lavoro di ricerca consiste nel simulare il funzionamento di un impianto virtualmente aggregato, evidenziando le opportunità derivanti dal *value stacking*, e valutando i flussi energetici e i risultati finanziari su base annuale. Nel modello qui trattato sono state introdotte modifiche che riguardano esclusivamente la descrizione dell'aspetto economico lasciando invariate le specifiche tecniche dell'impianto adottate nel modello originale. L'idea è di implementare un approccio ottimizzato per formulare una strategia di offerta combinata nei mercati dell'energia e dei servizi ausiliari, sfruttando il concetto di arbitraggio tra i mercati. Questo metodo riguarda in particolare il mercato infragiornaliero e del bilanciamento e consiste nell'acquistare e successivamente rivendere lo stesso tipo di energia nella stessa quantità a due prezzi differenti. Sono state studiate quattro diverse modalità operative con un'integrazione graduale e crescente nei mercati e i rispettivi problemi di ottimizzazione sono stati risolti utilizzando il solutore *Gurobi* attraverso il toolbox *Yalmip* installato nel software *Matlab*. Infine, sono state espresse considerazioni sull'incertezza legata a questo metodo, valutando fino a che punto è possibile adottare questa strategia di offerta durante la gestione dell'impianto.

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Nomenclature

Acronyms and Indices

AEL	Alkaline electrolysis
BESS	Battery Energy Storage Systems
BPP	Bipolar Plate
CHP	Combined Heat and Power Plant
DAM	Day Ahead Market
DER	Distributed Energy Resource
DR	Demand-Response
DSO	Distribution System Operators
FRP	Flexibility Requesting Parties
FRR	Frequency Restoration Reserve
GME	*Gestore Mercati Energetici*
GSE	*Gestore dei Servizi Energetici*
H2	Hydrogen
IDM	Intra-Day Market
MB	Balancing Market
MEA	Membrane electrode assembly
MILP	Mixed-integer linear programming
MPE	Spot Electricity Market
MPEG	Daily Products Market
MR	Real-Time Market
MSD	Ancillary Services Market
MTE	Forward Electricity Market
P2G	Power to Gas
PEM	Polymer electrolyte membrane electrolysis
PTL	Porous transport layers

PUN	National Single Price
PV	Photovoltaic
RES	Renewable Energy Source
RR	Replacement Reserve
SOEL	Solid oxide electrolysis
TSO	Transmission System Operator
VPP	Virtual Power Plant
YSZ	Yttria-stabilized zirconia
act	Active operation of P2G plant
DW	Downward service
exp	Export
imb	Imbalance settlement mechanism
imp	Import
mkt	Previous market
sby	Stand-by operation of P2G plant
$t \epsilon T$	Time instant
T	Transformer
UP	Upward service

Symbols

ΔS	Entropy change [kJ/mol]
ΔH	Enthalpy change [kJ/mol]
ΔG	Gibbs free energy change [kJ/mol]
E^0	Standard thermodynamic voltage [V]
E_{Therm}	Thermoneutral voltage [V]
U_{cell}	Electrolysis cell voltage [V]
n	Numbers of electrons
F	Faraday's constant [C/mol]
p_*	Partial pressure [bar]
a_{H2O}	Water acticity
i	Current density [A/m^{-2}]
I	Total current
R	Sum of ionic and electronic resistances [Ω]
LHV	Lower Heating Value [kWh/kg]

$\boldsymbol{c}_*^*$	Price [€/kWh, €/kg]
η_*	Efficiency
$\dot{m}_*^*$	Mass flow rate [kg/h]
α_*^*	Binary variable
β_*^*	Binary variable
γ_*^*	Binary variable
P_*^*	Power [kW]
$\overline{P^T}$	Rated Power [kW]

Chapter 1

1 Introduction

The first real global energy crisis is currently happening, and its effects will be seen for years to come. The invasion of Ukraine by Russia in February 2022 had a profound effect on the world energy industry, altering dynamics in supply and demand and shattering old trade agreements. Faster renewable energy transitions are the best solution to the issue and would have helped to alleviate its effects. Thanks to the unprecedented response from governments around the world, notably the “Fit for 55” package and “REPowerEU” in the European Union (EU), the current crisis could represent a turning point in history for a cleaner and more secure energy system.

Within the European Green Deal framework, the European Commission, with its 'Fit for 55' package of proposals, has set an important goal: carbon neutrality by 2050. To achieve this goal, greenhouse gas emissions must be reduced by at least 55% by 2030 compared to 1990 values and then complete the task within the next 20 years [1]. By taking these actions, Europe has put the gradual electrification of the economy promoting the share of variable renewable energy sources at the core of the EU decarbonization strategy. In addition, after the Russo-Ukrainian escalation, the role of electricity was additionally reinforced through the signing of a 210 billion euro investment plan, the so-called 'RepowerEU', with which Europe intends to renounce the import of fossil fuels from Russia by 2027 and cut two-thirds of imports by the end of this year. Several proposals in the plan are consistent with the decarbonization goals, including strengthening long-term energy efficiency measures from the 9% set by the 'Fit for 55' package to 13% and increasing the EU's 2030 target for renewables from the current 40% of 'Fit for 55' to 45% [2]. Increasing the weight of renewables will eventually reduce both the share of gas in the energy mix and the degree of foreign energy dependency and, not lastly, the price of energy. Such new goals require significant structural adjustments to the mix of technologies used in energy generation, including a change in the market structure.

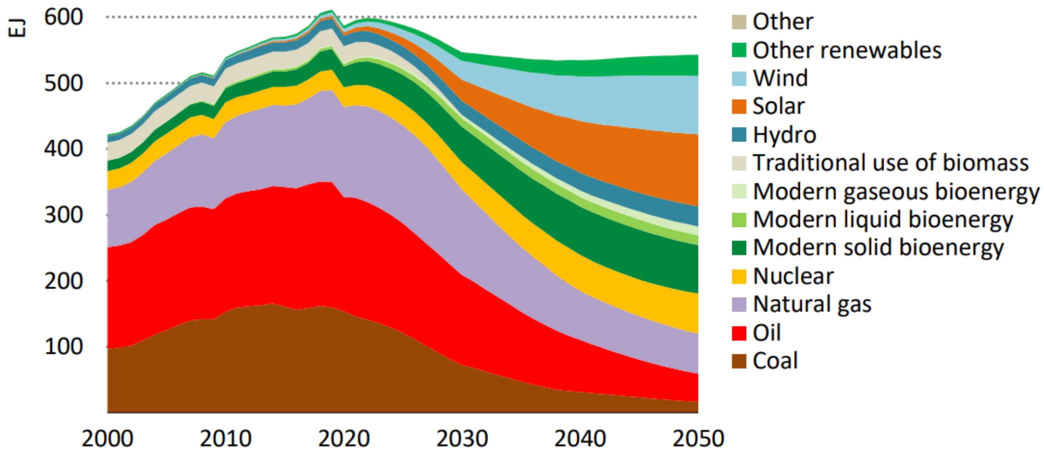

Figure 1.1 - Total primary energy demand by Net-Zero Emissions 2050 Scenario. Source: IEA [3]

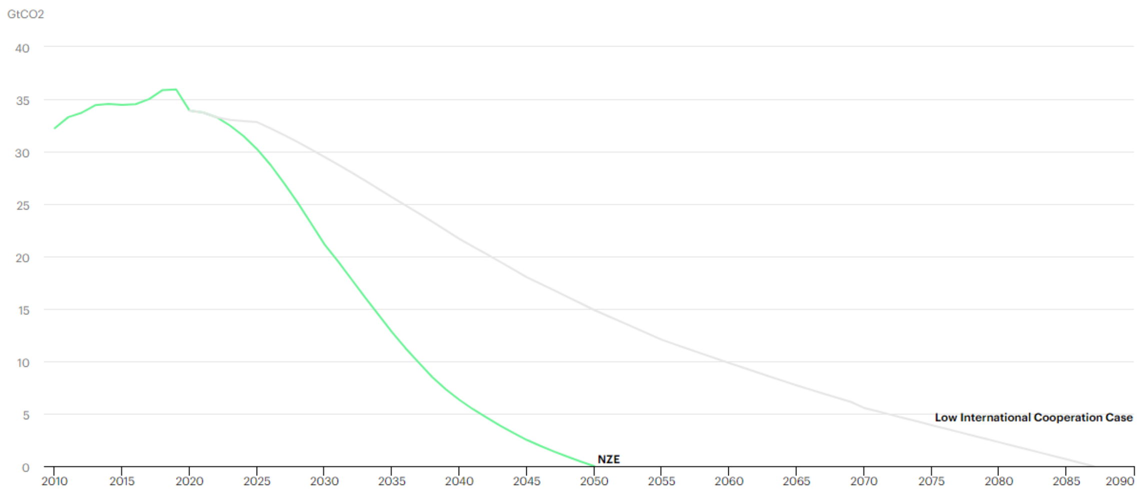

Figure 1.2 - Global energy-related carbon dioxide emissions in the Net-Zero and Low International Cooperation scenarios. Source: IEA [4]

1.1 The italian electricity market

The Italian electricity market, as it is currently conceived, was liberalised following the approval of Legislative Decree 79/99 of the year 1999, in order to promote a structural reorganization of the Italian electricity sector, dictated by EU Directive 96/92/EC. More in general, this was the result of a wider reform that involved the entire Italian electricity sector and subjected it to a process of 'unbundling', i.e. the separation of energy production, transmission, distribution and sales activities into separate corporate entities. The aim was to promote competition and to maximise the transparency and efficiency of natural monopolies, in accordance with free market contexts [5]. To speak of the electricity market, it is necessary to introduce the concept of the Italian Power Exchange (IPEX), which is the virtual meeting place of supply and demand and thus the location for wholesale negotiations of electricity. Thus, the two terms (electricity market and Power Exchange) are synonyms, and, in practice, this reveals itself as a telematic marketplace where programmes of injections and withdrawals of energy into and from the grid are defined through a pricing mechanism based on the balance between supply and demand. The main actors involved can be divided into supply and demand. The former consists of producers and importers. The latter is instead made up of wholesalers (exporters, eligible end customers[1] and the Single Buyer[2]), who carry out negotiations either on behalf of end customers or purely for trading purposes. Terna S.p.A. is the Italian TSO and is therefore the company that manages the transmission of electricity at high and very high voltage over long distances, as well as dealing with dispatching. To this end, it participates as a central counterparty in the MSD (see section below) in order to procure the necessary resources. Distributors are companies which, as the name suggests, distribute medium and low voltage energy on a local scale. The key role is entrusted to the *Gestore dei Mercati Energetici* (GME) which is a company controlled by the Ministry of Economy and Finance through an additional company called *Gestore dei Servizi Energetici* (GSE). The GME has the duty to organise and manage the electricity, natural gas and environmental markets[3]. The electricity market

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[1] Eligible end-customers are all those participants in the free market.

[2] The Single Buyer is a publicly controlled entity in charge of purchasing energy on behalf of consumers who have joined the protected market and not the free market.

[3] The markets for the environment are a set of markets dealing with the implementation of environmental policies, through the issuing of certificates and efficiency certificates.

takes place in advance with respect to the actual delivery of electricity. It consists of several trading platforms, divided into different time sessions. This structure is conceived to allow long-term planning on one hand and, on the other hand, the possibility to make short-term adjustments according to stipulated injection and withdrawal schedules and the provision of dispatching resources.

1.1.1 Market zones

Before entering the details of how the various markets work, it is necessary to briefly introduce the concept of market zones. In order to identify and eliminate any possible congestions caused by the grid's withdrawal and injections and to carry out technical controls, the GME divides the electricity grid into zones, either geographical or virtual. In addition to the above-mentioned reasons, there are advantages in terms of reduced production costs and increased efficiency on the grid, as the market will choose the best available plants. Each of the zones is characterised by a different electricity selling price, i.e. the zonal price, which is calculated from the intersection of the supply and demand curve and by physical limits of transit between neighbouring zones. Electricity is valued at a single price, called "*Prezzo Unico Nazionale*" (PUN, national single price) defined as the average of the zonal selling prices, weighted by zonal consumptions. These zones refer to:

- Geographical zones: portions of the national electricity grid for which there are physical limits on the exchange of energy with other neighbouring geographical zones (North, Central-North, Central-South, South, Sicily, Sardinia);
- Virtual zones: interconnection points with foreign countries (France, Switzerland, Austria, Slovenia, Corsica, Greece) or with a limited production pole (Rossano);
- Limited production poles: zones consisting only of production units, whose interconnection capacity with the grid is lower than the installed power of the units themselves [6].

1.1.2 Market structure

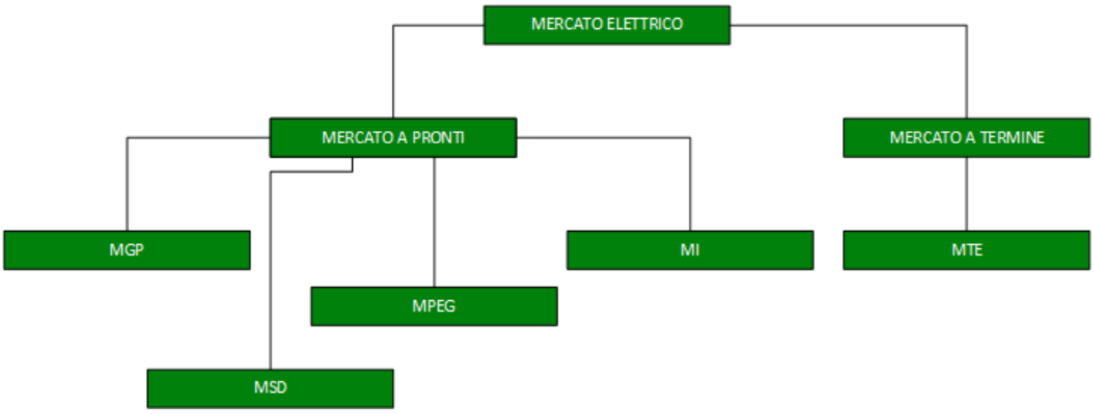


Figure 1.3 - Electricity market structure. Source: GME [7]

The electricity market consists of a series of market sessions, i.e. activities aimed at managing offers. It is divided into two large categories:

- Forward Electricity Market (MTE): based on bilateral contracts between sector operators, where the products traded tend to be standardised and priced at a fixed price. There is an obligation for physical delivery and withdrawal of electricity. Here all electricity market participants are automatically admitted. It is characterised by long delivery periods such as month, trimester and year.
- Spot Electricity Market (MPE): unlike the previous one, it is not based on the meeting of two separate parties, but each operator has the market itself as its counterpart, which provides for the meeting of supply and demand. Compared to the previous one, it is characterised by short-term delivery.

The Spot Electricity Market (MPE) is furthermore subdivided into:

- Day-Ahead Market (DAM);
- Intra-Day Market (IDM);
- Daily Products Market (MPEG);
- Ancillary Services Market (MSD).

1.1.2.1 Day-ahead market (DAM)

The Day-Ahead Market (DAM) is the main market where the wholesale electricity trading takes place. The results of this market, in terms of volumes and prices, have a marked influence on the other trading platforms. In it, energy is bought and sold on an hourly basis with reference to the following day, thus defining the injection and withdrawal schedules. Prior to each session, Terna provides the GME and the operators with preliminary information about the maximum and minimum geographical transit limits and the estimate of hourly and zonal energy demand, while the GME acts as the central counterparty and sends Terna the results of dispatching.
From an organisational point of view, trading opens at 08:00 on the ninth day before the day of actual physical delivery of energy and closes at 12:00 on the day before the day in question. Within 58 minutes (12:58pm), the results are processed by the GME and communicated to the interested parties.
In each session, bids are submitted indicating the quantity (MWh) and price (€/MWh) at which operators are willing to buy or sell.
After the close of the market session, an algorithm, based on the economic merit and respecting the transit limits between zones, orders the selling offers according to the marginal price concept, i.e. in increasing price order. The equilibrium price (intersection of the supply and demand curves) is then represented by the value of the highest offer accepted by the market for the purpose of covering the demand. All the other accepted offers, although lower, are remunerated at that price. Therefore, the fact of drawing up an economic merit order makes the DAM an auction and not a continuously traded market. If all the previously communicated limits are respected, the equilibrium price is the same for all zones. Otherwise, in the event of network congestions, the algorithm, to solve them, separates the market into the different market zones seen above and sets a zonal price for each of them by repeating the same methodology based on marginality. An exception is made for consumption units withdrawing from national geographical zones, whose bids are instead valued at the single national price (PUN).

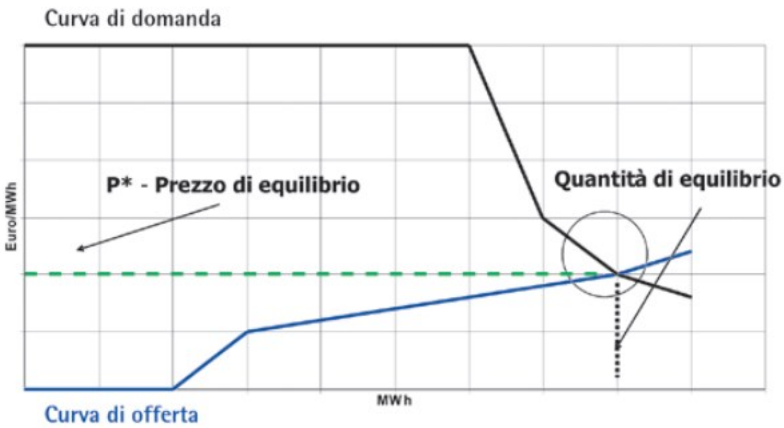


Figure 1.4: Determination of equilibrium price. Source: Vademecum della Borsa Elettrica [8]

1.1.2.2 Intra-day market (IDM)

The intra-day market (IDM) allows operators to define their schedule more accurately by making changes to what was established on the DAM through additional buying or selling offers. In this way it is possible to correct the results of the DAM bringing adjustments to the amount of energy consumed and the status of production facilities. Thanks to this, it is possible to support the volatility of non-programmable RES.

The way prices are generated is similar to that of the DAM, with the difference that all transactions (both buying and selling offers) are valued directly at the zonal price and not at the PUN. This leads to deviations from the offers accepted at the PUN at the withdrawal points during the DAM. For this reason, for each bid accepted in this market, the GME applies a non-arbitrage fee defined as the product of the quantity accepted and the difference between the zonal price and the PUN. For purchase bids, the bidder must pay the fixed fee if it is negative or receive the fee if it is positive; while for sale bids, the bidder must pay the fee if it is positive or receive it if it is negative.

Until September 2021, before the reform, the intra-day market consisted of seven sessions. In the first two (MI1 and MI2), bids were negotiated for the next day's 24 hours, while the subsequent sessions had a delayed closing time of four hours from each other:

- The MI1 session takes place after the close of the DAM, opens at 12:55 p.m. on the day before the delivery day and closes at 3 p.m. on the same day. The results of MI1 are announced by 3:30 p.m. on the day before the delivery day.

- The MI2 session opens at 12:55 p.m. on the day before the delivery day and closes at 4:30 p.m. on the same day. The results of MI2 are announced by 17:00 on the day before the delivery day.
- The MI3 session opens at 17:30 on the day before the delivery day and closes at 23:45 on the same day. MI3 outcomes are announced by 00:15 on the delivery day.
- The MI4 session opens at 17:30 on the day before the delivery day and closes at 3:45 on the delivery day. MI4 results are announced by 4:15 a.m. on the closing day of the session.
- The MI5 session opens at 5:30 p.m. on the day before the delivery day and closes at 7:45 a.m. on the delivery day. MI5 results are announced by 8:15 a.m. on the closing day of the session.
- The MI6 session opens at 5:30 p.m. on the day before the delivery day and closes at 11:15 a.m. on the delivery day. MI6 results are announced by 11:45 a.m. on the closing day of the session.

In 2021, in order to align with European directives on the internal energy market, the MI market operation process has been revised, introducing a continuous trading platform. Trading on the MI now takes place through three MI-A auction sessions and one continuous MI-XBID (Cross-Border IntraDay) trading session, allowing for the automatic matching of energy buying and selling proposals, with the possibility of placing new bids continuously during the trading sessions which are hourly. The MI-A auction sessions and the trading phases of the MI-XBID session do not overlap but follow each other in this order: MI-A1; MI-XBID phase I; MI-A2; MI-XBID phase II; MI-A3; MI-XBID phase III.

Regarding MI-A sessions:

- The MI-A1 session takes place after the close of the DAM, opens at 12:55 p.m. on the day before the delivery day and closes at 3:00 p.m. on the same day. The results of MI-A1 are announced by 3:30 p.m. on the day before the delivery day.
- The MI-A2 session opens at 12:55 p.m. on the day before the delivery day and closes at 10:00 p.m. on the same day. The results of the MI-A2 are announced by 10:30 p.m. on the day before the delivery day.

- The MI-A3 session opens at 12:55 p.m. on the day before the delivery day and closes at 10:00 a.m. on the delivery day. The results of the MI-A3 are announced by 10:30 a.m. on the delivery day.

As for the MI-XBID session, it is divided into three phases:

- The Phase I MI-XBID session opens at 3:30 p.m. on D-1 and closes at 9:40 p.m. on D-1.
- The Phase II MI-XBID session opens at 10:30 p.m. on D-1 and closes at 9:40 p.m. on D-1:

    - for the relevant periods corresponding to the first twelve hours of day D, one hour before the start of each relevant period (h-1);
    - for the relevant periods corresponding to the second twelve hours of day D, at 09:40 a.m. on day D.

- The MI-XBID Phase III session opens at 10:30 a.m. on day D and closes one hour before the start of each relevant period (h-1).

1.1.2.3 Daily products market (MPEG)

The Daily Products Market (MPEG) is the platform where the trading of daily products with energy delivery obligations takes place. All electricity market operators are admitted to this market and they participate in energy trading on a continuous basis. The tradable daily products are characterised by:

- "unit price differential": for such products, the price indicated in the formulation of bids and, therefore, the price that is determined as a result of the negotiation phase is the expression of the differential, with respect to the PUN, at which operators are willing to negotiate these products;
- "full unit price": for these products, the price indicated in the formulation of the offers and, therefore, the price that is determined as a result of the negotiation phase is the expression of the unit trading value of the electricity covered by the negotiated contracts.

On the MPEG, for both types of products mentioned above, Baseload delivery profiles (i.e. the portion of load that is constant throughout the day) and Peak Load (i.e. the portion of load that is subject to daily and seasonal variations) are negotiable.

1.1.2.4 Ancillary services market (MSD)

As the transmission system operator, Terna must ensure any time that supply and demand are balanced. In particular, it must take care to observe the voltage and frequency standards and energy transit constraints, even in the case of relevant unforeseen events. To this end, it needs appropriate resources, which may or may not be tradable on the MSD [5]. The former are remunerated according to the rules of that market, the latter are not tradable at all, because they are necessary for the security of the system and/or because their economic valuation is difficult to quantify. Therefore, the latter are made available immediately when the system connects to the grid and they may receive remuneration in an administered form or may not receive it at all, because the service in question is mandatory. The resources required for dispatching purposes are described below, while the technical requirements for enabling their supply are discussed further in the chapter.

Dispatching Resources

Scheduling congestion resolution: This consists of the availability of a generation unit to increase or decrease the amount of power to be injected into the grid with respect to what was previously agreed on the DAM and/or IDM. This is because the injection and withdrawal schedules have led to the violation of intra-zonal transit limits. This materialises, for each operator, as an obligation to make available the difference between the power agreed on these markets and the maximum/minimum power;

Primary reserve: As a result of an active power imbalance on the network, the frequency varies from its nominal value. To solve this problem, primary regulation is the first mechanism to ensure that it remains within the set limits. All enabled generating units (*unità di produzione abilitate*), which will be defined later, must provide an active power reserve of at least ±1.5% of their efficient power (for plants located in Sicily and Sardinia, this margin rises to ±10%);

Secondary reserve: The secondary regulation acts after the primary one, to bring the frequency back to the nominal value. Two symmetrical power bands, one upward and one downward, are required to qualified production plants;

Tertiary reserve: This is about the creation of a further power margin, either upward or downward, in addition to the secondary reserve. It is needed to deal with imbalances in the system and to replace and make available again the other regulating resources if these have already been exploited. It is divided into ready tertiary (*terziaria pronta*) and replacement tertiary (*terziaria di sostituzione*). The former goes to replenish the secondary reserve, as well as acting quickly in balancing, e.g. during load ramping hours. The second replenishes the tertiary ready reserve and compensates for production discrepancies due to non-programmable renewable sources (a plant in which it is not possible to vary its production in a controlled manner over time) or prolonged outages of generating units (Figure 1.5);

Balancing: In contrast to previous resources that are required to be available in advance, balancing consists of changing the injection level in real time in order to keep the balance between generation and load, resolve grid congestion and restore the correct secondary reserve margins;

Primary and secondary voltage regulation: Just as frequency is closely linked to active power, so are voltage and reactive power. Terna, with the aim of limiting the voltage level variation around the nominal point, mandatorily requires the relevant generation units (the definition of which will be provided later) and, optionally, smaller units, to make a reactive power margin available. If voltage regulation takes place on a local scale, it is called primary regulation, otherwise if it affects a regional context, it is secondary regulation.

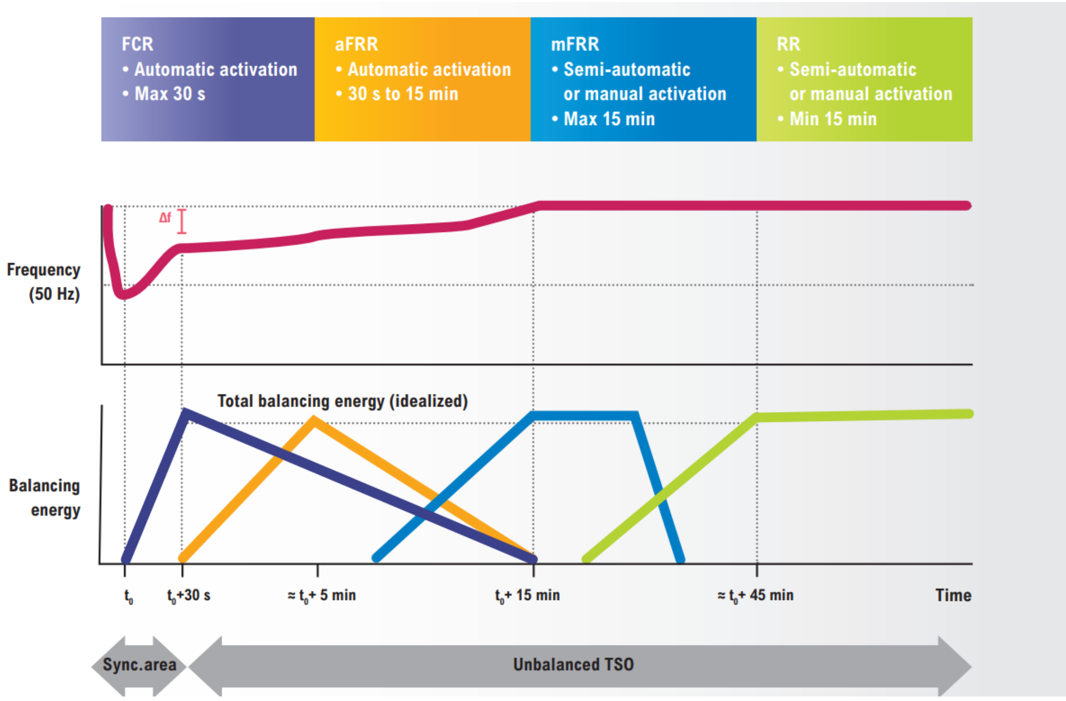


Figure 1.5: Balancing market processes for frequency restoration. Source [41]

Resources needed in case of rare events

- *Teleloading use* (*uso del telescatto*), i.e. the availability to disconnect from the grid in the event of an overload;
- *Load rejection*, i.e. the possibility for a thermoelectric generating unit, larger than 100 MW, to operate off-grid supplying only the auxiliary equipment, after an external fault;
- *Participation in the re-powering of the electrical system*, providing voltage and frequency regulation in response to a blackout, through autonomous start-up in the absence of external power supply. Alternatively, through the ability to perform load rejection and stay in this condition for a minimum of 12 hours;
- *Load interruptibility by consumer units*, i.e. the reduction or shutdown of their withdrawal, to reduce excessive active power demand.

Minimum Technical Requirements

In order to be authorised to supply dispatching resources, the plant must possess certain structural and performance characteristics [9]. Focusing only on dispatchable resources on the MSD, currently, the minimum condition required is to be a programmable unit and a relevant generation unit, i.e. with a size not lower than 10 MVA. In addition, there are further requirements depending on the type of service:

- For scheduling congestion resolution, the plant must be able to increase or decrease power by at least 10 MW within 15 minutes from the request.
- For secondary reserve, the plant must be able to increase or decrease the power by a quantity equal to the greatest between 10 MW or 6% of the maximum power within 200 seconds from the request; and to keep the service provision for a minimum of 120 minutes.
- For tertiary reserve ready, the plant must be able to increase or decrease power by at least 10 MW within 15 minutes from the request and in any case with a gradient of at least 50 MW/min; to start such changes within the first 5 minutes; and to keep the service provision for a minimum of 120 minutes.
- For tertiary reserve substitution, the plant must be able to increase or decrease power by at least 10 MW within 15 minutes from the request; to start such variations within the first 5 minutes; to complete the operation within 120 minutes; and to keep service provision without time limit.
- For balancing, the installation must be able to increase or decrease power by at least 3 MW within 15 minutes of the request, initiate such changes within the first 5 minutes and maintain service provision without time constraints.

Submission of offers on the MSD

The MSD is a market in which the type of resources exchanged, and the geographical location determine whether or not an offer is accepted, even beyond economic merit. On this market, Terna operates as the central counterpart (while for the other markets the counterpart is the GME) and offers that it accepts are remunerated at the presented price, according to the pay-as-bid method. Through this market, Terna procures the resources needed to manage and control the system (intra-zonal congestion resolution, power reserve creation, real-time balancing).
It is divided into the ex-ante MSD and the Balancing Market (MB).
On the ex-ante MSD, also called “scheduling stage” of the MSD market, energy trading takes place with reference to the hours of the following day. It is therefore linked to the DAM since the trading starts immediately after the results of the DAM have been announced, counterbalancing, in such a way, possible effects caused by the injection

and withdrawal schedules decided in the DAM. In particular, the TSO can acquire resources in order to create the necessary reserve margins to face possible contingencies according to the injection and withdrawal programs resulting from the energy-only market. Offers can be submitted from 12:55 p.m. to 5:00 p.m. on the day before the delivery day and in six scheduling sub-phases (MSD1-MSD6). In the MB, which is intended for the balancing of demand and supply offers in the real time, the acceptance of presented offers is only known after their actual activation for resolving real-time issues. There is a continuous submission of offers for the purchase and sale of energy for the 24 hours of the day of interest D. The submission of offers is possible from 10:30 p.m. on the previous day D-1 until 60 minutes before the start of the hour to which these offers relate. Only with regard to offers for balancing from Replacement Reserve (RR), the deadline for submission is 55 minutes before the hour of interest. Thus, similar to the IDM, it is a market that takes place during the day in question.

1.2 The italian electricity market reform

Non-programmable renewable power plants have a great advantage over conventional ones since, having nihil marginal costs, they are favoured in the economic merit order of the DAM. When the primary energy source is available, they satisfy and will increasingly satisfy an important share of demand. For this reason, it is expected that the total nominal capacity of renewable plants will exceed the demand peak by a wide margin, resulting in periods of overgeneration. At the same time, storage systems and other dispatchable technologies will need to be implemented to deal with low-generation periods and sharp drops in RES power.
The problem arisen in recent years is that the continuous growth of their installed capacity leads to an increasing difficulty in managing the national electricity system, due to their inherent characteristics. The transition makes grid balancing more difficult, which raises the demand for flexibility in both the long term and the short term. Indeed, this is confirmed by the 6,1 TWh increase in the volumes traded on the MSD in 2016 compared to 2011 [5]. This increase, concerning the resources needed by Terna (the Italian TSO) for dispatching, is justified as follows:

- Need for an increase in the general reserve for frequency regulation, both upward and downward:

This is the most easily intuitable result since, given the unpredictable nature of these sources, as RESs installed capacity increases, it becomes more and more difficult to predict, in real-time and with a certain precision, the portion of load not covered by them and therefore to be balanced.

- Need for greater and different use of fast reserve (secondary and tertiary ready '*secondaria e terziaria pronta*'):
  Due to the rise of non-programmable generators connected to the grid by static converters, the frequency response capabilities and grid inertia would gradually decrease. A rapid balancing is required by units with high modulation capabilities, very short response times and negligible in-service constraints [5], such as gas turbines.
- Need for an increase in switch-on of conventional programmable plants:
  The diminishing energy production from programmable plants, which are the only ones with regulation capacity, has led to a scarcity of such service (regulation capacity). To compensate for that, Terna is forced to request more frequently the switching on of conventional units that would otherwise be switched off.

From the above considerations, it is clear that the system is heading towards a situation where dispatching resources must be provided in real-time, a characteristic that the actual system is increasingly struggling to guarantee. In addition, there is the fact that the available reserve margin during peak hours is decreasing in Italy, due to the decommissioning of an increasing number of conventional plants that have reached the end of their useful life.
Furtherly, problems of infrastructural nature have also occurred, such as the overloading of some transmission grid lines or the upstream flow of power through the distribution grid. These facts are imputable to the geographical dislocation of these resources; RESs are also unevenly spread around the country, and the main consuming regions are relatively far from the places where energy is mainly produced. These facts led to a distributed generation in medium/low voltage [17].

In order to solve these critical issues, the possibility of opening up the MSD to new participants such as non-programmable renewable power plants, storage systems, and consumption units, was first introduced with the document DCO 354/2013/R/eel [18]. Subsequently, with DCO 298/2016/R/eel [19], the discussion began regarding the involvement also of non-relevant actors, both supply-side and demand-side, and how to do this, initiating a reform that is still ongoing. It is important to emphasize that the aforementioned reform does not affect the services traded on this market, but only the actors that participate in it.

From the situation just described, it is undeniable that the system needs 'flexible services'. Therefore, it needs dispatching resources provided by plants with adequate operational flexibility, i.e. rapid response and high modulation capacity. It is therefore appropriate to analyse how these services can be guaranteed by the new participants in the MSD since traditional plants are becoming less and less adequate and available.
Concerning the production of energy, the enlargement to non-relevant conventional units implies an additional contribution to all types of dispatching services already provided by currently qualified plants. In confirmation of this, according to an Authority survey for 2015, this measure allows for an increase in the installed capacity, by providing flexibility, of approximately 26 GW [5]. While of course, this cannot be the case of non-programmable renewable power plants since they are dependent on the availability of the primary energy source and therefore require certain arrangements.
Regarding storage systems, they play a key role in the system in this new context. They can, in fact, store energy produced by non-programmable plants and then release it at appropriate times. This allows maximum exploitation of these kinds of sources, avoiding system overloads and production constraints. For this purpose, batteries, which are storage systems easy to install, are well suited to congestion resolution, given the possibility of placing them in strategic locations of the grid. Another of their features is the possibility of 'peak shaving': absorbing energy from the grid when demand is low and feeding it in during peak demand hours. This operating mode combines well with the balancing service, due to the ability to keep the balance between generation and demand. This avoids the involvement of plants with higher marginal costs.
Finally, consumption units, being technologies used for other purposes than electricity generation, can provide resources for dispatching by acting on their withdrawal. They can be modulated or interrupted completely, participating in the so-called 'Demand-side Response Service'. However, attention must be paid to the terminology used when referring to these technologies, because in these cases upward service means a decrease in energy absorption from the grid, while downward service means the opposite. Special mention should be made of power-to-gas systems (section 1.3.1), which are atypical storage systems since they are seen as loads by the grid.

The common feature of all these new MSD participants, except for the relevant non-programmable renewable plants, is their small size, which does not allow them to be active in this market. This gives rise to the need to aggregate these players into a single large virtual plant, also called a Virtual-Power-Plant (VPP), capable of providing a significant resource performance to the management of the system. The commercial operator that makes this possible is the aggregator [20], which offers dispatching services on the MSD on behalf of the many small units in a certain area.
Following the considerations about the current electricity market operation and the trend regarding the flexibility products need by the TSOs, one of the most interesting technologies, expecting to have a large diffusion in the near future and that is the main focus of this thesis, is Power-To-Gas, which is addressed in the next chapter.

1.3 Value stacking

Value stacking can be defined as the inclusion and combination of multiple system services to enhance the economics of a project. This general concept can be applied to all facilities which have the chance of modulating their behaviour in time and, by doing so, to offer multiple products simultaneously, which appears to be the case of energy storage and distributed energy resources (DERs) connected to the electrical grid. Like conventional generation resources, energy storage devices can provide multiple services to the grid such as energy time-shifting, peaking capacity, and other crucial grid services which aim at their modulating power exchange in order to, for example, adjust the power balancing in real time. DERs can also offer a variety of benefits that contribute to making a project financially possible, including resilience, emissions reduction, demand response, and others.
Specifically in the DER context [32], by aggregating flexibility and providing flexibility services to various markets and market players, the aggregator of DERs is able to create value. This value can then be shared with the prosumer as a reward for shifting, reducing, or boosting his load or generation. To maximise the value of demand-side flexibility [33], aggregators must be able to take advantage from the value stacking i.e., providing different types of services to the Flexibility Requesting Parties (FRPs) from the same portfolio. Value stacking can be distinguished as follows:

1. In time: the provision of various services during different time frames. For instance, offering to the TSO a FRR balancing service in the morning and to the DSO a congestion management service in the afternoon.
2. In groups: The split-up of a portfolio in groups during a specific time period and activating one asset or a group of assets for one service and another asset or group for another one.
3. Double serving: provision of multiple services during the same time period by stacking activations from one asset, group or portfolio. This type of value stacking can be classified as double serving with single or multiple energy transfers:
    a. Double serving with a single energy transaction: it provides a combination of services with and without energy transactions. For instance, the DSO receives a congestion management service, but the aggregator and the DSO do not exchange energy. Subsequently, the reduction or increase in load or generation is offered on the wholesale market (meaning there is an energy transaction with the market).
    b. Double serving with multiple energy transactions: using the available flexibility to provide multiple services but, this time, considering energy transactions. For instance, 40% of the wind curtailment is sold on the wholesale market and the remaining 60% is activated as FRR.

In European countries, double serving is not allowed in the majority of flexibility service combinations. However, allowing the aggregator to offer several services simultaneously while employing a single asset, pool, or portfolio will benefit all parties involved economically (prosumers, aggregators, and FRPs) and will optimize the deployment of flexible assets, possibly lowering the cost of flexibility.

The study proposed in this work explores the economic opportunities that arise from enhanced opportunities resulting from a full market integration of a VPP, that combines one non-controllable and one controllable unit (PV and a P2G respectively).
This work proposes a comprehensive analysis of all the economic opportunities shown in Figure 1.6. Specifically, it investigates the balancing of forecast errors, the exploitation of arbitrage opportunities between markets, and the provision of secondary and tertiary frequency reserves.

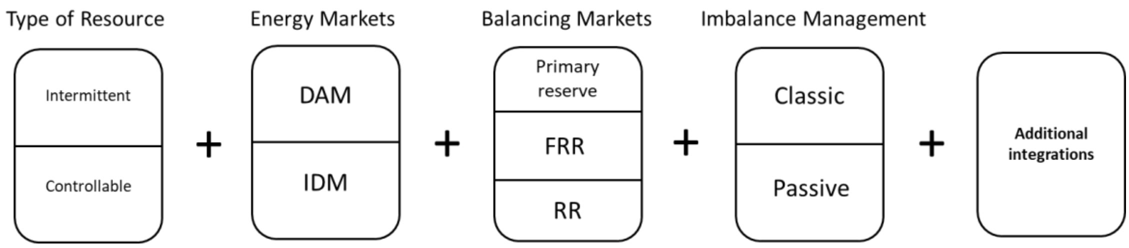


Figure 1.6: Concept of Value Stacking

1.3.1 Literature review on value stacking evaluation

This work adds to previous studies that look at the interactions of single units or VPP in different market contexts (for example single or multiple markets, in combination with controllable or uncontrollable resources, or providing additional integrations). VPPs that operate on multiple markets and that work in accordance with the principle of value stacking have been modelled looking at future energy scenarios [34] or typically include a BESS unit [35] in combination with PV units [36] and wind units [37]. Indeed, since distributed energy resources are becoming more and more widespread, photovoltaic/wind-battery systems are needed to keep the balance between demand and supply and the voltage within limits. Being able to control these systems allows to deliver multiple and stacked services. However, the intrinsic capacity constraints of BESS and the related operational restrictions put a limit on the flexibility of such VPPs. The main limitation of BESS is related to the fact that they can be charged or discharged up to a certain level which means that also the associated services are limited in such way and, once the limit has been reached, it is necessary to provide the opposite service in the opposite direction. Instead, VPPs with P2G [38, 39] units allow a wider range of flexibility and in this case any service can be offered without a set amount restriction.
Now a look at some interesting studies related to the value stacking will be presented; they are grouped according to the type of technology and combination adopted (PV, wind, BESS, P2G and others).

1.3.1.1 Combination of BESS with intermittent resources

In [34], the VPP is made up of combined heat and power plants (CHP), battery storage, biomethane, PV, wind power, and hydro power. In this context, three scenarios are defined based on simulations of future energy market conditions. These scenarios identify the possible additional revenues of the simulated virtual power plant comparing it to distributed energy resources which are not operated in a market-oriented way. Similarly, to what has been done in this thesis work, the initial phase involves importing the necessary forecast data related to weather, market prices, generation, and load into the VPP system through defined interfaces. Moreover, historical data are also incorporated as empirical values. The best bidding strategy for the operation of the DER portfolio is then determined by scheduling and trading optimization. The results of the model show that the market-oriented operation mode can increase the revenues of the VPP by 11% to 30% in the examined scenarios in 2030. However, the amount and the composition change according to the subsidies for the specific technology, the transient nature of power demand, and energy market price structures. In periods of negative electricity prices, the selective shutdown of renewable energy sources may result in additional cost savings. In addition, the control power demand for secondary and tertiary reserve is considered in all three scenarios and its increase is due to the rapid growth of the installed capacity of weather-dependent RES. Because of their flexibility to fluctuations of the spot market prices and the increasing demand for reserve capacity, battery storage, biomethane, and CHP units can offer to the VPP considerable competitive advantages.

In [36], a control method to offer distributed voltage control and frequency containment reserve (FCR) for photovoltaic-battery systems is proposed. The purpose of the FCR is to ensure an active power balance between generation and consumption within a certain area at a frequency close to the nominal frequency. When the grid frequency deviates from the nominal frequency, the FCR reserve capacity is automatically engaged. FCR is the fastest reserve required by transmission system operators (TSOs); suppliers must reach their full committed reserve capacity in less than 30 seconds. Currently, most BESSs are used for one of these three single applications: maximize PV self-consumption, reduce demand charges, or provide backup power. As a result, batteries waste more than half of their lifetime lying idle. Therefore, developing control methods that enable batteries to simultaneously perform numerous services is necessary (value stacking). Determining how much energy and power capacity of the batteries should be allocated to each service, minimizing the risk of service interruption, and reducing the risk of infringing battery constraints are difficult decisions to make when modelling such a control system.

The control methodology is divided into two phases: day-ahead and real-time.

In the day-ahead phase, the goal is to allocate fractions of the energy and power capacity of each battery to these services: maximize profits from frequency control; minimize the expected cost of reactive power compensation and batteries degradation; determine a

set of linear control policies. The optimization problem also tries to protect against operational limit violations and service unavailability. This protection is achieved by considering the uncertainty related to the photovoltaic power generation, the active power consumption, and grid frequency.
In the real time phase, policies are applied to manage frequency control while regulating voltage profiles and keeping battery energy contents within ranges.
The ability of the proposed control system to regulate network voltage profiles and respond to frequency deviations in accordance with the predetermined upward and downward reserve capacity profiles is demonstrated by simulation results over hundreds of scenarios.

The authors in [37] propose a system that consists of a large-scale wind farm coupled to an energy storage unit. The related constraints are calculated from storage device and wind power parameters in order to perform energy arbitrage, to control wind farm imbalance, and to support the grid during periods of peak demand. In [42], an optimization model for integrated wind-battery system is presented. The imbalance management is only partially assessed since the algorithm minimises only the power deviations between the real-time outcomes and the expected ones. In other words, [42] treats the imbalance only as a cost to be minimised without considering the conditions at a wider system-level. Instead, the algorithm presented in [37] changes this approach and intends to deliberately create imbalance positions, if profitable, in order to take advantage of them with the goal of maximizing the profit.
It can be noted that not all energy deviations are punished; indeed, since the imbalance prices (positive or negative) reflect the needs of the grid during real-time operation, the system is able to optimally respond to these prices by re-adjusting its delivery compared to its commitments. Compared to [42], this represents a fundamental contribution. In fact, the negative cash flows associated with the imbalance positions are now replaced by positive income streams. The considered revenues come from:

- Energy arbitrage on the wholesale energy market.
- Imbalance management mechanism of the combined system based on real-time imbalance prices.
- Participation in the Capacity Market.

1.3.1.2 Demand response

In [33], the authors examine the question to what extent demand response (DR) managed through aggregators can be employed to alleviate the effects of the solar generation uncertainty that results into aggregator imbalances. The demand response for internal balancing makes it possible to reduce these imbalances by shifting flexible loads.

Demand response is the term used to describe changes in power consumption of the consumers from their usual consumption in response to external influences like incentive payments and electricity prices. Aggregators act as intermediaries between electricity customers, who offer DR, and electricity market participants who seek for DR. To accomplish this, aggregators engage in a variety of energy markets (day-ahead and balancing markets are considered) and present DR in these markets to address with the uncertainty of RES generation. Internal balancing can be defined as the process of adjusting an electrical consumption within a portfolio in the real-time in order to minimize the expenses associated with each imbalance for the aggregator. The results demonstrate that demand response for internal balancing successfully lowers the individual imbalances of the aggregator. These outcomes, however, strongly rely on forecasts for solar generation.

1.3.1.3 Combination of P2G with intermittent resources

Regarding P2G, [38] suggests a cooperative approach between wind farms and P2G facilities to develop a coordinated bidding strategy that links the markets for electricity and natural gas. Specifically, wind farms participate in day-ahead, real-time and reserve markets, while the P2G facilities operate in day-ahead and reserve markets for arbitrage. Wind farms purchase reserve in a calculated way to avoid paying heavy imbalance penalties. However, since reserve market prices and real-time market imbalance penalty prices are uncertain and variable, wind power providers can decide whether to pay for negative imbalances or reserve capacity based on price signals. For this reason, the amount of bought reserve should be a compromise between the risk of a high penalty caused by a negative imbalance and the conservative over-purchase of reserve. The combination with P2G facilities enables their owners to exploit cheap electricity (provided by wind farms) to make a profit through arbitrage by selling the produced syngas in the natural gas market; this technique is beneficial when the price gap between electricity and natural gas is sufficiently wide. Additionally, P2G facilities can attend ancillary service markets by offering reserve services that wind farms can use. So, what has been proposed in [38] can increase the revenues of both wind farms and P2G facilities, relying on rea market data. Therefore, carefully purchasing reserve capacity in advance will alleviate the imbalance penalties during wind farm real-time market operation and using P2G facilities into reserve markets can boost the profit.

Instead, in [39], the economic feasibility of hydrogen storage in case of excess electricity production by wind power plants is examined. Stochastic modelling accounts for the risks associated with variable wind speed, variable spot market prices, and variable call of minute reserve capacity.

The advantages of hydrogen as a storage are that it can either help the wind park in using more of its capacity in case of grid failure, provide minute reserve, or take advantage of temporal price arbitrage on the electricity spot market.

The following aspects can lead to economic benefits:

1. Increase in the load factor of the wind farm: this is due to the storage capability, which allows the operator to continue producing energy even if the wind farm is disconnected from the grid for example in case of grid overload.
2. Temporal arbitrage: the possibility to purchase energy when spot market prices are low to produce hydrogen, which is then electrified again when spot market prices are high.
3. Provision of system services: thanks to the storage unit, the investor is able to provide system services in the form of reserve capacity to the grid operators.

To summarize, value stacking from deeper DER integration offers a significant added value over baseload operation. Therefore, adopting a sequential operation approach that use the entire spectrum of accessible market sessions not only significantly strengthens the economic case of the DER operator but also unlocks priceless flexibility resources for system operators.

Chapter 2

2 State of art

Power-to-gas (P2G) is a technology used to transform electrical energy into another energy carrier in a gaseous state, by means of the process of electrolysis, i.e. the separation of water into hydrogen and oxygen using electricity. This technology is developing rapidly as witnessed by both the increase in installed capacity and the reduction in costs. A recent review [10] surveyed more than 150 power-to-gas projects worldwide with and without methanation (catalytic/biological). Most of them are located in Germany, Denmark, the US and Canada. Regarding costs, the cost for electrolysers may be 70% lower by 2030 than they are today. In addition to the estimated decrease in the price of renewable energy, this can lower the price of renewable hydrogen to a range of 1,3-4,5 $/kg H2 (equivalent to 39-135 $/MWh) [11]. In general, the most economical hydrogen production conditions depend on the combination of the availability of a cheap surplus of electricity from non-programmable renewable sources, the capital and operating costs of electrolysers, and the market price of electricity [12]. Furthermore, to consider the produced gas to be renewable (green hydrogen) and thus useful for decarbonisation policies, the electricity used in the process must come from renewable sources. At the moment, on a total hydrogen demand of 94 Mt in 2021, the production of low-emission hydrogen (green hydrogen) was less than 1 Mt, with almost all of it coming from plants using fossil fuels with CCUS technology [11].

2.1 Scheme of a typical P2G plant

Concerning Figure 2.1, only the electrolysis process is needed to produce hydrogen, and it requires electricity and water as input. Whereas for the production of SNG, it is necessary to add a further step consisting of methanation, which has as input the hydrogen produced by the electrolysis and CO_2, without additional primary energy. It is necessary to interpose hydrogen storage between the two processes, due to their different load ranges and inertia. In addition, there are also by-products among the outputs, which can represent additional sources of gain. In particular, electrolysis also produces oxygen, while methanation is exothermic and therefore releases heat. Here is an illustration of the components of a typical P2G plant that directly affect the operation of an electrical network [13].

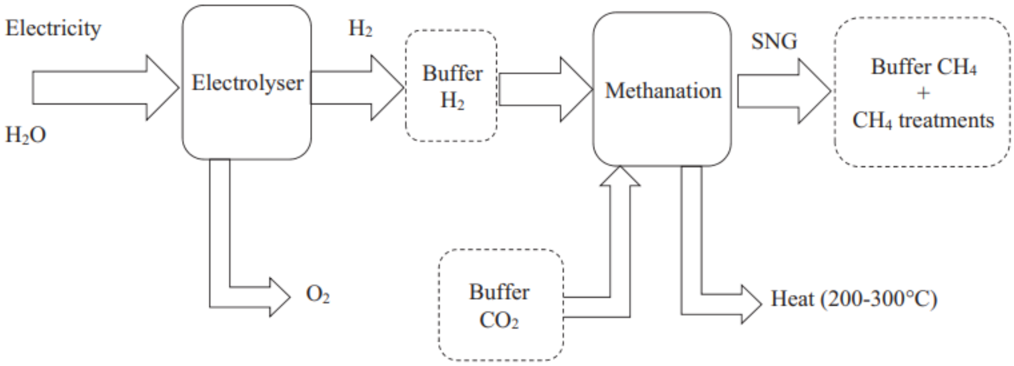


Figure 2.1: Scheme of a typical P2G installation [13].

Since in this work, only the sale of hydrogen is considered leaving aside other options such as H_2 storage and the delivery to a specific end-user, a brief presentation of the main electrolysers is necessary without investigating the other processes.

2.2 Principles of water electrolysis

2.2.1 Thermodynamics

Water can be separated into its elemental components, hydrogen and oxygen, according to the reaction (2.1):

$$H_2O\ (l) \rightarrow H_2\ (g) + \frac{1}{2}\ O_2\ (g) \tag{2.1}$$

At 25 °C and 1 bar, water is liquid while H_2 and O_2 are gaseous. If this chemical reaction takes place under isothermal conditions and follows a reversible path, the Gibbs free energy change (ΔG) is defined as:

$$\Delta G = \Delta H + T\Delta S \tag{2.2}$$

where T is the absolute temperature, ΔH is the enthalpy change and ΔS stands for entropy change.

At 25 °C, $\Delta G^0 = 237{,}23\ kJ/mol$, $\Delta H^0 = 285{,}83\ kJ/mol$, and $\Delta S^0 = 163{,}09\ kJ/mol$. Up to very high temperatures (over 2000 °C), the enthalpy change is positive, indicating that the process is endothermic ($\Delta H > 0$); the entropy change is positive since 1 mol of water results in 1,5 mol of gases; therefore, since the Gibbs free energy change assumes a positive value, the reaction is non-spontaneous. The total amount of energy needed to dissociate water is represented by the enthalpy change. A part of this overall energy is electric, and this part corresponds to the Gibbs' free energy change ΔG while the remaining part is thermal energy, and it is equal to the product between the temperature at which the process is run and the entropy change.

Considering water vapor, which is employed in SOEL cells, it can be dissociated according to:

$$H_2O\ (g) \rightarrow H_2\ (g) + \frac{1}{2}\ O_2\ (g) \tag{2.3}$$

in this case, $\Delta G^0 = 228{,}61\ kJ/mol$, $\Delta H^0 = 241{,}81\ kJ/mol$, and $\Delta S^0 = 44{,}32\ kJ/mol$. The enthalpy difference (44,02 kJ/mol) between reactions (2.1) and (2.3) corresponds to the enthalpy of vaporization of water.

The standard thermodynamic voltage (E^0) for electrolysis is given by:

$$E^0 = \frac{\Delta G^0}{nF} \tag{2.4}$$

where n is the number of electrons transferred per reaction (n = 2) and F is the Faraday's constant (F = 96485 C/mol). For liquid water at 25 °C, $E^0 \approx 1{,}23\ V$.

The enthalpy or thermoneutral voltage (E_{Therm}) is given by:

$$E_{Therm} = \frac{\Delta H^0}{nF} \tag{2.5}$$

For temperatures below 100 °C, $E_{Therm} \approx 1{,}48\ V$.

If the voltage applied to the electrolysis cell (U_{cell}) is < E^0, the non-spontaneous reaction does not take place because there is not enough energy. If $U_{cell} > E^0$ and < E_{Therm}, electrolysis occurs only if the heat from the surroundings is available; otherwise, the temperature of the electrolysis cell would decrease if no heat were supplied. At E_{Therm}, the dissociation of water occurs at constant temperature, with no heat exchanged to the environment; for this reason, this voltage point is named "thermoneutral". When $U_{cell} > E_{Therm}$, there is a practical interest in electrolysis. Under these circumstances, as the current density increases and more heat is generated, the process becomes exothermic.

Since entropy change strongly depends on temperature growing significantly with it and enthalpy change does not vary so much, the Gibbs free energy and related voltage fall. Consequently, as the temperature increases, less electrical energy is required to split the water. At higher operating temperatures, water electrolysis becomes less expensive because the cost of heat (to raise the temperature) is typically considerably lower than the cost of electricity.

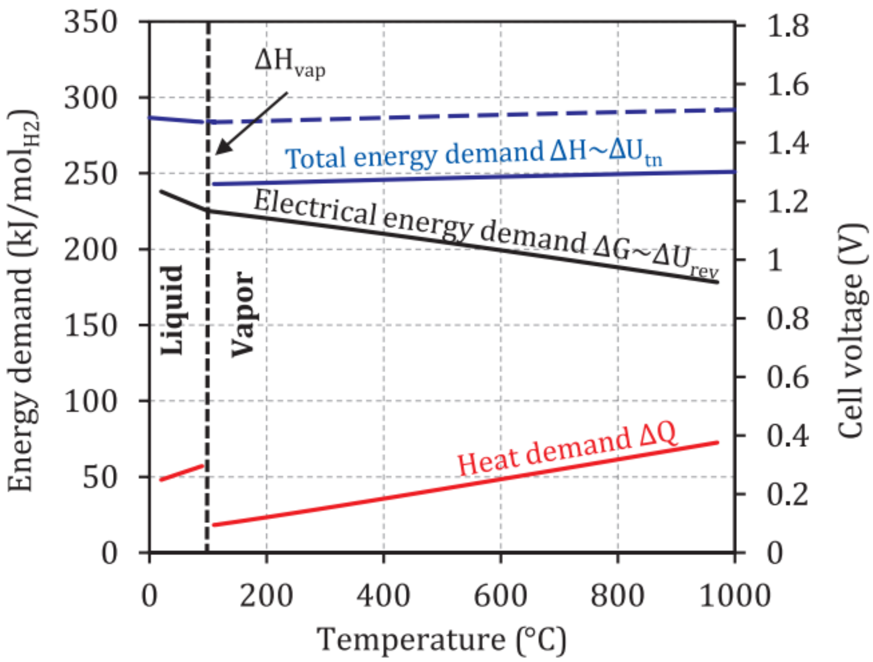


Figure 2.2: Total (ΔH), thermal (Q) and electrical (ΔG) energy demand of an ideal electrolysis process as function of the temperature. [14]

Nernst formula (2.6) gives the thermodynamic voltage needed to split water (E) as a function of E^0, T, water activity (a_{H_2O}), and partial pressure of the products (p):

$$E = E^0 + \frac{RT}{nF} \ln \frac{\sqrt{p_{O_2}}\, p_{H_2}}{a_{H_2O}} \tag{2.6}$$

According to equation (2.6), E increases as operating pressure increases, this means that water electrolysis requires greater electrical power to be performed. However, pressurized water electrolysis is intriguing because it has the potential to considerably reduce the energy consumption of the mechanical compression of hydrogen, which is normally necessary for transport and storage.

2.2.2 Efficiency and performance

The two voltages E and E_{Therm} can be used to define the water electrolysis efficiency:

$$\eta_{\Delta G} = \frac{E}{U_{cell}} \tag{2.7}$$

$$\eta_{\Delta H} = \frac{E_{Therm}}{U_{cell}} \tag{2.8}$$

As was previously said, electrolysis is of practical interest when $U_{cell} > E_{Therm}$, which is why $\eta_{\Delta H}$ is more frequently used. $U_{cell} \approx E_{Therm}$ and $\eta_{\Delta H} \approx 100\%$ at very low currents. However, U_{cell} must be considerably greater than E_{Therm} in order to have a significant flow of current across the system (and, subsequently, a larger hydrogen generation rate) to reach fair capital expenses (cost/$Nm^3 H_2\ h^{-1}$). An increasing portion of the electrical work supplied to the system is degraded into heat as the current increases. Under these circumstances, U_{cell} must rise to compensate for this energy loss, lowering the cell efficiency. The main causes of voltage loss in an electrolyser are charge transfer (kinetic) activities at the electrolyte/electrode interfaces, ionic transport through the electrolyte, and electronic conductivity.

Considering a current density i ($A\,m^{-2}$), U_{cell} can be defined as:

$$U_{cell} = E + \eta_a(i) + \eta_c(i) + IR_{(elect+ionic)}(i) \tag{2.9}$$

where $\eta_a(i)$ and $\eta_c(i)$ are the charge transfer overvoltage at the anode/electrolyte and cathode/electrolyte, I is the total current, and $R_{(elect+ionic)}$ is the sum of ionic and electronic resistances.

Figure 2.3 illustrates the performance of an electrolyser which is typically represented by a polarization curve that shows how U_{cell} (therefore the efficiency) changes as a function of the current density. The efficiency of the electrolysis process $\eta_{\Delta H}$ is typically greater than 75%, and with some types of electrolysers, it can be very close to the unit. However, other energy losses, namely those related to the electrical energy source, must be taken into account when considering a whole system of hydrogen production via electrolysis.

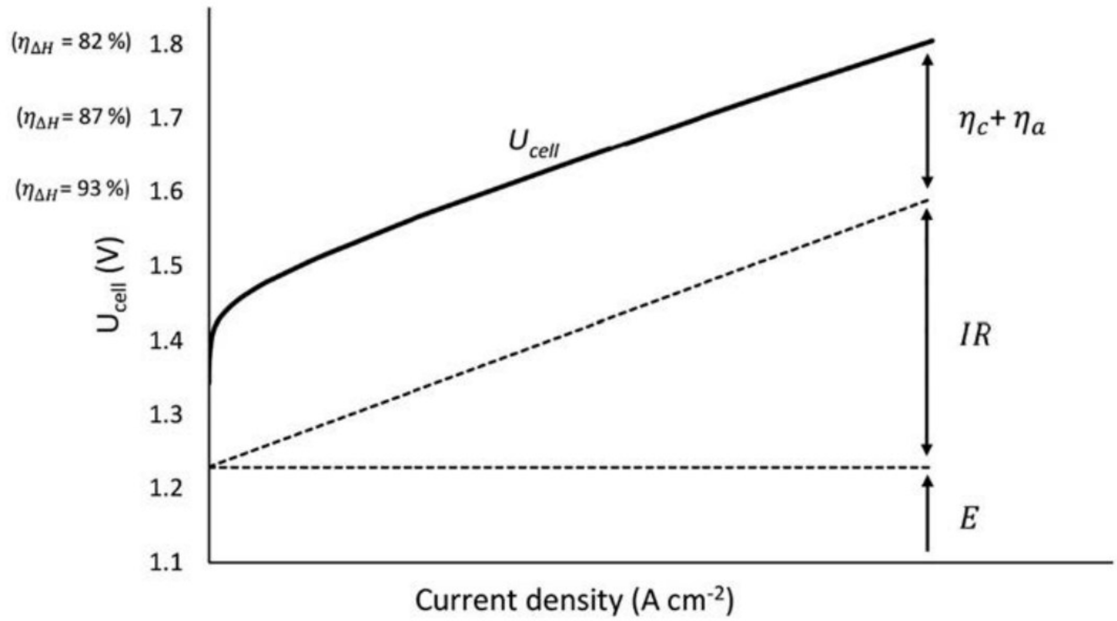


Figure 2.3: Example of a polarization curve (Ucell vs current density) of an electrolyser cell [15].

2.3 Electrolysers

The electrolyser is the tool used to conduct water electrolysis. An electrolyser is composed of at least one electrolysis cell. Usually in practice, an electrolyser is a stack of numerous identical elementary electrolysis cells connected in series. An electrolysis cell is a galvanic device inside which there are two electrodes: the cathode and the anode, connected to the electric current and separated by an electrolyte. The cell is subject to a continuous current flow while in operation. Mobile ions migrate along the electrolyte from one electrode to the other while electrons flow through the external circuit connecting the two electrodes. The complete chemical reaction can be divided into two steps that occur at the electrode/electrolyte interfaces. At the cathode, which is negatively charged, the reduction reaction takes place, while at the anode, which is positively charged, the oxidation reaction takes place [15]. Depending on the technology adopted, and more precisely on the type of electrolyte interposed between the two electrodes, the charge carriers change, which may be: OH^-, H^+ o O^{2-}. The various technologies with which water electrolysis can be performed are named after the type of electrolyte used in them. In particular, there are three of interest for a P2G plant: alkaline electrolysis (AEL), polymer electrolyte membrane electrolysis (PEM) and solid oxide electrolysis (SOEL).

2.3.1 Alkaline electrolyser – AEL

In commercial applications around the world, alkaline water electrolysis is a well-recognized, mature technique for the production of industrial hydrogen up to the multi-megawatt scale. The commercialization of this technology dates back to the beginning of the 20th century [15]. In the electrolysis cell, the electrodes are immersed in a liquid electrolyte and separated by a diaphragm. One mole of hydrogen (H_2) and two moles of hydroxyl ions (OH^-) are obtained from the reduction of two moles of alkaline solution at the cathode side of the alkaline electrolyser. The produced H2 can be collected from the cathodic surface. The remaining hydroxyl ions (OH^-) are then transferred to the anode side through the porous diaphragm. The hydroxyl ions (OH^-) are released at the anode, where they result in the production of one molecule of water (H_2O) molecule and half molecule of oxygen (O_2) [16]. The partial reactions at the electrodes are:

Anode $$2OH^-(aq) \rightarrow \frac{1}{2}O_2(g) + H_2O(l) + 2e^- \quad (2.10)$$

Cathode $$2H_2O(l) + 2e^- \rightarrow 2OH^-(aq) + H_2(g) \quad (2.11)$$

The main components of an alkaline water electrolysis cell are diaphragms, current collectors (gas diffusion layer), separator plates (bipolar plates), and end plates [16].

A diaphragm is a porous material with an average pore size of less than 1 mm. It permits to transmit the water and hydroxide ions (OH^-) from the cathode side to the anode side of the cell keeping, at the same time, the produced gases H_2 and O_2 separated. To enable ionic conduction between the electrodes, a liquid electrolyte is poured into this porous separator. The main characteristics that should be considered while choosing the diaphragm material are strong permeability to water, high ionic conductivity, and high corrosion resistance in alkaline environments. When compared to a PEM electrolyser, the diaphragm is responsible for an additional ohmic loss, which restricts the range of current densities. A typical working current density is $500\ mA\ cm^{-2}$ [15].

An aqueous solution of potassium hydroxide (KOH) at a concentration of 25–30% is the most typical used electrolyte. As the distance between the two electrodes increases, more electrolyte solution is required and higher ohmic losses occur. On the other hand, when the electrolyte volume is too small, a significant variation in reactant concentration happens during the operation, which lowers ionic conductivity. Due to these factors, the electrolyte content must be carefully controlled and replenished on a regular basis to prevent the build-up of impurities from the incoming water, corrosion of the metallic components, electrode degradation, and separator corrosion.

The electrodes are placed next to the electrolyte, their surface is covered with electrocatalysts that are needed to start the reactions. Electrodes typically consist of a porous metal structure (mesh, foam, perforated metal, sintered bodies, etc.) and of a large surface area coated with a catalyst. Alkaline electrolysis allows the use of non-noble metals like Ni, Co, or Fe, in contrast to PEM electrolysis, which requires noble metals to be employed because of the highly acidic media [15].

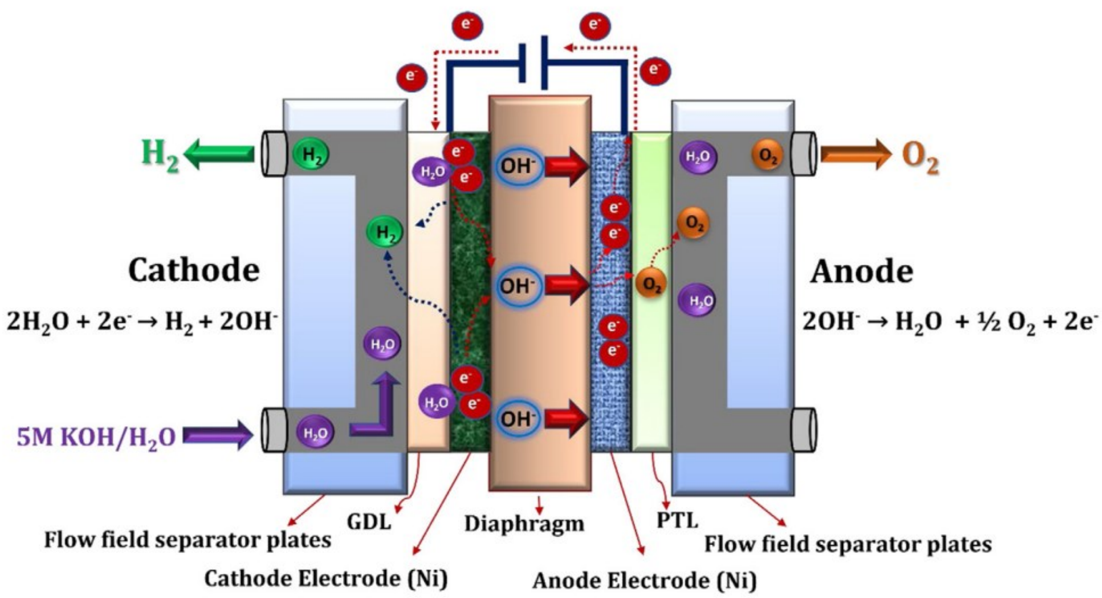


Figure 2.4: Scheme of alkaline water electrolysis working principle [16].

The important characteristic that an electrolyser must have to operate in a P2G plant is the operational flexibility. It must be able to work with a variable load over the time, without having repercussions that compromise its integrity and performance. In general, however, such systems respond very quickly to these types of signals. If kept at constant temperature and pressurised, it can go from stand-by to full load taking between 1 and 5 minutes. If, however, cold start-up is considered, i.e. when the electrolyser must first be brought to the operating temperature, then the operation to reach maximum load can take up to two hours. Keeping an electrolyser in stand-by mode involves losses that can weigh heavily in the economy of a P2G system. Indeed, it may remain in this state for several hours a day while waiting for favourable conditions in which to operate. In general, these losses may be due to the application of a protective anti-degradation current to the electrodes or to an auxiliary heating system to reduce reaction times, and these losses are common to all three technologies [14].

Alkaline electrolysis has some advantages overall, including the possibility to use inexpensive materials like Ni and a long lifetime (more than 10 years compared to 5 when using PEM electrolysis). Alkaline electrolysers, on the other hand, produce gases that are of lower purity, operate at moderate current densities, and are not well suited for use with intermittent power sources [15].

2.3.2 Polymer electrolyte membrane electrolyser – PEM

Globally several manufacturers developed large-scale (up to MW) PEM water electrolysers for industrial and transport applications. Regarding the working principle, at the anode, water is decomposed into oxygen, protons (H^+) and electrons. The oxygen is eliminated from the anode surface, the protons travel through the proton-conducting membrane toward the cathode side and electrons also move towards the cathode thanks to the external electric circuit. At the cathode, the recombination between protons and electrons happens producing H_2. The partial reactions at the electrodes are:

Anode
$$H_2O(l) \rightarrow \frac{1}{2}O_2(g) + 2e^- + 2H^+(aq) \tag{2.12}$$

Cathode
$$2e^- + 2H^+(aq) \rightarrow H_2(g) \tag{2.13}$$

The main components of a PEM water electrolysis cell are the membrane electrode assembly MEA (consisting of membrane and anode, cathode electrode materials), separator plates (bipolar plates), and gas diffusion layer and end plates.

The most used membrane is Nafion® which provides many advantages like high current density, high proton conductivity, high mechanical strength, and chemical stability. It fulfils the role of the electrolyte and therefore it divides the electrolysis cell in two halves in order to provide electrical insulation to the electrodes and to separate the produced gases in the two sides.

The electrodes are installed right next to the membrane. They include a catalyst coating on them that must be composed of a noble metal with a high economic value given the acidic environment created by the membrane to which they are subjected. In particular, platinum for the cathode and iridium for the anode.

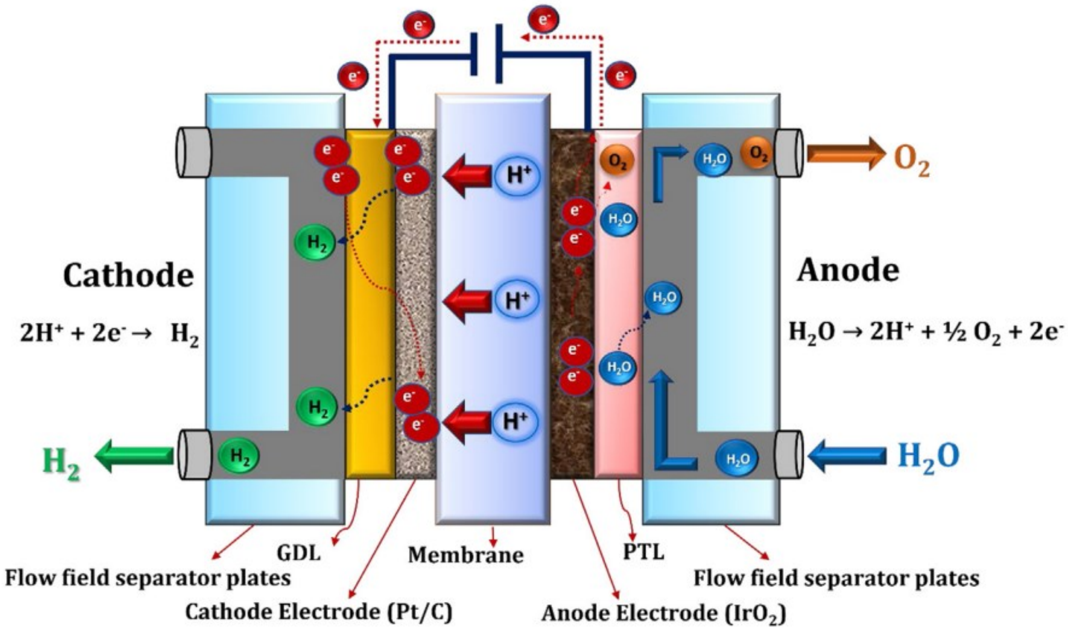


Figure 2.5: Scheme of PEM water electrolysis working principle [16].

The main advantages of PEM electrolysis are high current density up to 3 A/cm^2 and great flexibility. Higher current density means higher theoretical specific hydrogen production which can be four times greater than that of AEL technology cells. Regarding the flexibility, among the great advantages there is their wide load range; they can in fact work without any problems between 0-100% of the nominal load and, according to the manufacturer's specifications, even heavily overloaded. This is due to the fact that, unlike AEL electrolysers, the electrolyte (in this case the membrane) has low gas permeability. This characteristic does not allow, at low load regimes, the diffusion of hydrogen to the oxygen side, thus preventing the formation of a dangerous flammable mixture. The second advantage is the rapidity with which the load can be varied, which makes this technology ideal for coupling with intermittent power sources. If the system is kept at constant temperature and pressure, the transition from stand-by to maximum load is in the order of seconds. In the case of cold start-up, however, the time to reach maximum load is between 5-10 minutes [14]. The main drawbacks are the high costs due to the use of expensive materials (titanium in the BPPs and PTLs (Porous transport layers) and the noble metals used as electrocatalysts) and the low durability of the components [15].

2.3.3 Solid oxide electrolyser – SOEL

At the moment, this technology is at a pre-commercial stage. It is considered very promising and will be a viable option for power-to-gas systems in the future. Concerning the working mechanism, solid oxide water electrolysis operates at high temperatures, it produces hydrogen and oxygen while consuming water in the form of steam. Specifically, at the cathode side, water is reduced generating hydrogen (H_2) and oxide ion (O^{2-}) by adding two electrons. The hydrogen is collected while the oxide ion travels through the ion exchange membrane toward the anode side. Here O^{2-} is furtherly reduced generating oxygen and electrons, the oxygen is released from the anode surface and the electrons move to the cathode side travelling through the external circuit by the cathode's positive attraction [16].

Anode
$$O^{2-} \rightarrow \frac{1}{2}O_2(g) + 2e^- \tag{2.14}$$

Cathode
$$H_2O(g) + 2e^- \rightarrow O^{2-} + H_2(g) \tag{2.15}$$

SOEL cell consists of three main components: two porous electrodes and a ceramic electrolyte capable of conducting O^{2-} iones. The most used electrolyte is yttria-stabilized zirconia (YSZ) that guarantees great performance at high temperatures (700–850 °C) and high ionic conductivity. The most popular anode electrodes are made of perovskite materials, whereas the most advanced cathode material is a ceramic metal made of YSZ and nickel, which is a non-noble metal catalyst with good electronic conductivity [16].

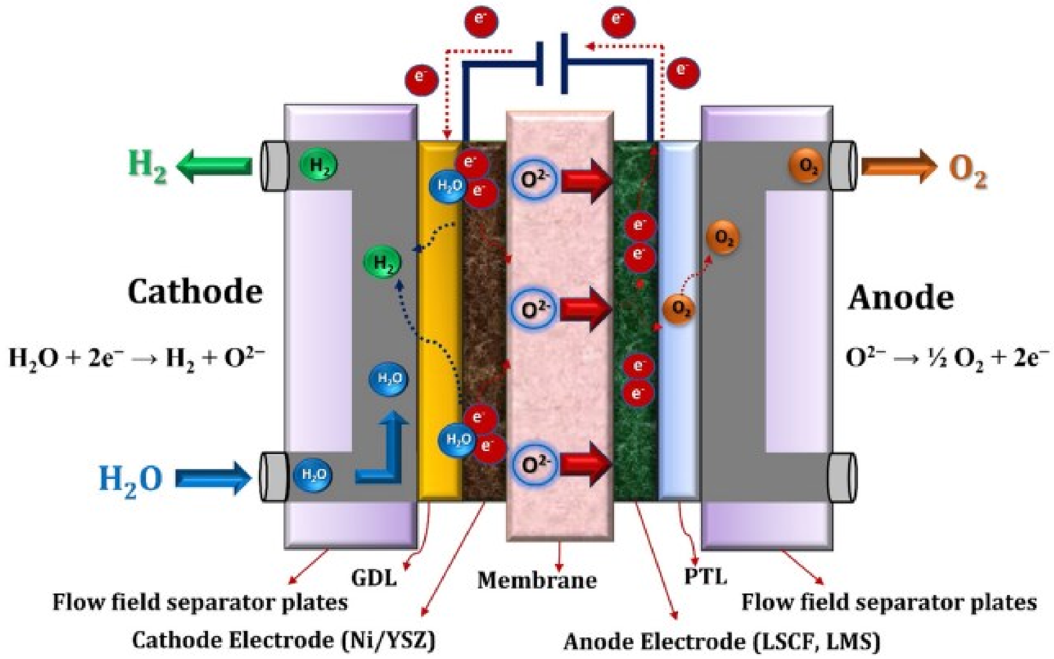


Figure 2.6: Scheme of solid oxide water electrolysis working principle [16].

As mentioned above, the solid oxide water electrolyser typically works with steam water at high temperatures. This can significantly lower the power needed to divide the water into hydrogen and oxygen and thus increasing the energy efficiency. An improvement in energy efficiency leads to a significant decrease in the price of hydrogen since the power consumption is the main factor in the cost of producing hydrogen by electrolysis. In addition, solid oxide water electrolysis presents two important benefits over the other electrolysis methods. The first advantage is its high working temperature, which favours the thermodynamic and the kinetic of the reactions and revealing also incomparable conversion efficiency. The second is that this type of electrolysis can be easily integrated thermally with downstream chemical synthesis, such as the production of ammonia and methanol. Additionally, solid oxide water electrolysis doesn't require electrocatalysts made of noble metals. Despite these advantages, SOEL has not yet been commercialized due to insufficient long-term stability. With yttria-stabilized zirconia thin electrolyte, the declared stability is just 20,000 hours [16].

Regarding the flexibility, another very important aspect is that a stack for electrolysis using SOEL technology can operate in a reversible way using the gas, which normally comes out as output, as input to produce electricity and heat. This results in a load range that varies from -100% to 100% of the nominal load, requiring 15 minutes to move from 1% to 100%. The disadvantage is that the system must be always kept at elevated temperatures to guarantee reaction times that are competitive with those of other technologies. Otherwise, a period of cold start-up lasting several hours is required to avoid overstressing the materials that make up the device [14].

Table 2.1: Main features of different types of electrolysers [15].

	Proton exchange membrane electrolyzer	*Alkaline electrolyzer*	*Solid oxide electrolyzer*
Electrolyte	Perfluorosulfonic acid (PFSA) membrane	KOH solution Anion Exchange Membrane (AEM)	Ceramic membrane, usually Yttria-stabilized zirconia (YSZ) or Scandia-dopedZrO_2
Electrodes	Anode: Iridium or Iridium oxide Cathode: Platinum on carbon	Anode: Ni Cathode: Mixed metal oxides, Ni/Co/Fe, etc.	Anode: Lanthanum strontium manganite/YSZ Cathode: Composite cermet, usually a nickel/YSZ cermet
Operating temperature	Ambient to 100 °C	Ambient to 120 °C	700–1000 °C
Operating pressure	Ambient to 30 bar	2–30 bar	10–40 bar
Operating current density	Up to 3 A cm^{-2}	0.5 A cm^{-2} (conventional) 1.25 A cm^{-2} (zero-gap)	0.5–1 A cm^{-2}
Efficiency ($\eta_{\Delta H}$)	70–80%	60–80%	Up to 100%
Load cycling[a]	Good	Weak	Good
Stop and Go cycling[b]	Good	Weak	Weak
Technology status	Mature	Mature (KOH solution electrolyte) Demonstration/R&D (AEM electrolyte)	Demonstration/R&D
Advantages	High current density range High hydrogen purity Great flexibility (On/Off cycling and transient operation)	Relative low cost High lifetime	High efficiency Non-noble metals Possibility of various important co-electrolysis reactions
Disadvantages	High cost (noble metals and Ti) Low durability	Low hydrogen purity Moderate current densities Weak load cycling	Improper sealing Low durability

[a]The ability to respond to rapid and repetitive changes in load, concerning how fast the electrolyzer responds to such variations and how they affect its lifetime.
[b]The capability of being switched off/on quickly and repetitively.

2.4 Flexibility offered by H_2 and P2G

Different types of supply and demand-side options can contribute to the flexibility of electricity systems, such as flexible conventional power plants, integration with neighbouring markets through improved cross-border transport capacity, curtailment of renewable production, storage, and more flexible loads. Many countries, including the EU, emphasize hydrogen's ability to provide flexibility (EU hydrogen strategy, [21]). In this situation, Power-to-Gas (P2G) plants, which generate hydrogen through electrolysis, can provide flexibility in three ways [22]:

- Time flexibility. Since hydrogen can be stored for a short or long time, hydrogen producers can adjust their position when they consume electricity depending on the energy market state without sending it immediately to the users. To this end, power-to-gas technology is particularly interesting when used in combination with surplus electricity production from intermittent sources, such as solar and wind, as it offers the possibility of storing the energy produced at times of high production but low demand, allowing for more efficient integration of renewable sources [23]. The role of P2G as a flexible energy source has been examined and compared to other options such as the battery, pumped hydro, and compressed air (hydrogen has an energy density that is 250 times higher than the one of pumped hydro storage) [24]. They discover that, compared to alternatives, P2G can store enough energy in reasonably sized facilities; however, it shows a relatively low efficiency and high costs (low efficiency implies either extra generation capacity to meet the demand either an extra storage capacity to meet the system needs; consequently, this corresponds into additional investments in both cases). Due to these high costs, it is generally not considered a viable storage option. Another way to provide flexibility to the electricity market by exploiting the P2G is adopting an energy hub concept in which electrolysers produce hydrogen when the electricity price is low, it is stored, and then it is used in fuel cells to generate electricity when the price of electricity is high. However, the efficiency of this conversion process is quite low and hydrogen storage is economically less attractive because it is difficult to compress [25]. This is indeed demonstrated by the majority of the large-scale P2G demonstration projects in which hydrogen is produced in order to be used also in other industries, such as transport, heating, and manufacturing [26].

- End-use flexibility. Hydrogen can be used to transport renewable energy to other sectors that require liquid or gaseous energy rather than electricity. It can be transported to another point of use through the natural gas grid ('blending' it with natural gas) or piped to dedicated infrastructures and used as it is for example as a fuel for transport vehicles. Alternatively, hydrogen can be combined with CO_2 to produce methane gas (methanation process), which can be fed into the natural gas grid without technical constraints but requires a CO_2 source for its production [21]. Regarding the injection of hydrogen into the natural gas grid, 'blending' can create problems for the infrastructure and for some users, and special precautions have been taken for the first injections. In Germany, there are several plants that, using power-to-gas technology, inject hydrogen into the natural gas infrastructure, or in sections of the network where there are no service stations with vehicle gas distributors or by limiting the hydrogen injection to 2% blending with natural gas if there are service stations that withdraw from the gas network. Also in Italy, an experiment has recently been conducted to introduce natural gas and hydrogen mixtures on a section of the network with only industrial users [21].

  This type of flexibility strengthens the sector coupling between the electricity, gas and hydrogen markets and it can be done in two ways: one-way and two-way. In the case of one-way sector coupling, the P2G produces hydrogen using

electricity and then it is supplied to external consumers replacing either the hydrogen derived from natural gas or simply natural gas. With the two-way sector coupling, the P2G can also work in the opposite way using the produced hydrogen to generate electricity. As a result, P2G is able to provide the electricity market with both supply and demand-side flexibility [22]. The importance of P2G in connecting the gas and electricity sectors is the topic of recent studies [27, 28]. They analyse the case in which P2G generates hydrogen using electricity and then injects it into the gas network. What has been found is that P2G plays a significant role whenever there is a high penetration of variable renewable resources and the price of electricity is low. The potential of P2G as a source of flexibility in electricity markets with high renewables share and high hydrogen demand has been addressed also from a social-welfare point of view (measured as the sum of consumer and producer surplus) [22]. What has been found is that investments in P2G become profitable when the carbon emissions are valued at 150-170 €/ton. Therefore, at lower carbon prices, P2G can only become a valuable source of flexibility with lower installation costs and higher electrolyser efficiencies. Since this carbon price is much higher than the current one, for example in the European Emissions Trading Scheme, it should be concluded that P2G is currently not a profitable social-welfare solution for providing flexibility to a context with high renewables shares.
- Locational flexibility. Hydrogen can be used to deliver energy to areas where electricity grids are less developed.

As a result, P2G has a huge potential to provide flexibility to the power system, at least technically.

Chapter 3

3 Model structure

In this chapter, after a brief introduction to the concept of optimization, the peculiarities of the original model will be described in detail highlighting the common aspects with the new code, and the modifications made during the thesis work will be presented.

3.1 Introduction to optimization

Any situation that involves decision making requires optimal planning, designing, and operation to minimize (or maximize) the results. In fact, there are numerous types of decisions we have to make in our daily lives; some of them involve complex issues, while others deal with much basic issues, like discovering the item in the shop with the lowest price or choosing the fastest way to get somewhere. In each of these circumstances, we must consider the factors affecting the underlying issue and identify the optimal solution that will enable to reduce costs, travel time, and other factors to a minimum. However, it becomes difficult to make optimal decisions because they cannot be based solely on experience and intuition as the system representing the problem becomes more complex (i.e., more variables and restrictions are taken into account). These problems become increasingly harder to solve because of the multi-objective criteria complexity, uncertainty in the system description parameters, and other factors. The development of computers and computational theory made it evident that putting tasks in a mathematical form made solving optimization problems much more practicable. The arrival of computers provided a much more viable alternative. Today, mathematical optimization is a crucial tool in all areas of engineering, business, finance, chemistry, biology, and other fields. When it comes to the planning, sizing, and operation of the energy system, energy utilities in particular use mathematical optimization as a fundamental tool.

To summarize, the definition of mathematical optimization is: "*the process of maximizing and/or minimizing one or more objectives without violating specified design constraints, by regulating a set of variable parameters that influence both the objectives and the design constraints* [29]".

3.1.1 Building a model

In this work, optimization techniques will be applied to solve specific problems, which will be described by a mathematical model and then implemented to be solved by the calculator. Creating a suitable model is the first stage in the optimization process. Creating a model means defining the process of expressing the problem's variables, constraints, and objective in mathematical terms [30].

An *objective* is a quantitative measure of how well the system we're trying to optimize is performing. The objective function numerically represents a quantity obtained through operations on the variables of the problem having applied a weight on their value, which will be minimised or maximised through optimisation. In some applications, two or more objectives could be required to fulfil different requests. Electrical utilities, for instance, could aim to minimize the operating costs and the energy losses associated with system dispatching. Whether we focus on the first or second objective, the problem solution will undoubtedly be different. If both objectives were taken into consideration, the solution would include a trade-off between the two objectives.

The *variables* are the components of the model for which we want to find values. They can be distinguished between decision variables and state variables. The former are the quantities of the system whose value is unknown and to which the optimiser will assign a value such that the objective function is minimised or maximised. They may be scalars, arrays or matrices (where, of course, using vectorization helps defining a set of equations involving a set of optimization variables at once). Three types of variables will be considered in this work: binary, integer or continuous. Binary variables assume values of 1 or 0, while integer and continuous ones assume values defined in the intervals imposed through constraints and belong to the set of integers $\mathbb{N}$ and reals $\mathbb{R}$, respectively. The second type focuses on the additional variables that are determined after the decision variables have been defined and are used solely to describe the mathematical model under examination. Consider, making an example related to this work, the power absorbed by the P2G, as a decision variable and, the resulting hydrogen production, as a state variable.

The *constraints* are functions that define the limits of the domain of the system, how the variables are linked together and the permitted values that variables can assume. They can be expressed using both equalities and inequalities. Therefore, constraints can be considered as conditions to be satisfied in order to obtain the solution to the problem under consideration. For example, in the plant under examination, the flexibility services (upward and downward) are limited to the rated power of the P2G.

In mathematical terms, the problem of optimizing an objective function $f(x)$ on the variables x and subject to constraints can be stated in this way:

$$\text{minimize} \qquad f(x)$$

$$\text{subject to} \qquad c_i(x) = 0 \qquad \forall i \in I$$

$$c_l(x) \leq 0 \qquad \forall l \in L$$

, where I and L are index sets for equality and inequality constraints, respectively. The feasible set is the set of points x that satisfy the constraints.

3.1.2 Optimization problem types

Identifying the category of optimization to which the model belongs is the second step in the optimization process. This stage is crucial since it will establish which algorithm, approach, and software best fits the considered situation. A good view of the optimization classification is provided by Figure 3.1.

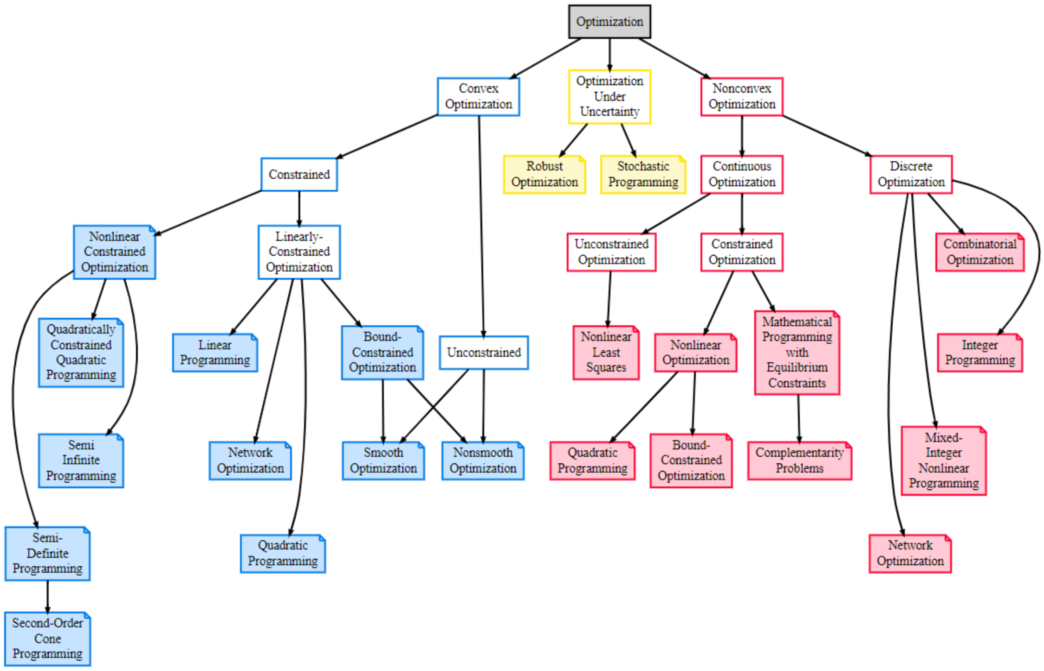


Figure 3.1: Classification of optimization problems. Source: [30]

- ***Convex Optimization*** versus ***Nonconvex Optimization***

A convex optimization is a problem in which the constraints are convex functions[4], and the objective is a convex/concave function depending on if minimization/maximization is needed. Linear functions are convex and therefore the respective optimization problems are as well. A convex optimization problem has a feasible region that is convex and is bounded by convex constraint functions. There can only be one globally optimal solution for a convex objective function and convex feasible region. There are numerous methods to address convex optimization problems.

Any optimization problem in which the objective or any of the constraints are non-convex is referred to as a non-convex problem. Many feasible regions and numerous locally optimal locations could exist for such a problem inside each region. Finding out that solution to this problem is not feasible or that the objective function is unbounded, or that the global optimum is across all feasible regions can take a lot of time.

[4] Geometrically, a function is defined as convex whenever a segment that goes from point (x1, f(x1)) to another point (x2, f(x2)) lies on or above the graph of f.

- *Continuous Optimization* versus *Discrete Optimization*

Variables in a generic model may assume values chosen from a discrete set or, in some circumstances, from a set that admits any real value. The discrete optimization problem arises when a model is exclusively described by discrete variables, which are frequently a subgroup of integers. More specifically, we are dealing with a binary optimization problem when the subgroup of integers is constrained to binary values (0 and 1). Models with only continuous variables, on the other hand, are continuous optimization problems. Different approaches to address the problem are possible depending on the considered situation; a combination of the cases mentioned above actually constitutes the most common case. Continuous optimization problems are typically easier to solve; this smoothness is due to the fact that the objective function and the constraints values at a point x can be used to extrapolate information about points in the nearby of x [30]. Although it is also possible to effectively handle discrete optimization problems because of the recent significant advancements in computing technology. Furthermore, many discrete optimization problems can be split into a series of continuous subproblems making it possible to use the fastest continuous optimisation.

- *Unconstrained Optimization* versus *Constrained Optimization*

A constrained optimization problem is defined when one or more equality or inequality constraints impose limits on the optimization variables. If not, it is the case of unrestricted optimization problem. Unconstrained problems typically have more theoretical than practical values since the majority of practical problems are limited by constraints [29]. When constrained problems are converted into unconstrained problems, a constraint is removed, and a penalty factor is substituted; for this reason, finding a solution to unconstrained problems is still highly important. Another important consideration that can be done regards the type of constraints which is applied. In fact, constrained problems can be categorized based on the type of restriction (e.g., linear, nonlinear, convex).

- ***Deterministic Optimization*** versus ***Stochastic Optimization***

  In deterministic optimization, the data used to describe the system is assumed to be known accurately. However, for many real-world issues, it is impossible to know exactly the data with accuracy for several reasons, resulting to solutions that do not correctly describe real systems. A first reason is simply due to the measurement inaccuracy. The second and more important reason is that some data provide information about the future and can never be known with absolute precision (for example, the price of energy in future periods). Instead, it is called non-deterministic optimization problem if the model takes into account in input data uncertainty and variability. This kind of problem can be solved using different approaches, specifically stochastic and robust methods.

Another way to identify the type of optimization problem is to classify it according to constraints, variables and the objective functions. Thus, there are multiple categories to which an optimization problem can be referred. A first distinction depends on the type of variables adopted: these can be continuous, discrete or mixed whenever both types are present in the model formulation. The latter category is very common in engineering; it is common to encounter situations that require both binary (turning a plant on or off) and continuous (power flows) variables. A second distinction concerns the constraints applied to decision variables. An optimization problem that has constraints on the variables is defined as a *constrained optimization problem* in which the constraints can be distinguished into linear and quadratic; otherwise, in the absence of constraints, it is an *unconstrained optimization problem*. Once the categories of the elements formulating the problem have been defined; it is possible, through combinations, to define their classification as shown in Table 3.1.

Table 3.1: Type of optimization problems

Variables	Constraints	Objective function	Classification	Nomenclature
Continuous	Linear	Linear	LP	Linear Program
Continuous	Linear	Quadratic	QP	Quadratic Program
Continuous	Quadratic	Quadratic	QCQP	Quadratic Constrained Quadratic Program
Mixed	Linear	Linear	MILP	Mixed Integer Linear Program
Mixed	Linear	Quadratic	MIQP	Mixed Integer Quadratic Program
Mixed	Quadratic	Linear	MIQCP	Mixed Integer Quadratically Constrained Program
Mixed	Quadratic	Quadratic	MIQCQP	Mixed Integer Quadratically Constrained Quadratic Program

3.1.3 Selection of the solver

The third phase in the optimization process is the selection of the software which must be suitable for the optimization problem under examination. The optimization software consists of two related but very different types of packages. These two are frequently bundled for reasons of marketing or operation and their distinction is often difficult to define clearly.

- The *solver software* is about solving a particular instance of an optimization model. The solver applies one or more solution methods returning then the outcomes.
- *Modelling software* is developed to support users in designing optimization models and evaluating their results. A modelling system accepts a description of the optimization problem in a symbolic form as input and provides the solution output. The ability of modelling systems to import data, invoke solvers, process results, and integrate with larger applications varies from solver to solver.

For this work, in particular, the modelling software is MatLab, within which YALMIP has been installed which is a toolbox through which it is possible to model and solve optimization problems using a specific syntax. To solve the implemented model, YALMIP allows a solver to be selected from those installed in the directory. In the case of this work, the solver, Gurobi, is used. The type of optimization problem implemented is a Mixed Integer Linear programming (MILP), due to the involvement of integer values such as binary variables, as it will be detailed further in the thesis. Most importantly, the selection of the software and solver has been driven by the possibility of building a customized model, including all the necessary decision variables to be optimized, and to run multi-period optimization, to simulate a system operation over a given time span, rather than on a single instance.

Refer to section 3.5 for a detailed description of the optimization process by dealing with variables, constraints and objective functions. Before this, however, it is necessary to explain how the VPP system is structured and how it operates across markets.

3.2 Modelled VPP

The modelled VPP consists of a PV unit having a rated power of 20 MW_{peak} and a PEM electrolyser P2G unit with a rated power of 6,2 MW_{peak} which is connected at medium voltage level. It is assumed that the two units are connected to the same primary substation in order to comply with the current Italian requirements for virtual aggregation. Similarly, the model can also be applied using non-controllable DERs other than PV, the only difference being in the generation profiles and forecast error handling. Moreover, for this model to still be viable, the P2G unit cannot be replaced by other controllable DERs such as BESS. These, in fact, are characterized by capacity constraints reducing the operational flexibility that is instead provided by the P2G and consequently, also reducing the opportunities for value stacking. A schematic representation of the VPP is given in Figure 3.2.

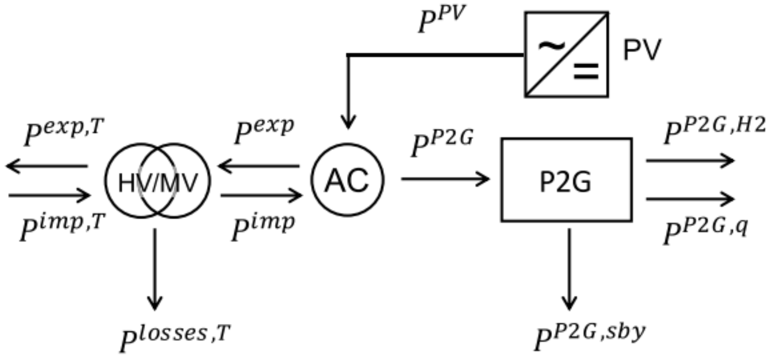


Figure 3.2: Power scheme of the modelled VPP. Source: [42]

In order to reasonably extrapolate zonal forecasts at the individual plant level, the VPP is assumed to be located in Sicily, an island of Italy, whose bidding zone is more restricted than others, mainly due to its geographical location and the associated weak interconnection with the mainland. Operational data for the PV unit are taken from historical forecasts made accessible by European transmission system operators (ENTSO-E) through its transparency portal [43].

Regarding the forecast errors, the normalized day-ahead forecast profile is used as input into the DAM session, instead, the actual forecast profile is applied as input to the IDM session. The generation profile employed in the balancing market and IDM is the same since they both have a gate closure of one hour before delivery. Applying perturbation coefficients to the IDM (or MB) profile results in the creation of the real-time power profile that is involved in the imbalance management process. These coefficients are derived using Gaussian distributions with the intra-day schedule, hour by hour, as the mean and a standard deviation of 5% [44].

The P2G plant is characterized by the operational parameters of a plant with the same dimensions which is located in the Mainz Energy Park [45], as shown in Table 3.2.

Table 3.2: Applied P2G model characteristics. Source: [42]

Parameter	Value
Min power	1.00 MW
Rated power	3.75 MW
Peak power	6.20 MW
Efficiency* at min power	65%
Efficiency* at rated power	55%
Efficiency* at peak power	49%
Load ramp	10%/s
Stand-by consumption	0.001 MW/MW_{rated}
Demineralized water consumption	9 kg/kg_{H2}
Demineralized water costs	0.0007 €/kg

* Regarding lower heating value, incl. all auxiliaries

From Table 3.2, the P2G unit has a load ramp of 10% of rated power per second, which means that it has the ability to vary very quickly the amount of absorbed energy enabling the participation in both the energy and balancing markets. With regard to energy markets, Italy requires that a ramping interval between two hourly products must be completed within 30 minutes. Instead, looking at the balancing markets, they require response times varying from 30 seconds for Frequency Restoration Reserve (FRR in ENTSOE terminology) to 15 minutes for Replacement Reserve (RR in ENTSOE terminology), as shown in Figure 1.5. All of them are broadly respected by the dynamic characteristics of P2G. Since the technical requirements do not impose any restrictions on the modelled VPP, FRR and RR services are treated without distinction in the model. Thus, the decision of the model to favour one product over the other is exclusively based on economic considerations like price forecasts. Other services like primary reserve or congestion management are not taken into account since they are either not publicly traded or have substantial modelling uncertainty because they are location-sensitive services.

As long as the regulatory framework for P2G units is still in the early stages of development, it is assumed that such unit purchases electricity from the Italian spot market as other large-scale consumers. Furtherly, in addition to the spot market price, it is assumed that the P2G unit pays grid charges as other medium voltage connected large consumers (grid charges resulted to be 15,77 €/MWh in 2019 [46]). Additional taxes for not being an electricity end-user are avoided. Regarding the spot market, prices are taken by the GME that makes them publicly available [47]. Based on a methodology derived from [48], a weighted average price is determined for the balancing market for each product category and time period.

3.3 Time sequence

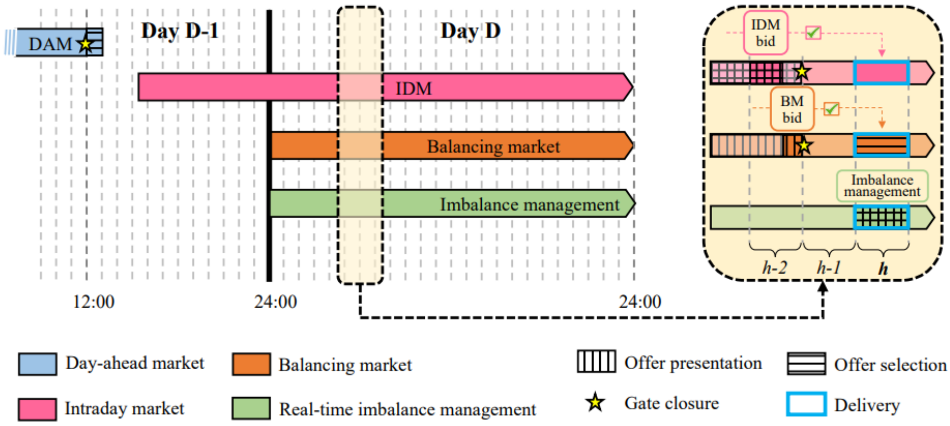


Figure 3.3: Time sequence. Source: [42]

Figure 3.3 shows the time sequence of the Italian energy and balancing markets with related bidding strategy for the delivery of the offers in a generic hourly time interval h. It also highlights the bid submission on different markets with respective gate closures and timeframes for the presentation, selection, and activation of the offers. The four markets, Day Ahead Market (DAM), Intra-Day Market (IDM), Balancing Market (MB) and Reserve Market (MR) are simulated sequentially. The DAM market is performed first because its closure precedes the opening of the other markets. Once this market is carried out, the entire pre-schedule is determined. Indeed, the DAM is negotiated in a single session on a pay-as-cleared basis. It closes at 12:00 on the day before delivery, and bid selection takes place by 12:55. At 12:00 the producer/consumer submits all its bids for all 24 time intervals of the following day creating the so-called baseline i.e. input schedule or uptake schedule. Then the publication of the outcomes takes place i.e., the merit order is created, producers are selected, and this results in the formation of a single price per market area and per time period.

Then trading on the IDM and MB takes place. Both markets are based on pay-as-bid mechanism. Considering that the bids are referred to the hour h, during the interval (h-2) buy and sell bids are made on both the IDM and MB markets. Once the IDM bids are submitted, they are immediately selected, as represented by the intersection of vertical and horizontal lines forming squares. Simultaneously, the submission of MB bids also takes place, and then, in the hour h, there is the actual delivery (acceptance) of the bids. In other words, during the hour h, no squares appear on the IDM path because the bids have already been selected in (h-2); while on the MB path, there is the selection of bids (horizontal lines) according to Terna's needs by receiving ex-post an adjustment. To be more precise, the submission of bids is slightly different from the reality where IDM and MB occur simultaneously. Here it has been assumed that first the bids on IDM take place (all at once since the optimizer is multi-period) and that these do not end exactly at the end of the interval (h-2), but a few minutes earlier. Then, once the new placement is known, MB occurs in the remaining minutes until the end of (h-2).

Finally, real-time imbalance management takes place. Here the VPP operator instantaneously makes the decision to either stay unbalanced or to turn on P2G to decrease (or even increase) the imbalance. In this time interval Terna undergoes what the operator decides to do, and then at the end (ex-post) Terna will evaluate whether the decision to increase or decrease the imbalance has been useful or not, rewarding or penalizing the operators.

An example only for illustration purposes: when there are 20 minutes to the end of (h-2) trading on IDM takes place (bid is submitted by VPP and immediately matched with a counterpart in the market, to take effect in hour h); 10 minutes before hour (h-1) trading on the MB market takes place, based on the outcomes of IDM trading: the VPP operator bids in MB but has no guarantee about the actual selection of its bid; after the next time interval (h-1), IDM trades become effective, modifying the DAM schedule, and the TSO can decide to select the bids presented by the VPP according to its needs in real time.

3.4 Original code

The starting point of this thesis work is a code formulated by the research group from the Department of Industrial Engineering at the University of Padua, relative to a recently published work [42]. For this reason, it is necessary to explain what the features of the original research work are, highlighting which aspects they have in common and their differences.

3.4.1 Original scenarios

In the original code, nine scenarios are presented. They are characterised by a gradual integration into the markets extensively discussed in 3.3. Of these nine scenarios, only scenarios VI, VII, VIII, IX are of interest for the purpose of this thesis, since these, as will be explained shortly, involve participation in both the intraday market and the balancing market. However, to better understand how these last four scenarios were developed and to further explain what is meant by 'value stacking', it is of particular interest to quickly explain how the scenarios prior to these last four also perform. Below, a description of all nine scenarios is given.

In the first scenario, the VPP is not integrated into any particular market mechanism. The P2G plant is a baseload which means that it operates at maximum capacity for the whole simulation horizon and absorbs as much PV generation as it can. In the DAM, excess PV generation is sold and shortages are purchased in cases where PV generation is not sufficient to run the P2G at maximum capacity. The IDM and MB markets are not carried out and so, imbalances resulting from PV forecast errors, not being corrected internally by modulating the P2G, are settled in real-time through the TSO's imbalance settlement scheme.

Scenario II simulates the integration of a light energy market in which the P2G no longer works as a baseload but its operation varies according to the economic convenience of operating in the DAM. Indeed, The PV generation can either be used by the P2G plant, which produces H2, or it can be sold on the DAM. Furthermore, if market prices are low enough to make economic H2 generation possible, the P2G plant can also draw power directly from the grid. IDM and MB are not carried out here either, and as a result, all imbalances are bought from the network in real-time.

Scenario III adds the subsequent IDM interaction but does not account for DAM forecast errors. The MB market is not carried out here either, so once again, all imbalances are bought by the network during MR.

In addition to the previous scenarios, scenarios IV and V introduce two approaches to managing imbalances. In scenario IV, the forecast inaccuracies of the PV that occurred during the DAM are made up by using the IDM. As a result, only real-time imbalances remain after the IDM, and the network purchases them during the MR market because it is unable to intervene with the P2G.

In scenario V, it is necessary to try in all possible ways to compensate for imbalances coming from PV forecast errors through the internal flexibility of P2G to minimize imbalances. This way of operating is what it should be done in reality i.e., doing everything possible to keep the promise made without looking at the imbalance prices to stay unbalanced. For example: the owner of the plant had promised to increase his production by a certain amount because he believed he would be able to produce more with the PV; if something happened to prevent that, he would have to withdraw less with P2G resulting as if he was delivering more as he had promised. Operating in this way may not necessarily be advantageous because hydrogen production, as will be explained later, has a production optimum, and so it may turn out that it would have been more economically profitable to pay the imbalance charge without invoking the flexibility of P2G. Instead, acting in this way helps the TSO by reducing the imbalances but eventually reducing economic return. The real-time adjustment is therefore carried out without knowledge of potential imbalance prices, which may result in economic losses or reduced revenues depending on the eventual imbalance price.

In scenarios VI and VII the balancing market interaction is introduced with the VPP offering balancing services according to its adjusted IDM baseline. In scenario VI the tertiary reserve, called Replacement Reserve (RR), is offered either in upward or downward direction while scenario VII offers also the second balancing service, namely the faster secondary reserve, called Frequency Restoration Reserve (FRR), also offered in both directions. In both scenarios the imbalance management is treated as in scenario V.

Finally, scenarios VIII and IX expand the imbalance management process to the passive balancing. This requires the P2G to be able to forecast the imbalance prices and correct the internal imbalances accordingly in order to avoid economic losses. Scenario VIII applies a limited passive balancing which considers only the relative adjustment of real-time imbalances resulting from remaining PV forecast errors. Here real-time imbalance is also controlled with P2G i.e., it is decided when it is convenient to use P2G and when it is convenient to pay the imbalance charge.

Scenario IX unlocks the unlimited passive balancing and therefore it represents the highest level of VPP integration into energy markets. The VPP takes advantage of the forecast on the imbalance prices not only to avoid internal imbalances but also to make an economic profit by modifying on purpose the P2G profile and deviating intentionally from the predetermined energy market schedules. For example: if there is even just one hour during the year when, by injecting a small additional amount of energy into the grid, you are able to earn a high imbalance charge; then the P2G would immediately shut down and inject energy into the grid generating a very high revenue. Note that the charges become revenue if there is a position such that, even by staying unbalanced, leads to a benefit to the grid because perhaps the grid frequency is dropping and therefore the TSO requires someone to deliver more. By staying unbalanced, a lower withdrawal is like providing more electricity to the grid.

Table 3.3: Scenario compositions with different levels of market integration of the VPP. Source: [42]

Market integration scenario	Day-ahead market interaction	Intraday market interaction	Balancing market interaction	Imbalance management interaction
Scenario I: *Baseload*	Price inelastic[a]	Not considered	Not considered	Classic approach[b] w/o internal flexibility w/o market correction
Scenario II: *Light energy market integration*	Price elastic	Not considered	Not considered	Classic approach[b] w/o internal flexibility w/o market correction
Scenario III: *Intermediate energy market integration*	Price elastic	Partially Price elastic[c]	Not considered	Classic approach[b] w/o internal flexibility w/o market correction
Scenario IV: *Full energy market integration*	Price elastic	Price elastic[d]	Not considered	Classic approach[e] w/o internal flexibility
Scenario V: *Active imbalance management*	Price elastic	Price elastic[d]	Not considered	Classic approach[f]
Scenario VI: *Light balancing market integration*	Price elastic	Price elastic[d]	RR only	Classic approach[f]
Scenario VII: *Full balancing market integration*	Price elastic	Price elastic[d]	RR & FRR	Classic approach[f]
Scenario VIII: *Limited passive balancing*	Price elastic	Price elastic[d]	RR & FRR	Passive balancing with limitation[g]
Scenario IX: *Unlimited passive balancing*	Price elastic	Price elastic[d]	RR & FRR	Passive balancing[h]

[a]P2G operated at full capacity.
[b]VPP imbalance position exposed to day-ahead & intra-day forecast errors of PV.P2G does not perform internal imbalance correction and no imbalance correction performed in IDM.
[c]IDM operation does not consider day-ahead forecast errors of PV.
[d]IDM operation considers day-ahead forecast errors of PV.
[e]VPP imbalance position exposed to intra-day forecast errors of PV. P2G does not perform internal imbalance correction.
[f]Forecasting the system's imbalance price and the deviation of VPP's programmed profile to counter PV intra-day forecast errors even if it involves an economic loss. This leads to the minimization of internal imbalance.
[g]Forecasting the system's imbalance price and deviating VPP's programmed profile to counter PV intra-day forecast errors only if economically sensible.
[h]Forecasting the system's imbalance price and deviating VPP's programmed profile to counter PV intra-day forecast errors and to exploit arbitrage opportunities.

3.4.2 Original optimization framework

As can be seen in Figure 3.4, in the original model, four optimization problems are solved sequentially for each time step of one hour to model the participation in subsequent markets recalling the market structure and the bidding mechanism as previously depicted in section 3.3. The optimization mechanism considers the latest updated price and generation forecasts relying on the commercial position (baseline) generated by previous market sessions. This flexible framework enables the simulation of various levels of commitment (scenarios), and producing various economic outcomes. From Figure 3.3, the DAM is the first modelled market session followed, in sequence, by IDM, MB, and MR. The market sessions related to DAM and MR are not affected by the modifications made to the code since they precede and follow the IDM and MB markets, respectively; therefore, they are simulated in the same way in both codes. See Section 3.5.1 in which the objective functions and constraints associated to these markets are explained in more detail and with mathematical formality. Regarding the remaining IDM and MB markets, these are simulated in two distinct stages with different objective functions. This is the peculiar feature on which the changes made to the code focus.

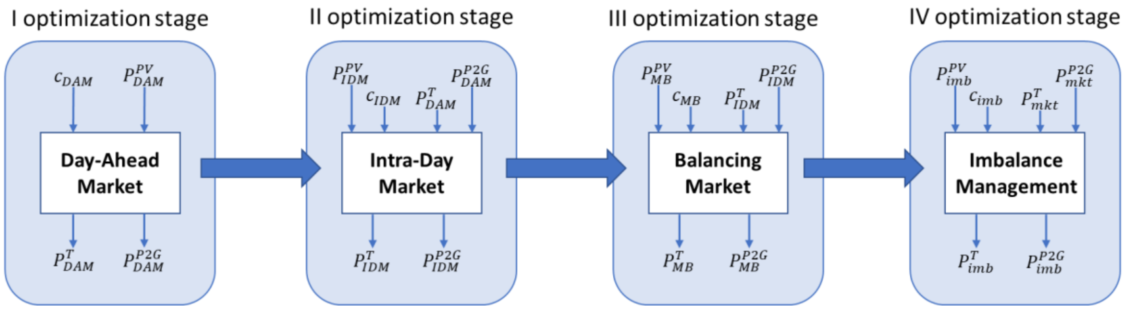


Figure 3.4: Schematic overview of the optimization framework with sequential market interactions and respective input and output variables. Source: [42]

3.5 Changes applied

In the original code, the decisions that the optimizer makes on IDM depend only on the goodness of predictions about PV generation without looking at how MB develops. In contrast, in MB additional bids are made regardless of what has been decided previously on IDM.

The idea of the new code is to integrate the operation in both IDM and MB markets. Integrating the two markets means that the model can search for an optimal bidding strategy that includes the operation in both the markets whereas in the original code the decisions in the two markets are taken in sequence. This change in the approach allows to create a baseline with the IDM i.e., to determine a trading position in the IDM by exploiting that market to create the conditions for increasing the profit in the next market session (MB). Thus, the IDM is exploited not only to correct any PV forecast errors but also to increase the capacity availability for ancillary service bidding in a specific future time interval. This is possible assuming of having a certain confidence about what may happen in the MB i.e., supposing that the TSO needs a certain amount of reserve in that specific future time interval of the day. A quick example: knowing that Terna is willing to pay a very high price on MB in order for the operator to shut down the plant (providing upward service) then the best choice would be to run the P2G at maximum capacity (6,2 MW) during the IDM so as to increase the consumption as much as possible in the IDM in order to take advantage of a larger reduction (6,2

MW – 0 MW) on the MB, hence improving the profit margin. And this is precisely what enhanced optimization approaches with cross-market arbitrage means i.e., buying and then later reselling the same good (energy) and in the same quantity at two different prices. These conditions are purposely created on IDM leading to a situation where the availability to offer ancillary services is maximized during profitable time windows.
Note that the simultaneity of the two markets is not questioned and is respected in both codes and in fact, temporally, the modified code behaves exactly like the original code (see Section 3.3), the difference being in the logic of how the bids are presented on IDM.

3.5.1 Calculation methodology

In consideration of what has just been said, the main change to be made will be to combine the blocks related to the IDM and MB markets. The optimizer itself will decide how to operate by adapting the bidding strategy according to the estimated price in IDM and MB, respectively.
The scenarios considered in this work and on which changes are more evident are VI, VII, VIII, IX since these are the scenarios in which both IDM and MB markets take place (see Section 3.4.1). Regarding the technical constraints of P2G, these obviously remain the same because the performance characteristics are unchanged (see Section 3.2). Summarizing, the main improvement to the method is the objective function of the IDM and MB markets, which are now gathered in a single model and will be solved by a single optimization (Figure 3.5). However, the changes made are such that the choices made by the optimizer on IDM and MB are displayed separately as it will come in handy when evaluating the results.

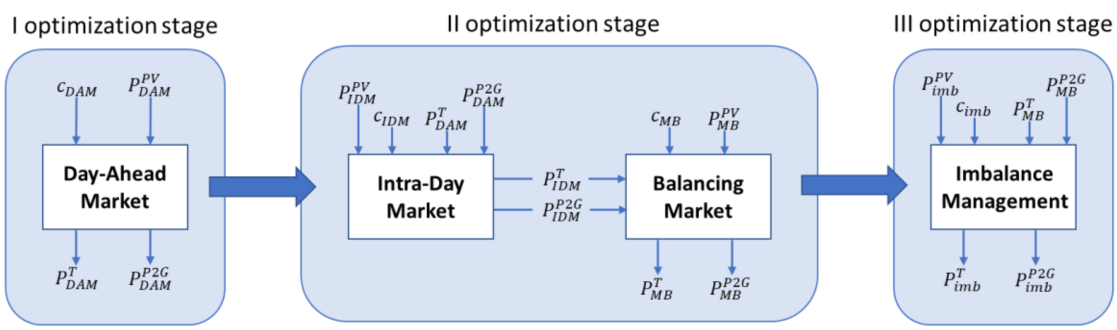


Figure 3.5: Schematic overview of the optimization framework with sequential market interactions and respective input and output variables.

As it can be seen from Figure 3.5, the new modified code includes three optimization problems that are solved sequentially for each time step of one hour of the entire optimization horizon (one year, 8760 h). The second stage is characterized by a cross-market optimization, and it comprehends the intra-day and the balancing market. Each of these optimization problems, which take into consideration the outcomes of the previous market, has a distinct objective function but comparable restrictions. In order to keep the discussion simple, formulas are reported for a generic instant t and then they are used to optimize the full horizon. Regarding the convention of signs, for P2G the input power has positive sign consequently, the output power from PV and the grid is considered positive.

3.5.1.1 Day-Ahead Market (DAM) participation

The first modelled market session is the day-ahead market (DAM), the goal of the VPP is to minimize the operating costs of the considered period. The objective function (**3.1**) consists of two parts: the gross power (import and export) exchanged with the grid, and the output and input streams of the P2G plant, i.e. the amount of hydrogen produced and the amount of water consumed. In this configuration, the objective function considers the costs of importing energy from the grid and buying water for the electrolysis process. On the other hand, exporting energy to the grid and selling hydrogen are considered as revenues. According to the explanation on the previous subsection, respective prices are derived.

$$\min_{P_{DAM}^{imp,T},\, P_{DAM}^{exp,T},\, \dot{m}_{DAM}^{P2G,H2},\, \dot{m}_{DAM}^{P2G,H2O}} Obj_{DAM} = \sum_{t\in-T} \Big(c_{t,DAM}^{imp} P_{t,DAM}^{imp,T} + c_{t,DAM}^{exp} P_{t,DAM}^{exp,T} + - c_{t,DAM}^{P2G,H2} \dot{m}_{t,DAM}^{P2G,H2} + c_{t,DAM}^{H2O} \dot{m}_{t,DAM}^{P2G,H2O} \Big) \tag{3.1}$$

The objective function is subject to a set of constraints that guarantee the power balance for all the components of the VPP and that model the functioning of the whole plant. To ensure the power balance of the VPP, the sum of all powers injected and absorbed must be equal zero for each instant t. For this purpose, constraint (3.2) assures that the total power downstream the transformer is equal to zero (Figure 3.1).

$$P_{t,DAM}^{imp} + P_{t,DAM}^{exp} + P_{t,DAM}^{PV} - P_{t,DAM}^{P2G} = 0 \tag{3.2}$$

Where:

- P_t^{PV} is the photovoltaic generation profile. As explained before, it is a known input of the model.
- P_t^{imp} and P_t^{exp} are the net import and the net export powers flowing through the transformer. They are variables managed by the solver.
- P_t^{P2G} is the power absorbed by the P2G plant inclusive of standby and losses. It is also a variable.

These variables are furtherly linked by the constraints (3.3)-(3.6):

- Import and export are constrained as in (3.3).
- (3.4) set lower and upper limits.
- (3.5) avoid the simultaneity between import and export powers by using binary variables (they can assume only values 0 and 1).
- (3.6) model the actual power exchanged with the market by dividing and multiplying the net powers P_t^{imp} and P_t^{exp} by the transformer efficiency.

$$P_{t,DAM}^{T} = P_{t,DAM}^{imp} + P_{t,DAM}^{exp} \tag{3.3}$$

$$0 \leq P_{t,DAM}^{imp} \leq \alpha_{t,DAM}^{imp}\overline{P^T}, \qquad -\alpha_{t,DAM}^{exp}\overline{P^T} \leq P_{t,DAM}^{exp} \leq 0 \tag{3.4}$$

$$\alpha_{t,DAM}^{imp} + \alpha_{t,DAM}^{exp} \leq 1, \qquad \alpha_{t,DAM}^{imp}, \alpha_{t,DAM}^{exp} \in \{0,1\} \tag{3.5}$$

$$P_{t,DAM}^{imp,T} = P_{t,DAM}^{imp} \Big/ \eta^T, \qquad P_{t,DAM}^{exp} = P_{t,DAM}^{exp} \cdot \eta^T \tag{3.6}$$

Another set of equations define the operation of the P2G plant (3.7)-(3.8). The P2G can operate in two modes: or in standby, with a power consumption $P_t^{P2G,sby}$ of 3,75 kW (corresponding to the losses during the standby of the plant), or in active mode with a minimum power of 1 MW. Also in this case, the introduction of binary variables is useful to mutually exclude the two operating modes (3.8).

$$P_{t,DAM}^{P2G} = \beta_{t,DAM}^{P2G,act} P_{t,DAM}^{P2G,act} + \beta_{t,DAM}^{P2G,sby} P_{t,DAM}^{P2G,sby} \tag{3.7}$$

$$\beta_{t,DAM}^{P2G,act} + \beta_{t,DAM}^{P2G,sby} = 1, \qquad \beta_{t,DAM}^{P2G,act}, \beta_{t,DAM}^{P2G,sby} \in \{0,1\} \tag{3.8}$$

A closer look at the objective function. As mentioned above, this consists of two parts: one related to the exchange with the grid and one related to the P2G. The second part multiplies the quantities of H2 produced and H2O consumed by their respective €/kg price. However, in the code it is not defined in this way but as a function of the power entering the P2G. The idea is to obtain a curve showing the gain in euro as a function of the power absorbed by the P2G. This is all because it is as if the solver considered the derivative of this objective function (based on masses). This derivative is discontinuous (Figure 3.6) and has its minimum points coincident with the breaking points of the efficiency curve that defines the net equivalent power $P_t^{P2G,H2}$ (3.9) which is associated with the production of H2. As suggested in [49], the piecewise linear approximation is used to linearize $\eta_{P2G}(P_t^{P2G,act})$ (Figure 3.7) in order to avoid non-linearity. This power is then divided by the Lower Heating Value (LHW) of hydrogen (33,33 kWh/kg), to get the mass flow rate of the hydrogen that has been produced (3.10).

$$P_t^{P2G,H2} = P_t^{P2G,act} \cdot \eta_{P2G}(P_t^{P2G,act}) \tag{3.9}$$

$$\dot{m}_t^{P2G,H2} = \frac{P_t^{P2G,H2}}{LHV^{H2}} \tag{3.10}$$

$$\dot{m}_t^{P2G,H2O} = \dot{m}_t^{P2G,H2} \cdot 9 \tag{3.11}$$

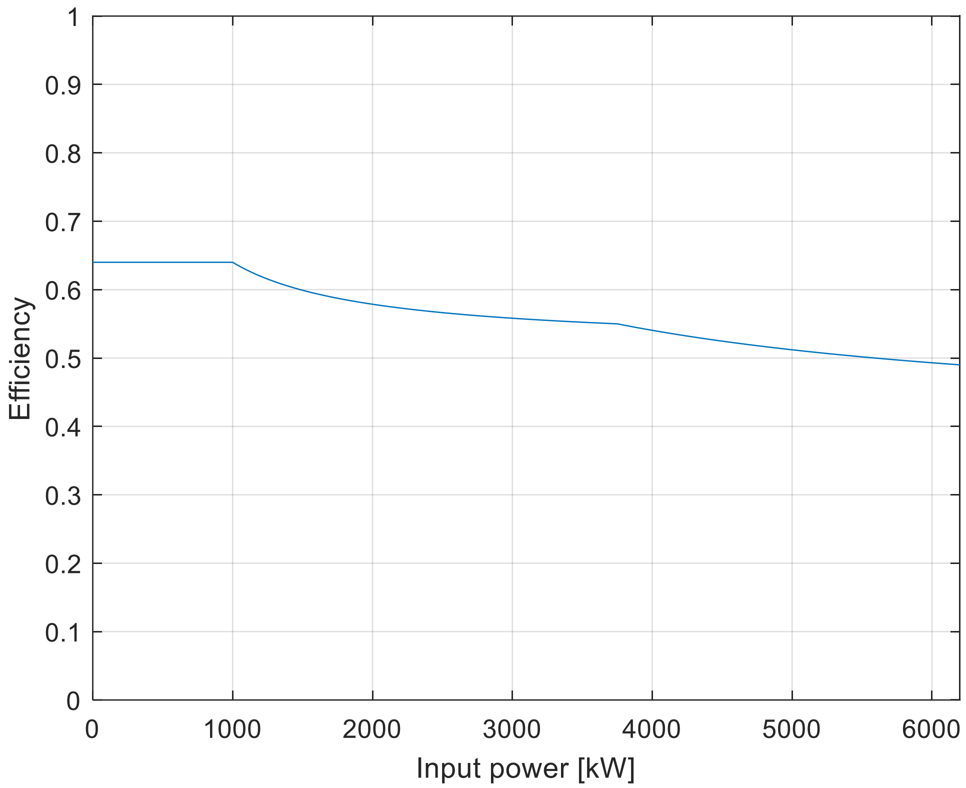


Figure 3.6: Efficiency vs Input power

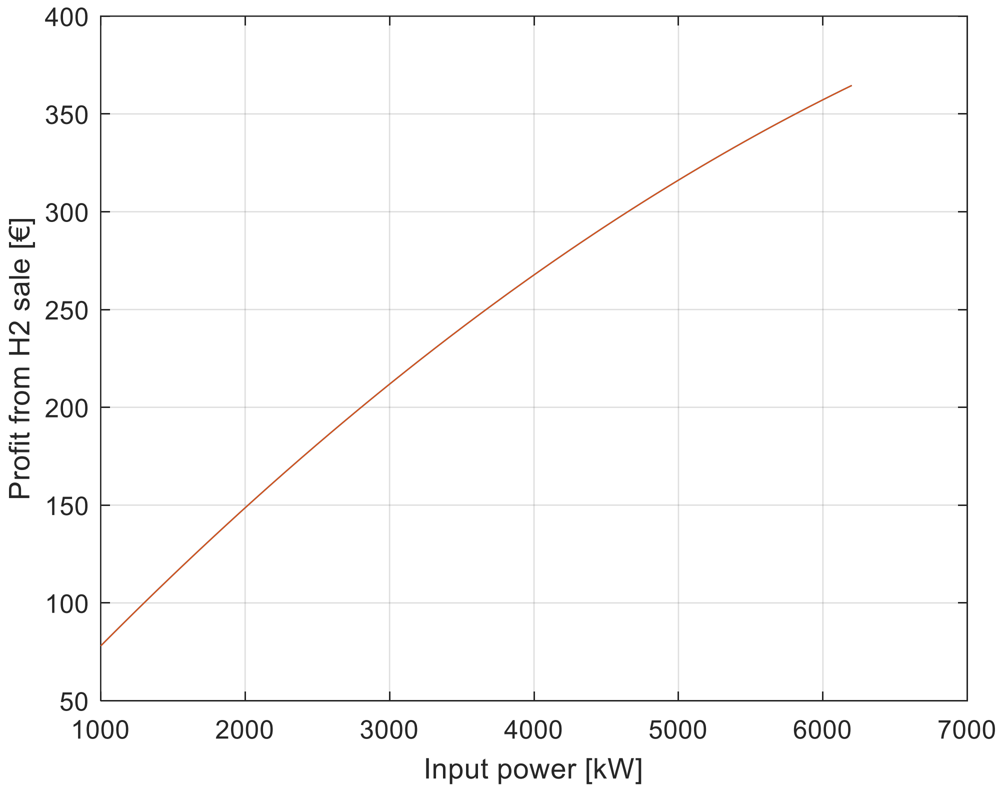


Figure 3.7: Profit from H2 sale vs Input power

An example just to understand the logic behind the optimizer: assuming an energy purchase price of 60 €/MWh, then buying 3 MWh from the energy market would cost approximately 180 €. Instead, looking at the profit curve of the sale of H2 in the gas market, it can be seen that with a P2G input power of 3 MW, the gain is approximately 210 € by selling H2 (Figure 3.8). Therefore, the optimizer will position itself at the point where the difference between these two curves is maximum (Figure 3.9), i.e. where the profit, given by the difference between selling H2 and buying energy, is maximum. In this example, the maximum point is reached at approximately 2850 kWh. It is debatable whether Figure 3.8 andFigure 3.9 show a simplified result because they only consider the sale of H2 while leaving out the purchase of H2O. However, these results are approximate just to explain the logic followed by the optimizer. In the code, an objective function of P2G provided with both contributions (selling H2 and buying H2O) is obviously adopted.

The objective function related to P2G is similar for all markets with the only difference that in the DAM it refers only to that market session while, for other markets, it also has to consider the history of previous markets and thus it is more articulated.

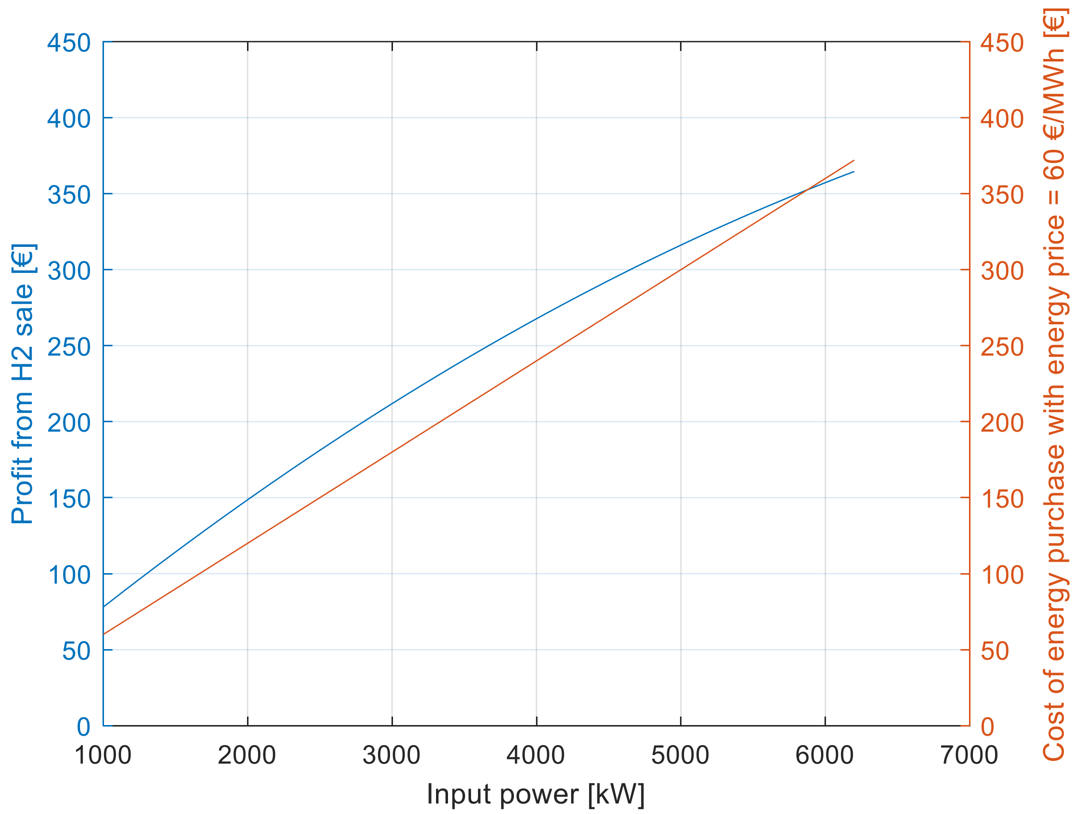


Figure 3.8: Profit from H2 sale & Cost of energy purchase assuming energy price = 60 €/MWh vs Input Power

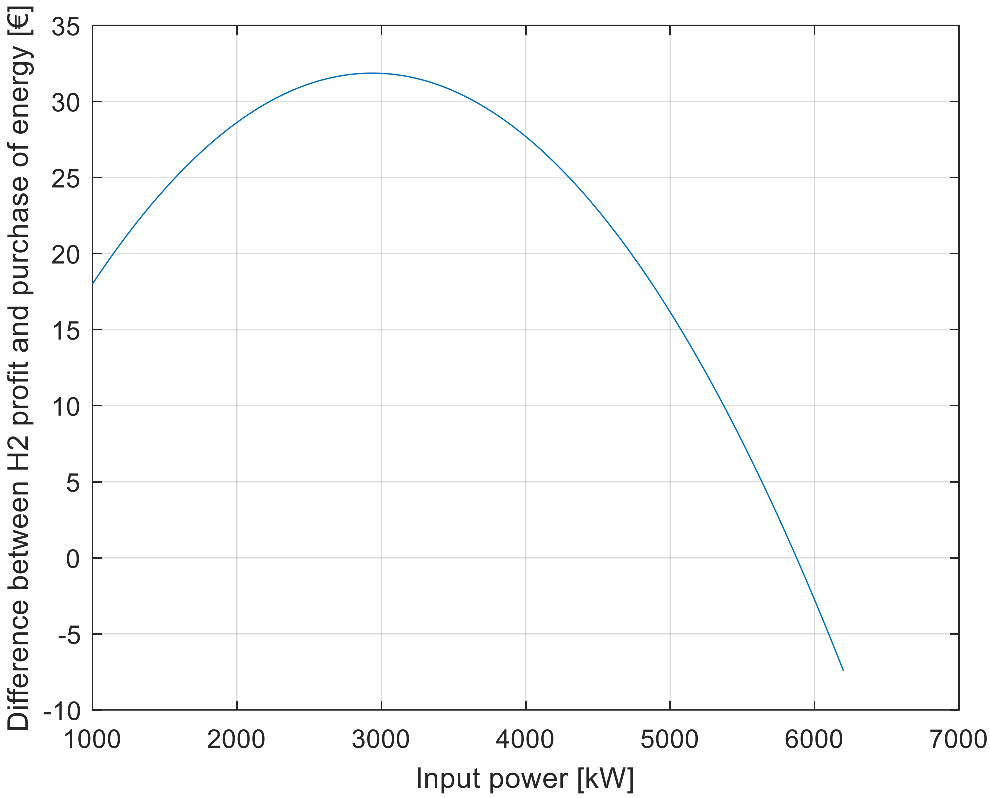


Figure 3.9: Difference between H2 profit and purchase of energy assuming energy price = 60 €/MWh vs Input Power

3.5.1.2 Intra-Day Market (IDM) and Balancing Market participation

The second step of the optimization process models the participation of the VPP in the intra-day market (IDM) and in the balancing market (MB). In this stage, the two markets, which were previously separate and simulated in two distinct stages, are combined. The optimizer will simultaneously optimize both markets by defining both the IDM and MB power profiles.

In the original model, the history of the DAM P_{DAM} (P_{DAM}^{T} and P_{DAM}^{P2G}) is the input of the IDM while the power profiles P_{IDM} (P_{IDM}^{T} and P_{IDM}^{P2G}) are the variables. Finally, the history of the IDM P_{IDM} (P_{IDM}^{T} and P_{IDM}^{P2G}), once defined at the output of the block related to the IDM, is the input of the MB while the power profiles P_{MB} (P_{MB}^{T} and P_{MB}^{P2G}) are the variables that, once defined, will enter the block related to imbalance management MR. Now, by joining the two blocks in the modified model, P_{IDM} is no longer defined at the exit of the IDM block but is 'shifted' within MB. In other words, P_{IDM} is no longer a scalar as it was in the initial model (Figure 3.4) but will have to vary (Figure 3.5) in such a way as to influence P_{MB} (P_{MB}^{T} and P_{MB}^{P2G}) and to make the gain obtained by the optimizer as large as possible (Table 3.4).

Table 3.4: Input and variables of the two model

		INPUT	VARIABLES
ORIGINAL	IDM	P_{DAM}^{T} P_{DAM}^{P2G}	P_{IDM}^{T} P_{IDM}^{P2G}
	MB	P_{IDM}^{T} P_{IDM}^{P2G}	P_{MB}^{T} P_{MB}^{P2G}
MODIFIED	IDM + MB	P_{DAM}^{T} P_{DAM}^{P2G}	P_{IDM}^{T} P_{IDM}^{P2G} $P_{MB}^{T} = f(P_{IDM}^{T})$ $P_{MB}^{P2G} = f(P_{IDM}^{P2G})$

Since the gate closure of these two markets is placed for both one hour before delivery, the same updated PV production profile has been applied to both markets. The new objective function is the sum of the two separate original functions. Specifically, the part related to the IDM aims to maximize the deviation from the previous profile at the transformer interface in case of exports and to minimize it in the case of imports. In addition, the P2G plant behaves like a flexible market player which is able to modify its consumption profile in response to the updated price inputs. Instead, regarding the MB part, the objective functions comprehends the costs associated with the change in the P2G operation brought by the participation in the balancing market as well as the costs associated with to the services offered by the VPP.

$$\min_{\substack{P_{IDM}^{imp,T},\, P_{IDM}^{exp,T},\, \dot{m}_{IDM}^{P2G,H2},\, \dot{m}_{IDM}^{P2G,H2O} \\ P_{MB}^{DW},\, P_{MB}^{UP},\, \dot{m}_{MB}^{P2G,H2},\, \dot{m}_{MB}^{P2G,H2O}}} Obj_{ID+MB} = \tag{3.12}$$

$$= \sum_{t\in T}\Big(c_{t,IDM}^{imp}\big(P_{t,IDM}^{imp,T} - P_{t,DAM}^{imp,T}\big) + c_{t,IDM}^{exp}\big(P_{t,IDM}^{exp,T} - P_{t,DAM}^{exp,T}\big) + c_{t,MB}^{DW}P_{t,MB}^{DW} - c_{t,MB}^{UP}P_{t,MB}^{UP} +$$

$$- c_{t,IDM}^{P2G,H2}\big(\dot{m}_{t,IDM}^{P2G,H2} - \dot{m}_{t,DAM}^{P2G,H2}\big) + c_{t,IDM}^{P2G,H2O}\big(\dot{m}_{t,IDM}^{P2G,H2O} - \dot{m}_{t,IDM}^{P2G,H2O}\big) +$$

$$- c_{t,MB}^{P2G,H2}\big(\dot{m}_{t,MB}^{P2G,H2} - \dot{m}_{t,IDM}^{P2G,H2}\big) + c_{t,MB}^{P2G,H2O}\big(\dot{m}_{t,MB}^{P2G,H2O} - \dot{m}_{t,IDM}^{P2G,H2O}\big)\Big)$$

It is therefore a matter of defining new variables and reconsidering the constraints by including both the IDM and BM variables at the same time. The objective function is subject to the constraints (3.3)-(3.11) (replacing the subscripts DAM with IDM and MB), plus the constraints associated with the definition of upward and downward services (3.13)-(3.19). It is important to distinguish the subscripts IDM and MB. For example, considering the binary variables α_t^{imp} and α_t^{exp}, they must be distinguished between IDM and MB so to avoid forcing the two strategies to behave identically, doing both import and both export contemporarily. This is not acceptable since the optimiser must be allowed to choose the direction of operations for the two markets separately. Upward and downward services can be provided by deviating from the previously obtained power exchange profile. A downward service can be identified as an increase in import or as a decrease in export. While an upward service can be attributed to a reduction in import or an increase in export. Equations (3.13)–(3.17) model these behaviours. The flexibility services are bounded to the rated power of the P2G as shown in (3.18), and, since these services are mutually exclusive in each hour t, binary variables are employed also in this case as in (3.19). Note that equations (3.13) are given for a generic previous market mkt since they will be also applied in the imbalance management process.

The fundamental difference between the two models can be seen in equations (3.13) where:

- In the original model, $P_{t,mkt}^{imp,T}$ and $P_{t,mkt}^{exp,T}$ are the results of the IDM session which are scalars (known) and they compose the history of the MB;
- In the modified model, $P_{t,mkt}^{imp,T} = P_{t,IDM}^{imp,T}$ and $P_{t,mkt}^{exp,T} = P_{t,IDM}^{exp,T}$ which are variable and they are not defined yet.

$$P_{t,mkt}^{imp,T} - P_t^{imp,T} = P_{t,\Delta}^{imp}, \qquad P_t^{exp,T} - P_{t,mkt}^{exp,T} = P_{t,\Delta}^{exp} \tag{3.13}$$

$$P_{t,\Delta}^{imp} = P_t^{imp,UP} + P_t^{imp,DW}, \qquad P_{t,\Delta}^{exp} = P_t^{exp,UP} + P_t^{exp,DW} \tag{3.14}$$

$$P_t^{DW} = P_t^{imp,DW} + P_t^{exp,DW}, \qquad P_t^{UP} = P_t^{imp,UP} + P_t^{exp,UP} \tag{3.15}$$

$$-\overline{P^{P2G}} \le P_t^{imp,DW} \le 0, \qquad 0 \le P_t^{imp,UP} \le \overline{P^{P2G}} \tag{3.16}$$

$$-\overline{P^{P2G}} \le P_t^{exp,DW} \le 0, \qquad 0 \le P_t^{exp,UP} \le \overline{P^{P2G}} \tag{3.17}$$

$$-\gamma_t^{DW}\overline{P^{P2G}} \le P_t^{DW} \le 0, \qquad 0 \le P_t^{UP} \le \gamma_t^{UP}\overline{P^{P2G}} \tag{3.18}$$

$$\gamma_t^{DW} + \gamma_t^{UP} \le 1, \qquad \gamma_t^{DW}, \gamma_t^{UP} \in \{0,1\} \tag{3.19}$$

What is important to specify is that $P_{t,IDM}^{imp,T}$ and $P_{t,IDM}^{exp,T}$ are the result of the IDM; P_t^{UP} and P_t^{DW} are the results of the MB while their sums are $P_{t,MB}^{imp,T}$ and $P_{t,MB}^{exp,T}$ which become the histories of MR. It is as if MB is formally the complete unique market.

3.5.1.3 Imbalance management (imb) process

The third, and last, optimization stage is the imbalance management (imb) process. In this stage, the objective function is defined with the deviation of the profile at the transformer interface measured as $P_{t,imb}^{DW}$ and $P_{t,imb}^{UP}$ and the change in P2G operation quantified by $(\dot{m}_{t,imb}^{P2G,H2} - \dot{m}_{t,mkt}^{P2G,H2})$ and $(\dot{m}_{t,imb}^{P2G,H2O} - \dot{m}_{t,mkt}^{P2G,H2O})$. The imbalance management process happens in real-time once the actual generation of the PV plant is known and the price and sign of zonal imbalance can be potentially predicted. This stage is modelled in sequence with the previous ones because it occurs once both energy and service markets sessions are closed for a specific time frame, therefore no further bidding can be done by the VPP operator in such markets, and those strategies are simply executed.

$$\min_{P_{imb}^{DW}, P_{imb}^{UP}, \dot{m}_{imb}^{P2G,H2}, \dot{m}_{imb}^{P2G,H2O}} Obj_{imb} = \sum_{t \in T} \Big(c_{t,imb}^{DW} P_{t,imb}^{DW} - c_{t,imb}^{UP} P_{t,imb}^{UP} + \tag{3.20}$$

$$- c_{t,imb}^{P2G,H2} \left(\dot{m}_{t,imb}^{P2G,H2} - \dot{m}_{t,MB}^{P2G,H2} \right) + c_{t,imb}^{P2G,H2O} \left(\dot{m}_{t,imb}^{P2G,H2O} - \dot{m}_{t,MB}^{P2G,H2O} \right) \Big)$$

The P2G operating modes in the imbalance management process which are interesting for this elaborate are the following.

- In scenarios VI and VII, the P2G is prioritised in the imbalance management making adjustments to reduce, partially or completely, imbalances internally. In these scenarios, the P2G deviates from the scheduled absorption profile to address PV imbalances even though it results in an economic loss. To put this into practice, updated prices $c_{t,imb}^{DW}$ and $c_{t,imb}^{UP}$ are applied to minimize $P_{t,imb}^{DW}$ and $P_{t,exp}^{DW}$. The actual prices are used to evaluate the economic outcomes after the proper power profiles have been generated.
- In scenario VIII, the P2G decides to take part in the correction of internal imbalances only if it results in an economic gain, taking into account (predicted) TSO imbalance prices. Equations (3.21) ensure that the downward and upward imbalance services are constrained to the internal imbalance need of the VPP, $imbal_t$ defined in (3.22).

$$0 \leq P_{t,imb}^{DW} \leq imbal_t, \qquad 0 \leq P_{t,imb}^{,UP} \leq imbal_t \tag{3.21}$$

$$imbal_t = P_{t,imb}^{T} - P_{t,mkt}^{T} \tag{3.22}$$

- In the final scenario IX, P2G is used to carry out what is known as passive balancing. The VPP fully exploits the imbalance prices since they are exactly forecasted in order to benefit economically from them. This economic benefit can even be achieved by intentionally increasing the imbalance if the price difference between imbalance prices and P2G costs is positive.

Chapter 4

4 Results

The following section discusses the modelling results of the different levels of enhanced operation modes for the VPP. Firstly, an overview of the results is given in form of annual energy flows and financial outcomes. This analysis highlights the implications of an extended implementation of the operation modes. It is supported by a comparison between the overall economic outcomes of the scenarios of the two models summarising the economic implications of gradually increasing market integration. After that, the implications of the cross-market arbitrage are outlined with a detailed analysis of an exemplary day highlighting the different behaviour of the VPP in the two models. This highlights the influence of market conditions as input factors on VPP decisions and illustrates the operation's interdependencies on successive markets. Finally, an analysis of the uncertainty associated with the use of this method is presented, testing the risk aversion of the operator of the plant.

4.1 Economic and energy flow overview

Table 4.1: Comparison of the operational results of the two models with respect to the scenarios under consideration.

	Energy markets			Balancing markets				Imbalance management		Total		
Original	**DA**	**IDM**		**MB**		**IDM + MB**		**MR**		**Absolute**		**Relative**
Scenario VI	1430,1 k€	115,4 k€		775,9 k€		891,3 k€		-1,1 k€		2320,3 k€		88 k€/MWVPP
Scenario VII	1430,1 k€	115,4 k€		1065,0 k€		1180,4 k€		0,8 k€		2611,3 k€		99 k€/MWVPP
Scenario VIII	1430,1 k€	115,4 k€		1065,0 k€		1180,4 k€		10,2 k€		2620,7 k€		100 k€/MWVPP
Scenario IX	1430,1 k€	115,4 k€		1065,0 k€		1180,4 k€		1385,4 k€		3995,9 k€		152 k€/MWVPP
Modified												
Scenario VI	1430,1 k€	-292,0 k€	-352,9%	2022,1 k€	160,60%	1730,2 k€	94,1%	-1,3 k€	22,6%	3159,0 k€	36,1%	120 k€/MWVPP
Scenario VII	1430,1 k€	-384,0 k€	-432,7%	2624,4 k€	146,40%	2240,4 k€	89,8%	0,3 k€	-59,1%	3670,8 k€	40,6%	140 k€/MWVPP
Scenario VIII	1430,1 k€	-384,0 k€	-432,7%	2624,4 k€	146,40%	2240,4 k€	89,8%	9,0 k€	-11,2%	3679,5 k€	40,4%	140 k€/MWVPP
Scenario IX	1430,1 k€	-384,0 k€	-432,7%	2624,4 k€	146,40%	2240,4 k€	89,8%	1324,3 k€	-4,4%	4994,7 k€	25,0%	190 k€/MWVPP

Several aspects can be discerned from Table 4.1 that identify the logic and goodness of the implemented model. Firstly, the social cost from the interaction with the DAM is the same for all scenarios and for both models, the DAM is therefore "in common" and in fact the first stage of the optimization process has not been modified. Moreover, it should be noted that all the scenarios in the original model have the same IDM result, as a consequence of the sequential approach between IDM and MB bidding strategies; in the modified model, the social cost of IDM for scenario VI is different from all the others. This is because only the RR service is provided on the MB in scenario VI and therefore, due to arbitrage between the IDM and MB markets, this results in different outcomes (and VPP placements) than in scenarios VII, VIII and IX. In addition, while in the original model the IDM results are all positive (revenues), in the modified model these are all negative (costs) but this does not affect the validity of the new model since the sum of the two markets (IDM + MB) must be considered and this is much more significant in economic terms. The results of the MR market turn out to be essentially the same for both models even though their difference in percent is significant in some scenarios, due to variations being comparable with the absolute value, however not impacting the grand total. This can also be seen in section 4.2 where the MR power profiles are very similar between the two models. Note that the percentages reported in the Table 4.1 are calculated as the difference between the results of the modified and the original scenarios and then divided by the original model result; for example, taking the IDM+MB sum, there is a factor of almost 2 between 1730,2 k€ and 891,3 k€ for the scenarios VI. Finally, looking at the column of the table related to the total, there are important percentages in favour of the new model, and thus the changes seem to have brought the desired results.

In scenario VI, for instance, the modelling of an operation strategy which is integrated into the energy and balancing markets is discussed. The P2G is flexible and responds to pricing incentives from both types of markets while attempting to compensate for PV forecast inaccuracies. Furtherly, the strategy in the IDM is not devoted to adjust the power exchange in case of better IDM prices or updated PV generation forecasts, but to create a more profitable baseline to increase arbitrage with the balancing market. From the Sankey diagram of Figure 4.1, the interaction with the balancing market results into a considerable amount of imported and exported electricity. Downward services of the product category RR results into 8,65 GWh of electricity imports to the VPP. On the export side, upward services results into 21,66 GWh. They are both significant and, in particular, the sales made in the MB become the most important contribution among all exiting energy flows given the position taken by the VPP in the IDM on purpose.
The purchase and sale of imbalances are exiguous (0,18 GWh and 0,25 GWh respectively) because the goal of this scenario is to minimize imbalances by operating

internally with P2G even if this results in economic losses. In fact, this turns into a negative economic result (-1,3 k€).
The total annual cash flow of this operating mode amounts therefore to 3159 k€ or ~120 k€/MW of VPP capacity which is 36% higher than the corresponding scenario of the original model.

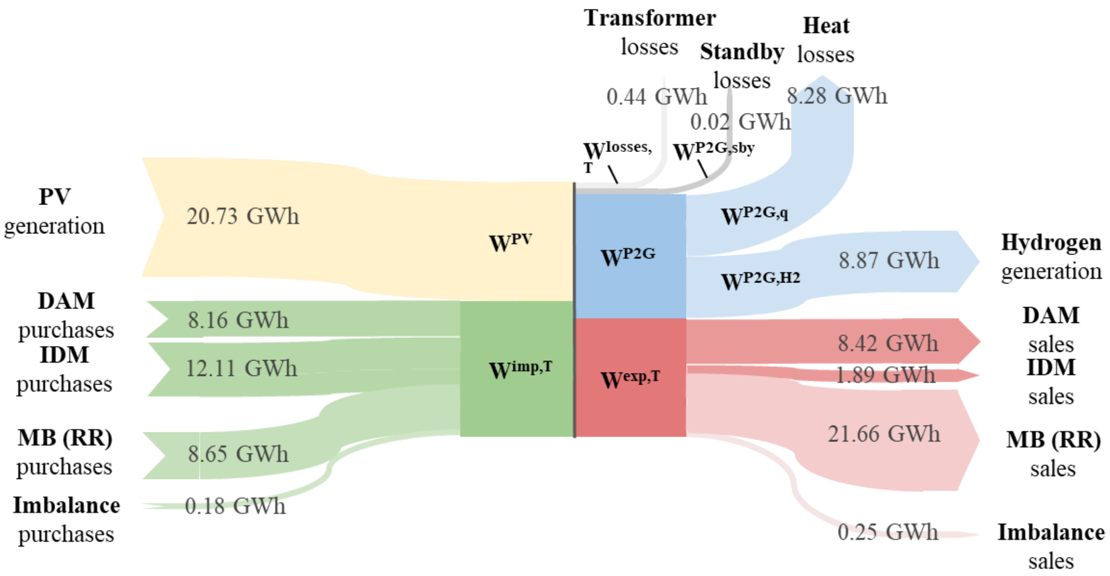


Figure 4.1: Sankey diagram of the modelled VPP under Scenario VI for the entire year 2019.

It is interesting to see the potential of passive balancing in managing imbalances. In scenario VIII, the prediction of the imbalance prices of the system and the adjustment of the real-time forecast errors enhance the annual cash flow of the model related to the imbalance management by 9,0 k€. Instead, scenario IX extends this approach to a total readjustment of the grid exchange profile potentiating the associated cash flow up to 1324,3 k€ which is almost the same amount as from previous energy market interactions. This operation mode results into an overall 4995 k€ or ~190 k€/MW of VPP capacity which is 25% higher than the corresponding scenario of the original model. This massive gain is associated with the involved large energy flow that is connected with unlimited passive balancing. By coupling real-time adjustments to the (predicted) imbalance prices as if they were regular market prices, the model enables the VPP to absorb 24,77 GWh by assuming a short market position on purpose by consuming more than it was previously scheduled on energy and balancing markets. With an average imbalance price of 22,3 €/MWh during these hours, the VPP benefits from the import of cheap electricity contributing passively also to the system stability (as the overall system is long in these hours). Instead, in hours where the system is short, the VPP is encouraged by high imbalance prices to hold a long position by consuming less than scheduled and exporting 4,77 GWh at an average price of 140,13 €/MWh excluding grid charges of 15,77 €/MWh (Figure 4.2).

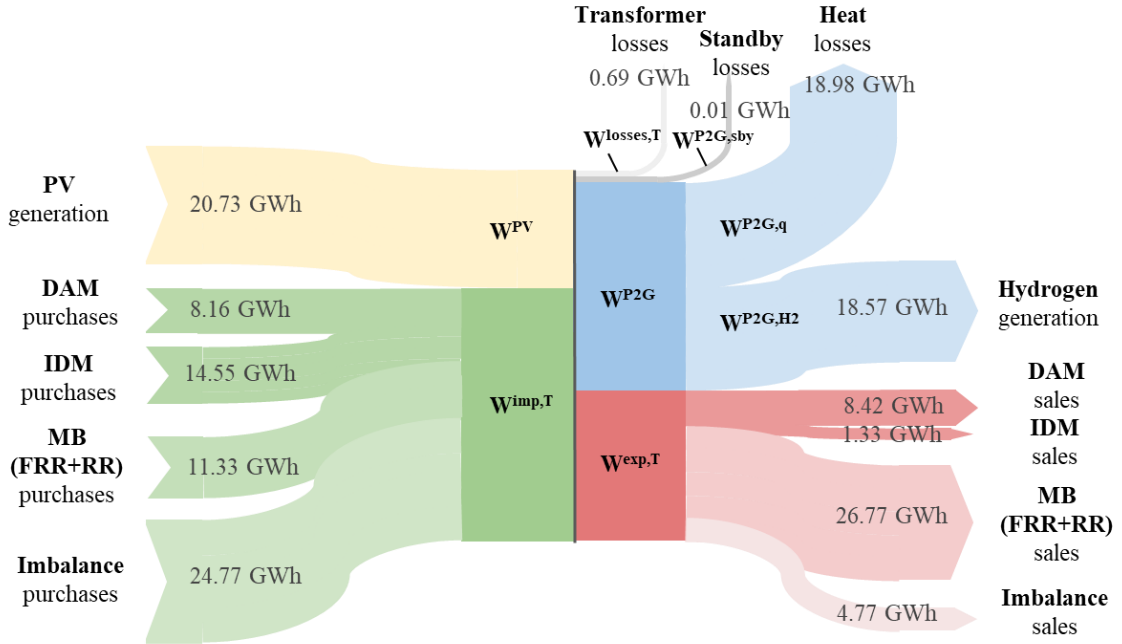


Figure 4.2: Sankey diagram of the modelled VPP under Scenario IX for the entire year 2019.

Table 4.2: Energy flows for all the scenarios of the modelled VPP. Time horizon: entire year 2019. Bidding zone: Sicily, Italy.

ENERGY FLOW	SCENARIO VI	SCENARIO VII	SCENARIO VIII	SCENARIO IX
PV generation [GWh]	20,73	20,73	20,73	20,73
DAM purchases [GWh]	8,16	8,16	8,16	8,16
IDM purchases [GWh]	12,11	14,55	14,55	14,55
MB purchases [GWh]	8,65	11,33	11,33	11,33
Imbalance purchases [GWh]	0,18	0,20	0,34	24,77
DAM sales [GWh]	8,42	8,42	8,42	8,42
IDM sales [GWh]	1,89	1,33	1,33	1,33
MB sales [GWh]	21,66	26,77	26,77	26,77
Imbalance sales [GWh]	0,25	0,30	0,34	4,77
H2 generation [GWh]	8,87	9,00	9,04	18,57
Heat losses [GWh]	8,28	8,68	8,74	18,98
Standby losses [GWh]	0,02	0,02	0,02	0,01
Transformer losses [GWh]	0,44	0,45	0,59	0,69

4.2 Analysis of an exemplary day

To better illustrate how the different steps of market integration influence the operational decisions of the VPP, it is shown how the power profiles of the VPP change in the sequential phases of the optimization process on the exemplary day 07.07.2019. Power profiles are shown for all the four scenarios considered. This analysis is carried out in parallel with a comparison between the two models (the original and the modified one) in order to justify the outcomes of Table 4.1. The prices of the balancing market are plotted together with the prices of the energy markets as this underlies the reasoning of arbitrage between the two markets (Figure 4.3). As will be seen from the pictures, the optimizer will take well-defined decisions by exploiting the price differences between the prices of the IDM and MB markets.

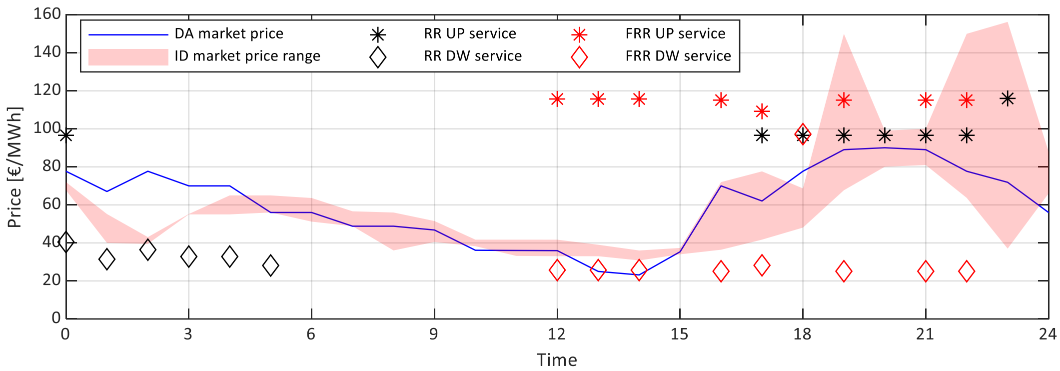


Figure 4.3: DAM and IDM prices combined with balancing market prices, on an exemplary day (07.07.2019) in the Italian market zone of Sicily

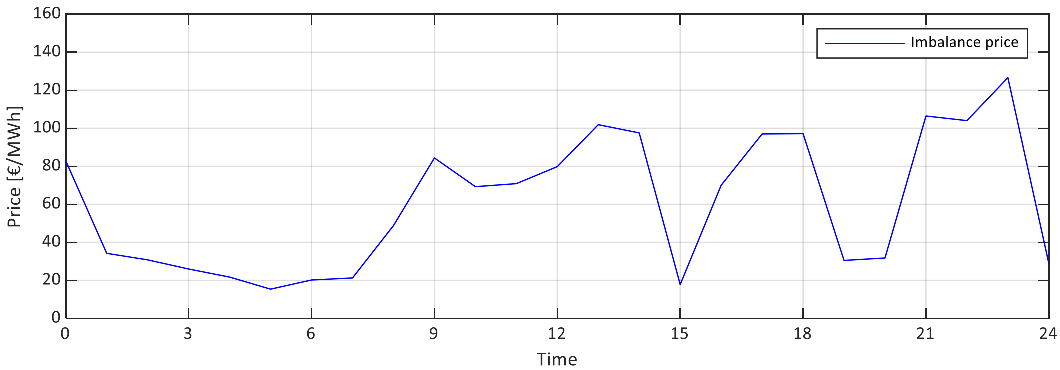


Figure 4.4: System's imbalance prices on an exemplary day (07.07.2019) in the Italian market zone of Sicily

4.2.1 Analysis of an exemplary day - Scenario VI

Before starting with the analysis, it is important to make a premise. Since, as said before, the economic result of the DAM is the same for all the scenarios in both the original and the modified model, a brief explanation about this market session is given only in the section dedicated to scenario VI without repeating it for all other scenarios.

From Figure 4.5 it can be seen that, in the first four hours of the day, the PV generation (red line) is zero, the P2G (blue line) is on standby consuming 3,75 kWh importing this energy from the grid (black line). From 5:00 to 6:00, the P2G starts absorbing about 1100 kWh of energy coming partly from PV generation (about 200 kWh) and the remaining from the grid (about 900 kWh) since the energy provided by the PV is not enough. Considering the interval from 12:00 to 1:00 as an example, the PV is producing about 9700 kWh, the P2G absorbs part of this energy (6200 kWh) by working at its maximum capacity, and the remaining part of the generation from PV is exported to the grid (about 3500 kWh). The optimizer's movements can be attributed to the fact that the cash flows from electricity import and export are also optimized together with the cash flow from hydrogen production. As a result, there is no import of electricity during night hours since prices are too high, a gradual increase in self-consumption during the morning when DAM prices fall due to an increase in PV generation, and an increase in electricity exports during high price hours such as between 17:00 and 18:00.

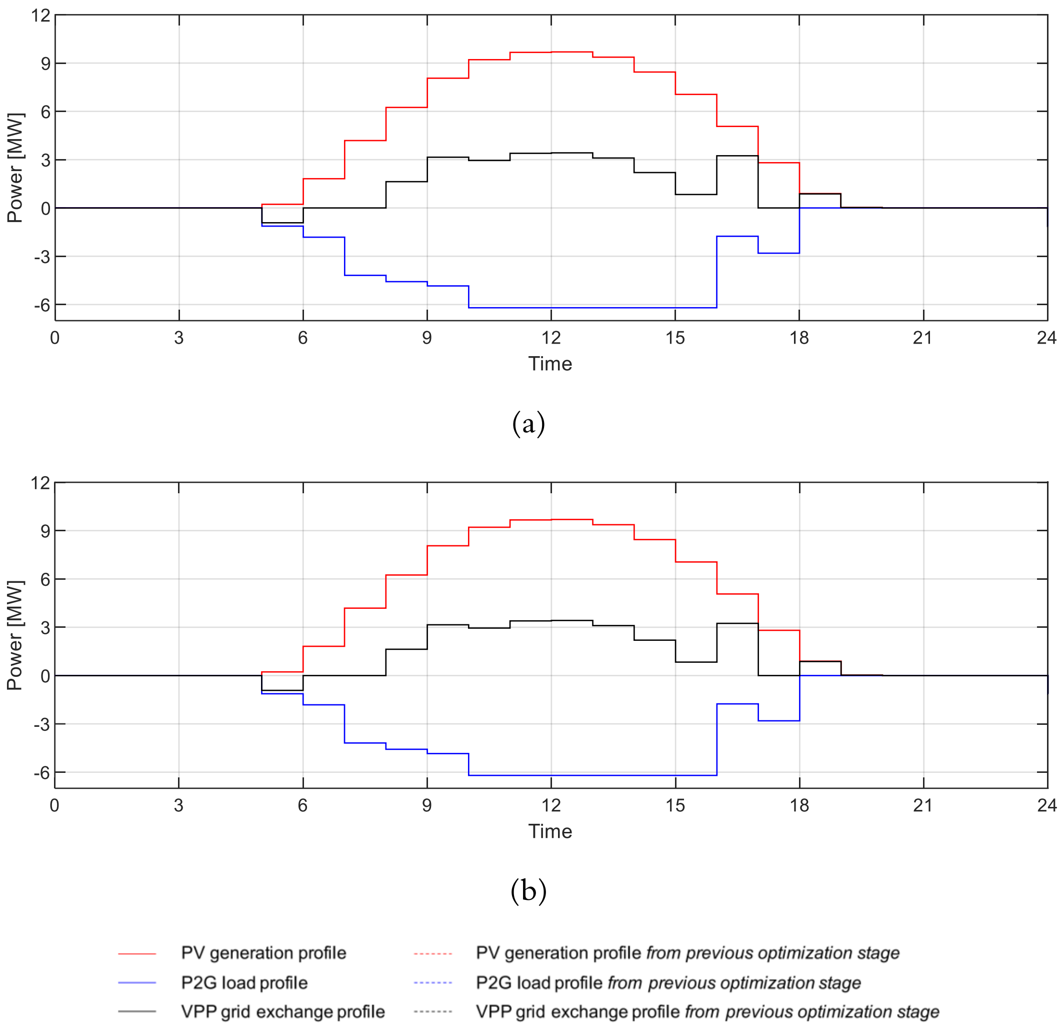


Figure 4.5: VPP power profiles offering on DAM considering an exemplary day (07.07.2019) in the Italian market zone of Sicily. Scenario VI. Original model (a) vs Modified model (b)

Looking at the IDM market, The VPP deals with a new set of prices and an updated forecast of the PV generation profile. This leads to an adjustment of the P2G profile, as can be seen from the switch from dashed to solid line in Figure 4.6. However, it must be remembered that the IDM is performed differently in the two models. In the original model, this market is simulated alone in the second stage of the optimization process. In contrast, in the new model, this market is carried out together with the MB market and both combine to constitute the second stage of optimization. This last consideration leads to different responses of the P2G and, consequently, different slack exchange profiles since the goal of the optimizer has changed from the original to the modified model.

Considering the original model (Figure 4.6-(a)), the P2G unit absorbs the difference in PV generation, for example in the hour 6:00–7:00, since prices are too low to sell electricity conveniently on the IDM. On other occasions, such as 8:00-10:00, the new IDM prices might be higher so that not only the additional forecasted PV generation is sold, but also the consumption of the P2G is slightly decreased to increase furtherly the IDM sales. In contrast, the comparably lower IDM prices in the early morning hours with low PV generation encourage the VPP to absorb a significant amount of electricity through the P2G unit.

Instead, regarding the modified model, the choices taken by the optimizer during the IDM depend on the condition of the MB. The optimizer exploits the existing price differences between the two markets; therefore, it creates a baseline during the IDM, which, taken singularly, might not seem as profitable as in the original model, but that creates a larger margin of profit in the MB. Indeed, the P2G behaves in a different way in Figure 4.6-(b) respect to Figure 4.6-(a). Hence, Figure 4.6-(b) and Figure 4.7-(b) must be considered together.

Regarding the downward and upward services, the first ones allow for the use of electricity at a low price, such as between 20–40 €/MWh on the exemplary day (Figure 4.3), which is below the price of energy markets. Instead, the second ones allow for the sale of electricity at high price, for instance in the range from 95–120 €/MWh on the exemplary day, which is above the price of energy markets.

The hours of the exemplary day in which differences can be seen are the following:

- 1:00-6:00: During the IDM, the P2G is in standby mode and consequently the import from the grid is minimal. More specifically, in the hour 5:00-6:00, to keep the P2G in standby (3,75 kWh), there is a small export (237 kWh) that leads to a gain of 81 € since the PV starts to generate 241 kWh. In correspondence, during the MB the P2G works at maximum power absorbing all the energy from the grid (also here there is a small change during the 5:00-6:00 hour). This choice is done because the optimizer sees that there is a very large price difference between IDM and MB prices. Indeed, RR downward service (Figure 4.3) costs less than buying electricity from the grid (around 30 €/MWh respect to around 40-60 €/MWh). Therefore, it is better to not operate (neither buying nor selling) during the IDM in order to buy less expensive electricity during the MB to produce hydrogen. Indeed, the optimizer spends more or less 200 € in each of these six hours buying from the grid and then earns about 350 € in each of these hours selling hydrogen, generating a net profit of about 150 € in each hour.
- 17:00-21:00: In the IDM, the P2G operates at its maximum capacity and to do so, it draws energy from PV and the grid. In the MB, P2G shuts down completely by reselling everything it had purchased in the IDM to the grid and offering an upward service. Indeed, the price of the RR upward service is above the average IDM price making it profitable to provide such services. In each of these hours,

switching off the P2G results in a cost from the non-production of hydrogen of about 360 € in each hour and a revenue of about 600 € in each hour from the sale of energy into the grid.

- 22:00-24:00: similar to the 17:00-21:00 hours. Noteworthy is the higher gain in the hour 23:00-24:00 due to a higher service price of 120 €/MWh. It is certainly more convenient to switch off P2G by providing such a profitable upward service than to generate hydrogen.

Note that from 6:00 to 17:00, the power profiles of the markets IDM and MB are coincident. The optimizer does not exploit the MB session since in these hours there are no MB average market prices either (Figure 4.3), and therefore no offers have been accepted.

As far as the MB session in the original code is concerned (Figure 4.7-(a)), this market is carried out in the third optimization stage. Here, the decision on the choices to be made is not based on the arbitrage between IDM and MB, but MB is executed once the IDM is concluded. The reason behind the decisions taken by the optimizer in the MB is the ability to provide such services based on the positioning assumed by the VPP on previous energy markets. For example, in the night hours from 19:00 to 23:00, upwards services are not feasible since the P2G has a baseline of zero and there is not generation from the PV available. On the other hand, around noon with plenty of PV generation, downward services (seen as increase in import and decrease in export) are inconvenient since the P2G absorbs already close to full capacity and a reduction of the grid exchange could only be achieved by the curtailment of the PV. Therefore, the VPP presents these offers whenever it is possible. Generally, it offers upward services during the day when the PV generation is available and not completely sold, while downward services anytime the P2G is not yet working at full capacity.

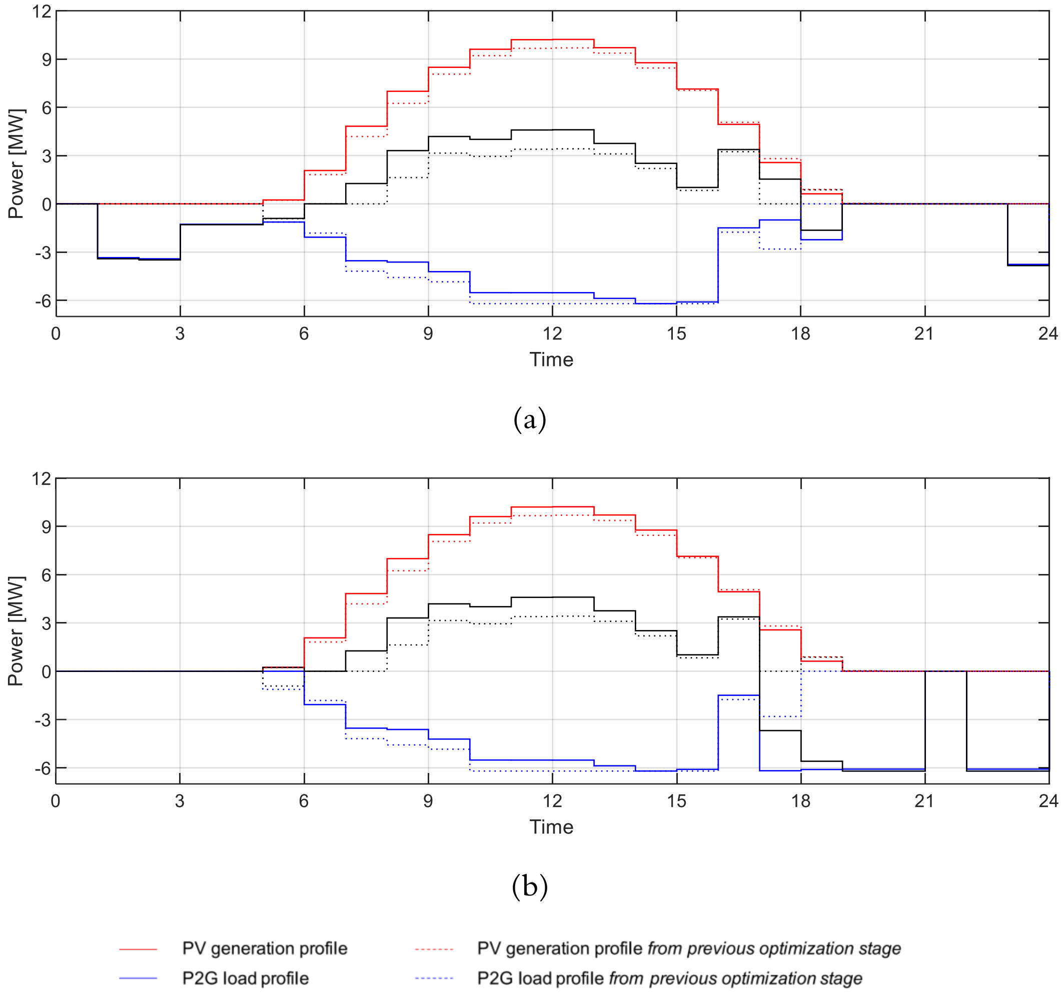


Figure 4.6: VPP power profiles offering on IDM considering an exemplary day (07.07.2019) in the Italian market zone of Sicily. Scenario VI. Original model (top) vs Modified model (bottom)

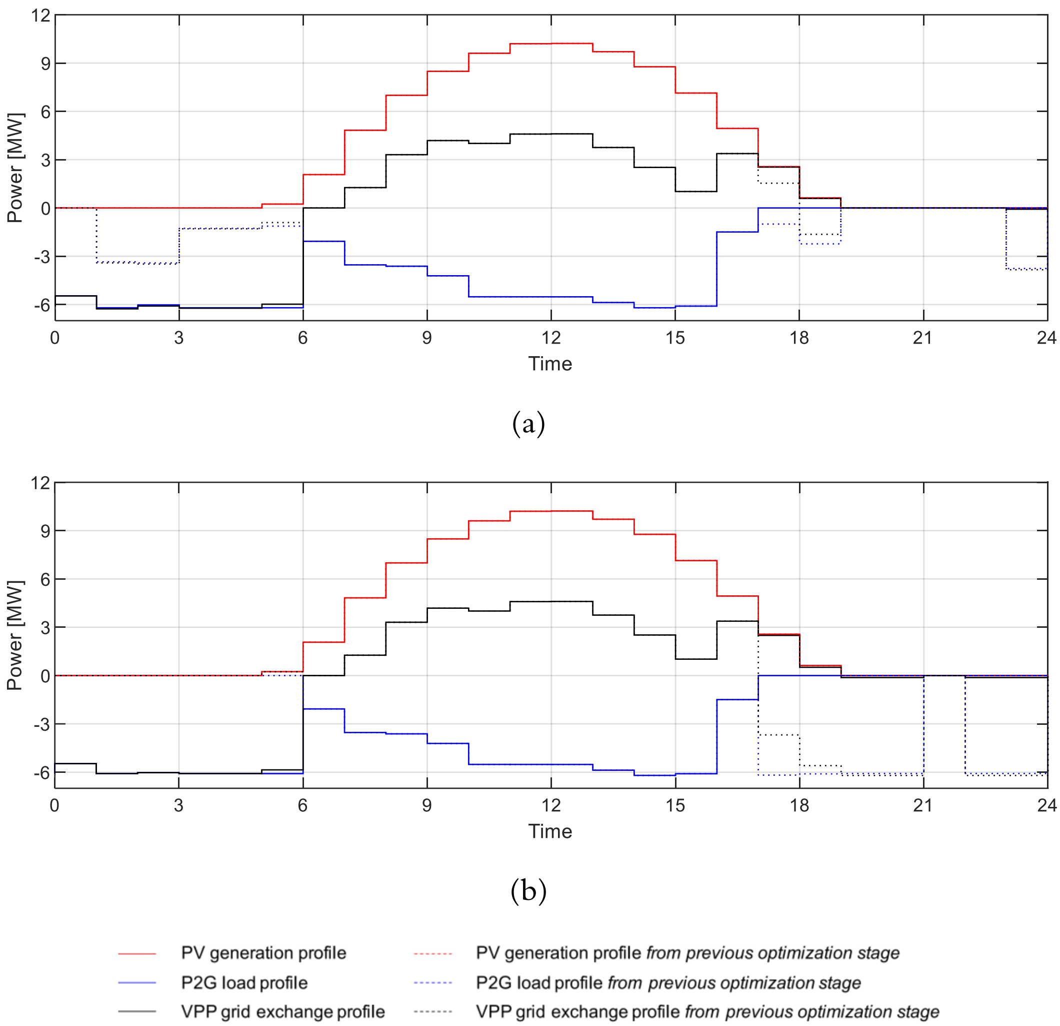
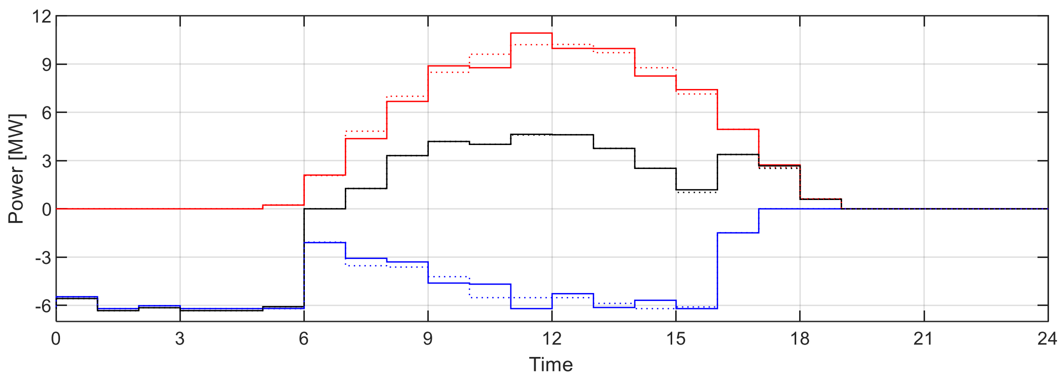


Figure 4.7: VPP power profiles offering on MB (RR provision) considering an exemplary day (07.07.2019) in the Italian market zone of Sicily. Scenario VI. Original model (top) vs Modified model (bottom)

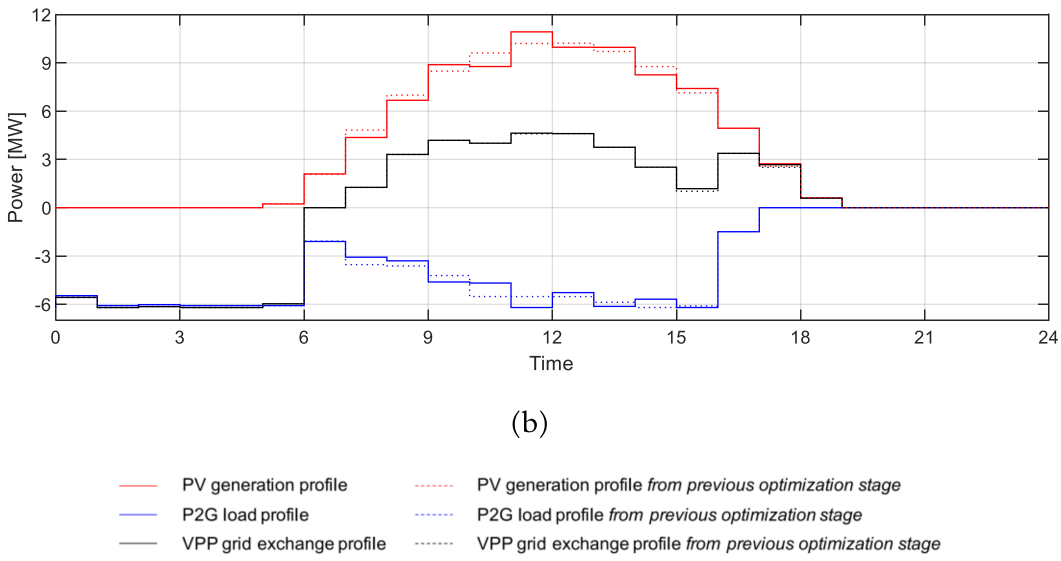
In the last optimization stage, The VPP must deal with the remaining real-time imbalances that can no longer be compensated in the energy markets. In Figure 4.8, the real-time forecast error of the PV is represented as the difference between the dashed and full red line while the remaining imbalance of the entire VPP is represented as the difference between the dashed and full black line. As outlined in the previous section, in scenarios VI and VII the VPP decides to use its internal (P2G) flexibility to reduce imbalances as far as possible ignoring potential economic consequences. The plant tries to eliminate its real-time imbalances for all hours of the day (look at the dashed and full black line) with the exception of the hours 15:00-16:00 and 17:00-18:00 in which the remaining imbalances of the plant are not completely eliminated but just reduced because of technical constraints of the P2G. For example, in the hour 15:00-16:00, the increase in PV production, is partially absorbed by P2G which reaches maximum capacity thus not being able to absorb more and to provide additional internal flexibility.

The remaining surplus is therefore injected into the grid. In such a case, it is said that the VPP assumes a long imbalance position.
Note that in the hour 17:00-18:00 the P2G does not intervene to eliminate the imbalance since, starting from the stand-by condition, it needs that the difference between the red dashed line (PV forecast on MB, 2568 kWh) and the red solid line (new PV forecast on MR, 2564 kWh) is greater than, or equal to, 1000 kWh i.e., the minimum operating power of the P2G. In contrast, in the 6:00-7:00 hour when the PV imbalance is less than 1000 kWh anyway (2568 kWh - 2564 kWh = 200 kWh), the P2G intervenes to eliminate the imbalance because it was already at a power greater than 1000 kWh.

The reasoning behind the MR is the same for both models, the only difference being in the positioning created in the MB. However, incidentally, no difference can be seen between Figure 4.8-(a) andFigure 4.8-(b). See Figure 4.14.



(a)



(b)

Figure 4.8: VPP power profiles offering on MR considering an exemplary day (07.07.2019) in the Italian market zone of Sicily. Scenario VI. Original model (top) vs Modified model (bottom)

The extreme behaviour of the optimizer can be seen in Figure 4.9, which represents the sum of upward and downward services, and the power absorbed by the P2G. The two curves are specular to each other: when the optimizer sees convenience in doing either upward or downward service then it pushes the P2G to behave drastically. This is also due to the fact that the P2G starts absorbing energy (at minimum capacity, i.e., 1000 kW) to produce hydrogen if the price of energy is below a certain value by gradually increasing capacity as the price decreases until it reaches peak capacity at a certain price. Assuming a hydrogen sale price of 4 €/kgH2, the resulting marginal electricity price at which the P2G starts producing hydrogen is a spot market price of 78,00 €/MWh (Figure 4.10). Thus, below this price, the algorithm drives the VPP to consume the PV generation through the P2G unit, while beyond this price, it rather sells it to the grid. Since the efficiency of the P2G decreases as the load increases (non-linear efficiency curve: peak operation of the P2G corresponds to an efficiency of 49%, while an optimized operation corresponds to a range of efficiencies between 65% and 49%), the price must fall below 58,50 €/MWh (Figure 4.11) until it becomes economically convenient that the P2G consumes the PV generation at full capacity. Thus, below 58,50 €/MWh, P2G always operates at maximum capacity. Moreover, considering additional grid charges for the consumed electricity, the spot market price must drop even below 62,23 €/MWh (which corresponds to the previous 78,00 €/MWh minus grid charges) before the algorithm instructs the VPP to start purchasing electricity from the grid to produce hydrogen in case no PV generation is available.

Stated that, since the downward service is always less than 58,50 €/MWh (except for the hour 18:00-19:00), when the optimizer sees a downward service, it will push the P2G to behave in an extreme way by operating at the maximum capacity of 6,2 MW. In contrast, since the upward service is above 78,00 €/MWh, the optimizer always has the opportunity to inject into the grid whenever an upward service occurs; by doing so, the P2G will tend to shut down.

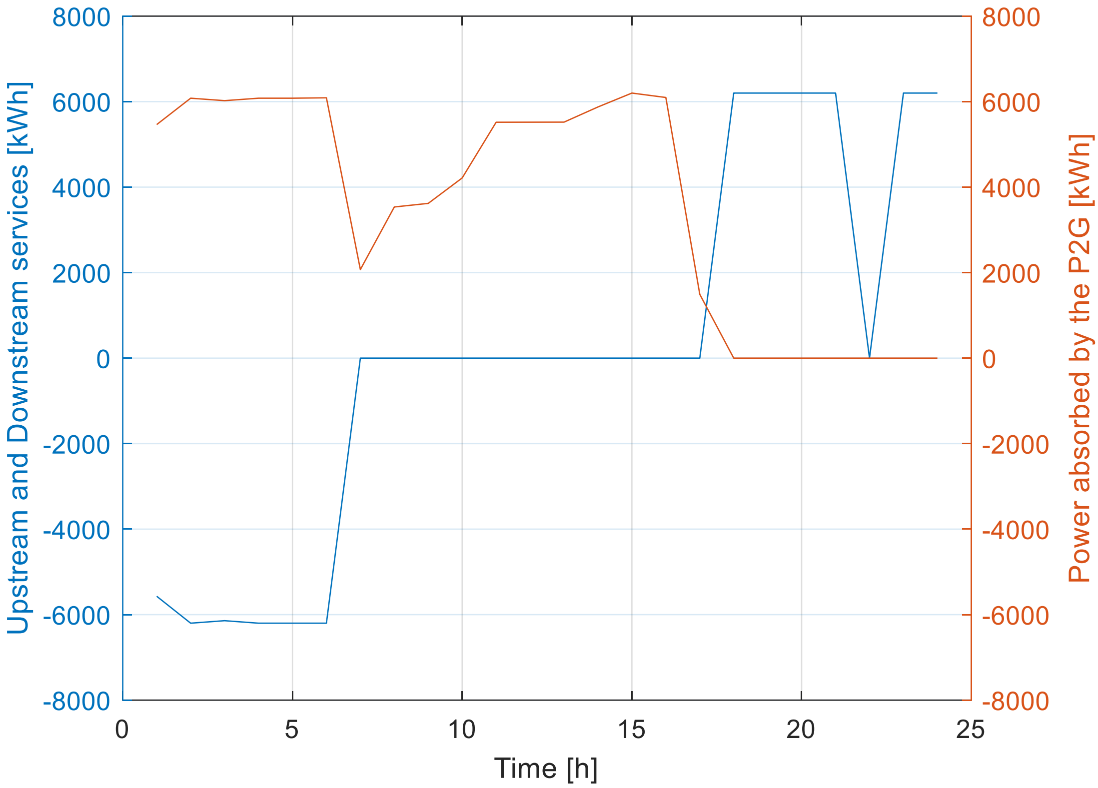


Figure 4.9: Upward and Downward services & Input Power of the P2G in the considered hours of the exemplary day (7/7/2019)

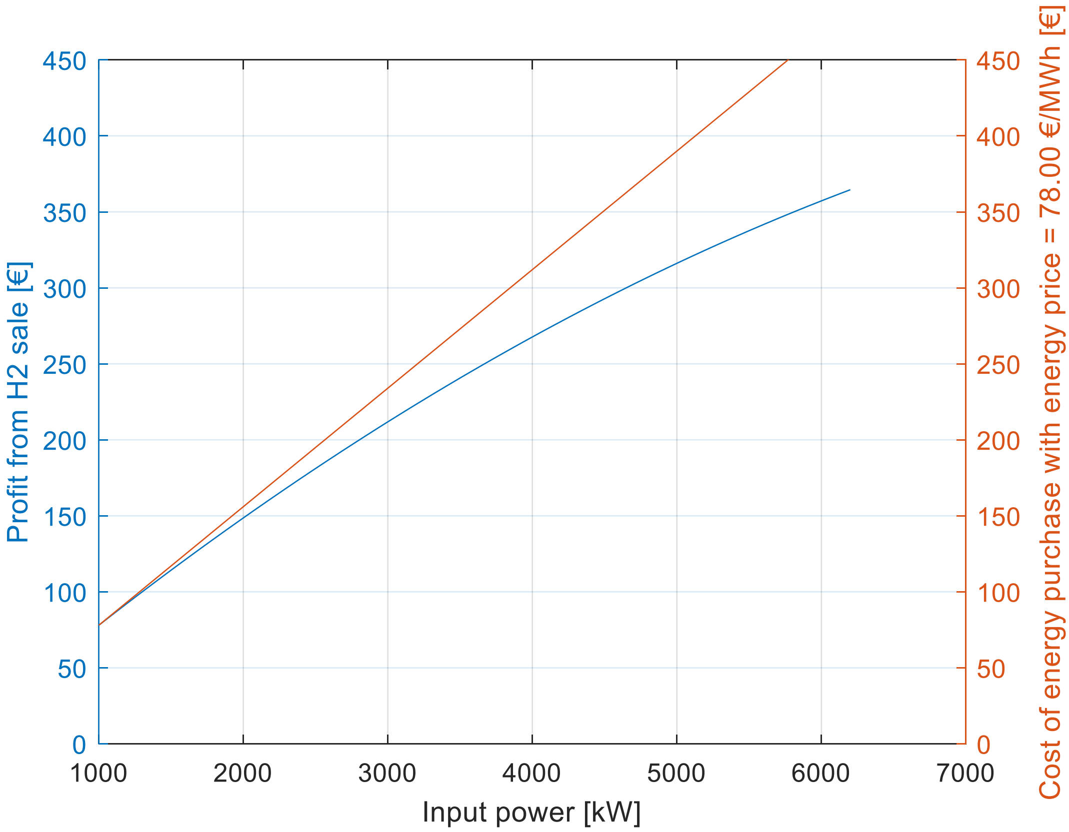


Figure 4.10: Profit from H2 sale & Cost of energy purchase assuming energy price = 78.00 €/MWh vs Input Power

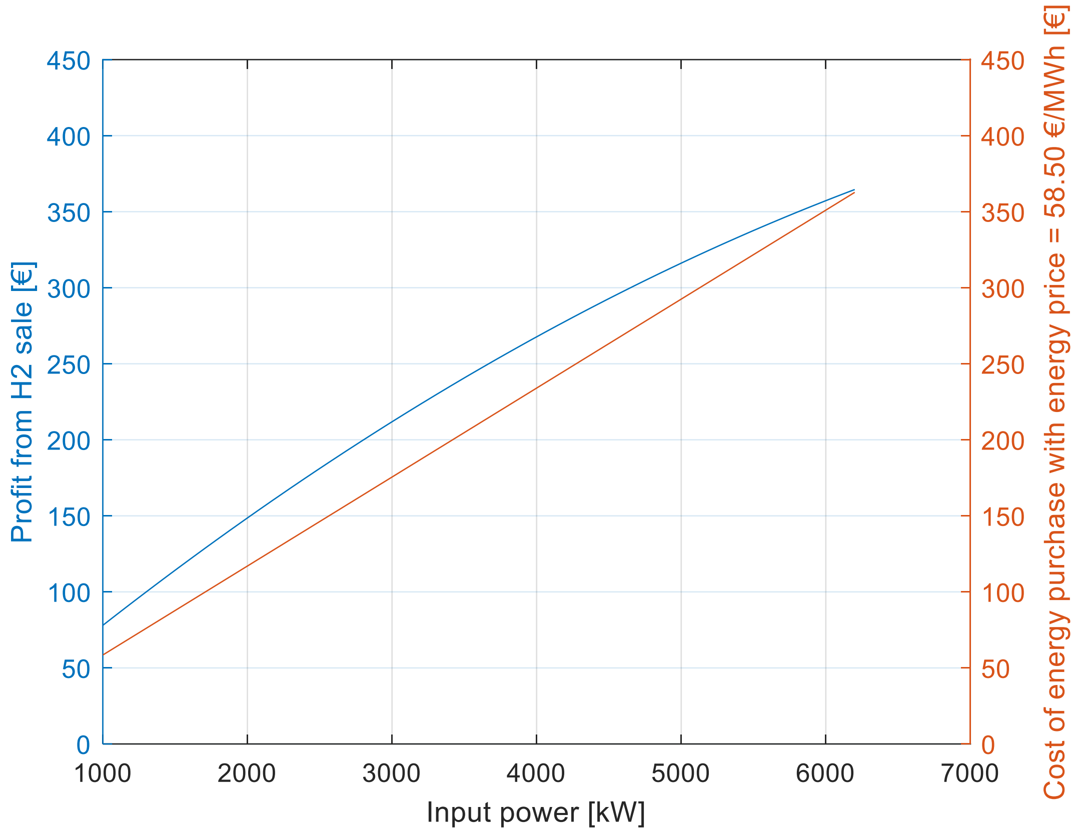


Figure 4.11: Profit from H2 sale & Cost of energy purchase assuming energy price = 58.50 €/MWh vs Input Power

4.2.2 Analysis of an exemplary day - Scenario VII

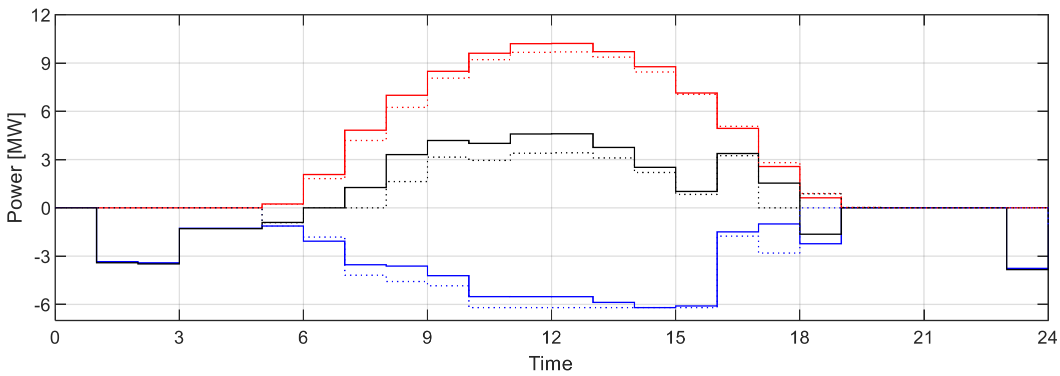
As mentioned above and as it can be seen from Table 4.1, the economic results for DAM are the same for all scenarios which means that the power profiles are also identical. So, refer to Figure 4.5 for consultation of the DAM power profiles referring to the exemplary day.

On the other hand, as far as IDM and MB are concerned, Scenario VII shows differences from Scenario VI since bids are presented here for FRR service as well. In particular, it can be observed:

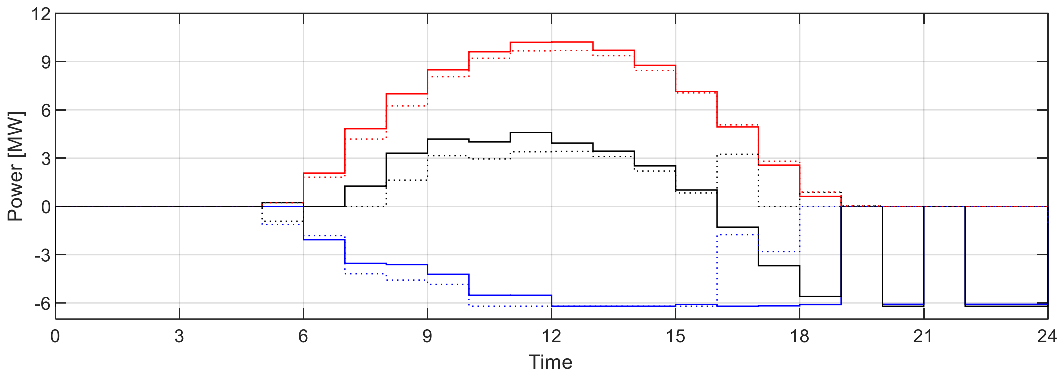
- Until 12:00, the power profiles of IDM (Figure 4.12-(b)) are the same as those in Scenario VI (Figure 4.6-(b)) because the only services that can be offered are of the RR type. This is also true for MB, so until 12:00 the profiles in Figure 4.13-(b) are the same as those in (Figure 4.7-(b)).
- During hours 12:00-15:00, bids for both upward and downward FRR service are submittable (Figure 4.3). So, in these hours, on the IDM the P2G absorbs even more energy than Figure 4.6-(b) bringing itself to maximum capacity and buying

energy at an IDM price of about 35 €/MWh. Later in the MB, the P2G injects energy into the grid, thus shutting down, offering an upward FRR service that is remunerated at about 120 €/MWh. From Figure 4.3 it can be seen that in both considered hours, the possibility of submitting both upward and downward FRR offers appears, and clearly it is only possible to offer in one direction. The optimizer chooses which offer to make based on the price difference between the asterisk related to upward service and the upper line of the red area (representing the purchase price on IDM) and between the square related to downward service and the lower line of the red area (representing the sale price on IDM).

- During 16:00-18:00 hours, the P2G absorbs energy at maximum capacity on the IDM and then shuts down completely on MB offering a very profitable upward FRR service (about 110 €/MWh).
- During the hours of 19:00-20:00 and 21:00-22:00, on the IDM, the VPP sells electricity to the grid at a price of about 70 €/MWh shutting down the P2G to buy then electricity at a very low price (about 30 €/MWh) and running the P2G at maximum capacity as the VPP chooses to offer a downward FRR service.
- Conversely, during the hours of 20:00-21:00 and 22:00-24:00.



(a)



(b)

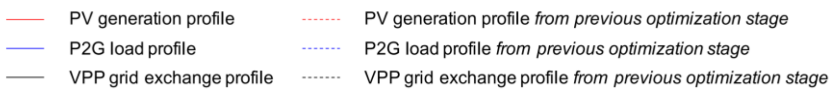
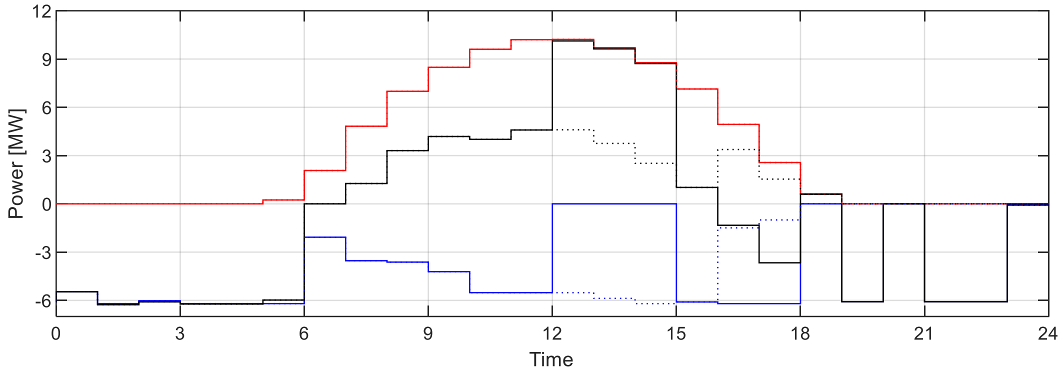
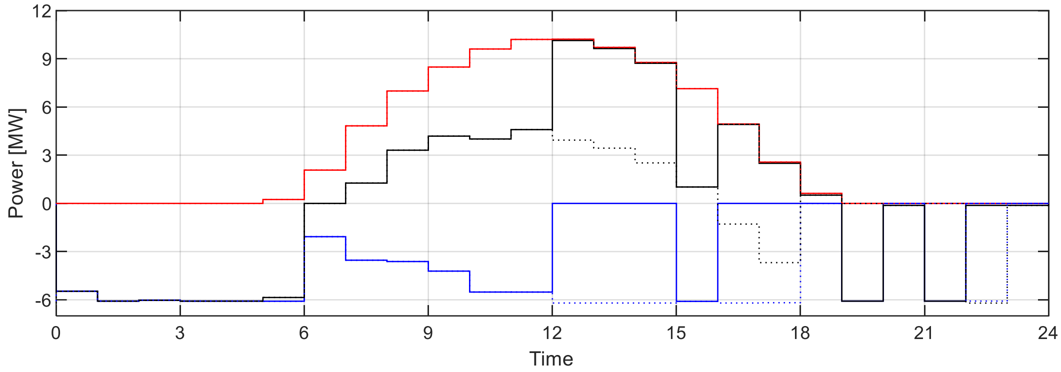


Figure 4.12: VPP power profiles offering on IDM considering an exemplary day (07.07.2019) in the Italian market zone of Sicily. Scenario VII. Original model (top) vs Modified model (bottom)



(a)



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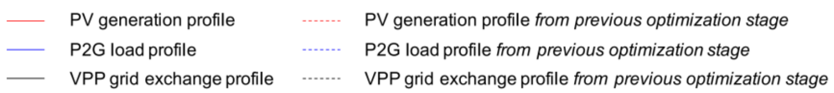


Figure 4.13: VPP power profiles offering on MB (RR & FRR provision) considering an exemplary day (07.07.2019) in the Italian market zone of Sicily. Scenario VII. Original model (top) vs Modified model (bottom)

In Figure 4.14, differences can be observed between the power profiles of the two models (modified and original), which was not seen in Figure 4.8. These differences are due to a different MB market positioning, preceding MR, in the two cases.

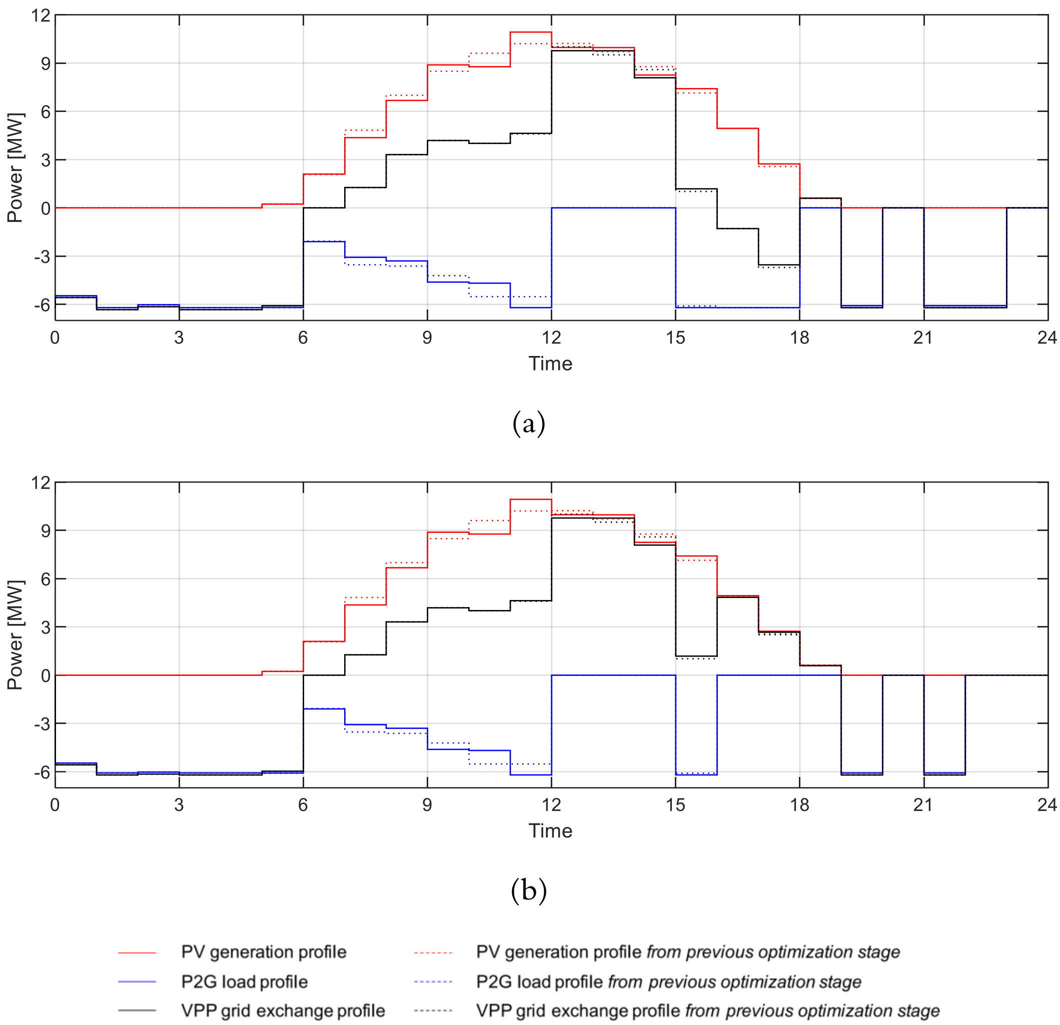


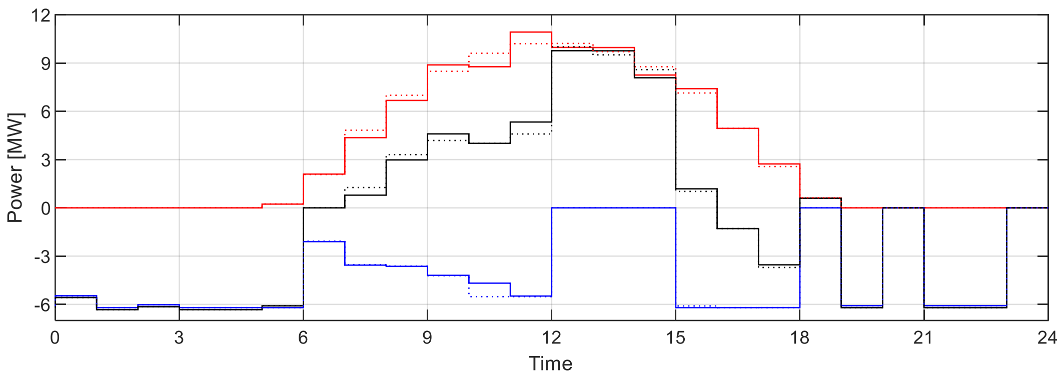
Figure 4.14: VPP power profiles offering on MR considering an exemplary day (07.07.2019) in the Italian market zone of Sicily. Scenario VII. Original model (top) vs Modified model (bottom)

4.2.3 Analysis of an exemplary day - Scenario VIII

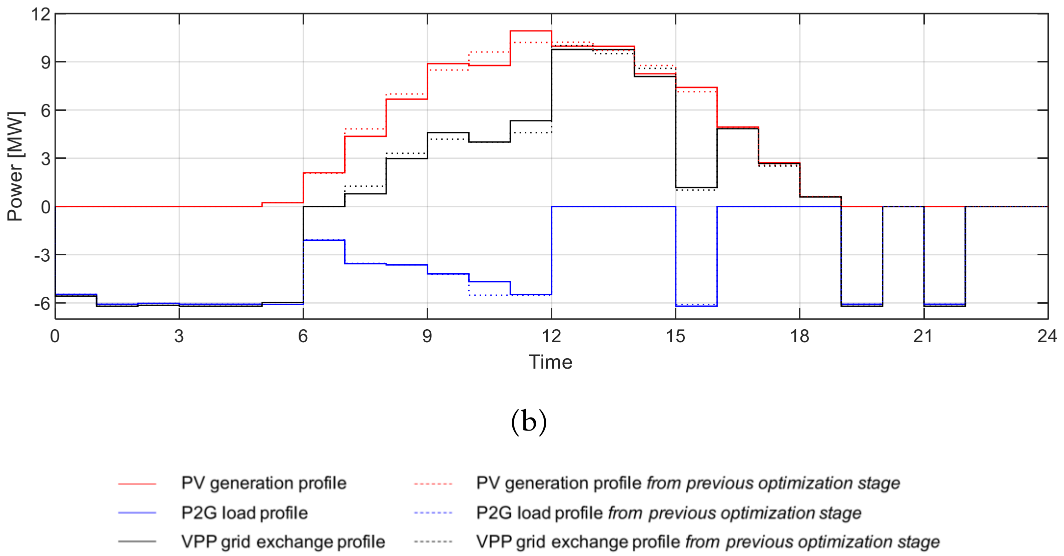
See Figure 4.5, Figure 4.12-(b) and Figure 4.13-(b) for the DAM, IDM and MB profiles respectively. As extensively explained in the previous section, scenario VIII displays a first form of passive balancing. The goal is to reduce imbalances deviating from the programmed profile of the VPP to counter PV intra-day forecast errors only as far as economically profitable (leaving the plant unbalanced rather than incurring in economic losses) by taking into account projected imbalance prices.

In Figure 4.15-(b) the plant prefers to eliminate its real-time imbalances only in some hours staying, instead, unbalanced in others. For example:

- In hours 7:00-9:00, the VPP takes a short position (i.e., is injecting less electricity than scheduled) despite having the ability to modulate P2G to fix this imbalance. However, it prefers to stay unbalanced and pay the imbalance charge rather than generate hydrogen.
- In hours 9:00-10:00 and 11:00-12:00, the VPP takes a long position (i.e., is injecting more electricity into the grid than scheduled) without involving P2G but injecting the surplus PV generation directly into the grid considering this choice the most convenient.
- In the hours 13:00-14:00 and 17:00-18:00, the VPP has a long imbalance position. With the imbalance prices being reasonably high around 100 €/MWh in these hours (Figure 4.4), the VPP prefers to sell its imbalance at this price rather than turning on the P2G to settle it internally by producing hydrogen.
- Instead, in the hour 14:00-15:00, the VPP assumes a short imbalance position. However, with the P2G baseline being zero in this hour, the VPP has no internal flexibility to cope with this imbalance.
- The VPP assumes a long position also in the hour 15:00-16:00. The PV is producing more, the VPP would like to eliminate this imbalance because it may not be profitable (it is seen more convenient to absorb energy with P2G to produce hydrogen rather than selling it to the grid), and in fact it absorbs as much as possible with P2G up the point where it reaches maximum capacity, while the other portion is injected into the grid.



(a)



(b)

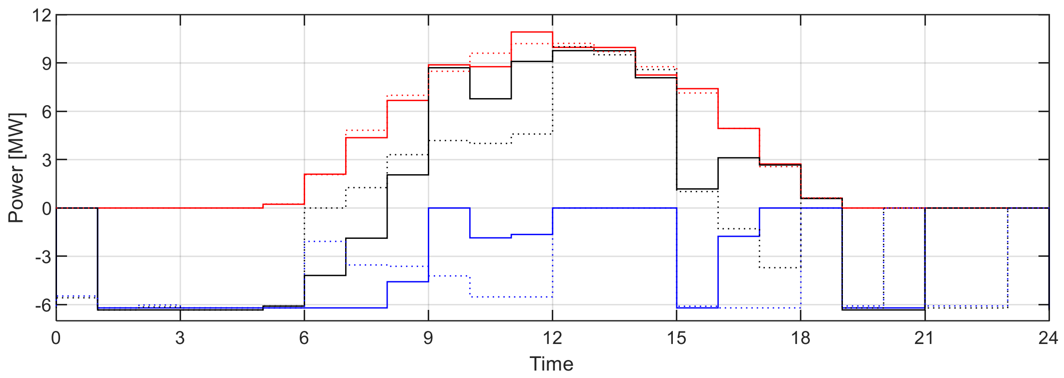
Figure 4.15: VPP power profiles offering on MR considering an exemplary day (07.07.2019) in the Italian market zone of Sicily. Scenario VIII. Original model (top) vs Modified model (bottom)

4.2.4 Analysis of an exemplary day - Scenario IX

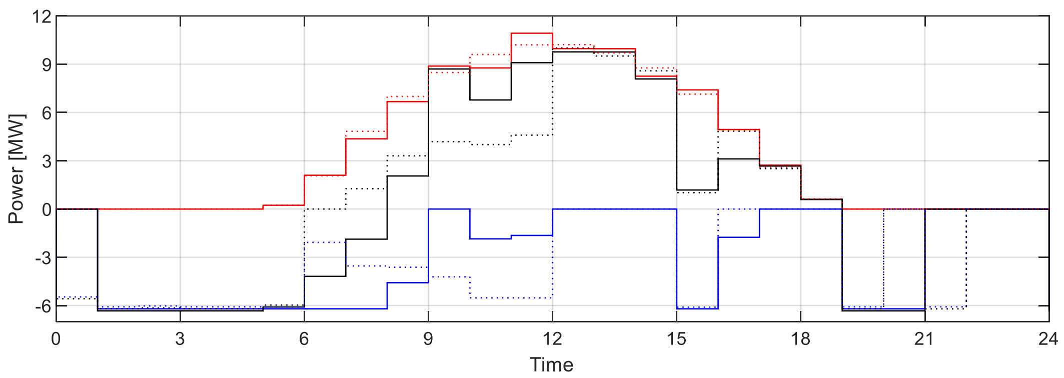
See Figure 4.5, Figure 4.12-(b) and Figure 4.13-(b) for the DAM, IDM and MB profiles respectively. In this scenario, the passive balancing is implemented. The flexibility of the VPP is used to exploit to the maximum level the real-time imbalance price ultimately causing shifts in the grid exchange profile. In fact, the difference between the black dotted line and the black solid line is visibly very high in certain hours of the day. This manifests in higher absorption from the grid during the morning when imbalance prices are low meaning that the overall system is long. Instead, high imbalance prices push the VPP to inject more/consume less, probably because the system is short in these hours.

Note that the optimizer returned in real-time at the same position in both models (Figure 4.16). However, the dotted lines (positioning on MB) are different between

Figure 4.16-(a) and Figure 4.16-(b) (see for example hours 17:00 and 18:00), meaning that different amounts of services are offered upward or downward on MR that generated different profits, or costs.



(a)



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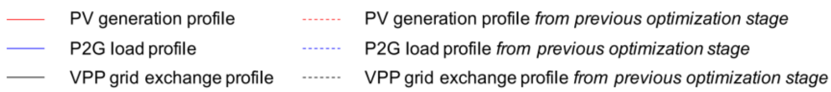

Figure 4.16: VPP power profiles offering on MR considering an exemplary day (07.07.2019) in the Italian market zone of Sicily. Scenario IX. Original model (top) vs Modified model (bottom)

4.3 Uncertainty about the acceptance of offers in the MB market

Resuming Figure 3.3, in the DAM and IDM markets the bidding and acceptance of offers occurs simultaneously as soon as a match between demand and offer takes place. In the MB market it is necessary to wait for real-time for the TSO, according to its needs, to announce which offers have been accepted. The results of Table 4.1 are obtained assuming that the bids submitted by the VPP operator in the balancing market are accepted with an acceptance rate of 100%. This situation differs from the reality where bids are not always accepted. In this section, an analysis is proposed to understand how the gain changes as the acceptance rate changes and what is the rejection rate beyond which the presented method is no longer convenient. To understand this, it is necessary to apply the same rejection rate to both models and identify which percentage makes the result of the modified model equal to that of the starting model. At that percentage, it will be useless to apply the proposed model. It will then be up to the plant operator, based on his risk aversion, to decide whether or not to apply this method as the uncertainty in the MB market changes.

The procedure implemented is applied to the scenarios of both models (new and original) and it is as follows. Vectors regarding the gains from power exchange with the grid in the MB and the gains associated with the amount of hydrogen sold by P2G in the MB are considered since their sum returns the social cost related to this market. These are repeated 1000 times to form two matrices with dimensions 1000x8760 (the second dimension being the yearly time horizon of 8760 hours). In each of these 1000 instances, a given percentage of the bids are randomly rejected in MB across the simulated horizon. Each row, therefore, represents a possible combination as Matlab randomly cancels, considering for example the case that 5% of the bids are rejected, 5% of the bids (cells) that are not null (obviously the null cells are not considered since no bids were submitted in those hours). The choice of creating a thousand combinations has been made to make the results more statistically sound, operating with randomly selected rejection series. In fact, Matlab might randomly eliminate one very profitable bid rather than another less profitable one. Then these two matrices are summed together, obtaining a single total social cost for each of the thousand combinations. Finally, these thousand values are averaged, obtaining the average social cost over MB for that given percentage, and that value is shown in Table 4.3. This procedure is repeated for different percentages. It is interesting to visualize how these combinations are distributed in a Gaussian curve so that we can identify quite clearly where the peak of the curve is located. The x-axis shows the number of combinations that fall within an interval range (understood as a revenue range) while the y-axis shows the revenue of the sum of the two IDM + MB markets (Figure 4.17).

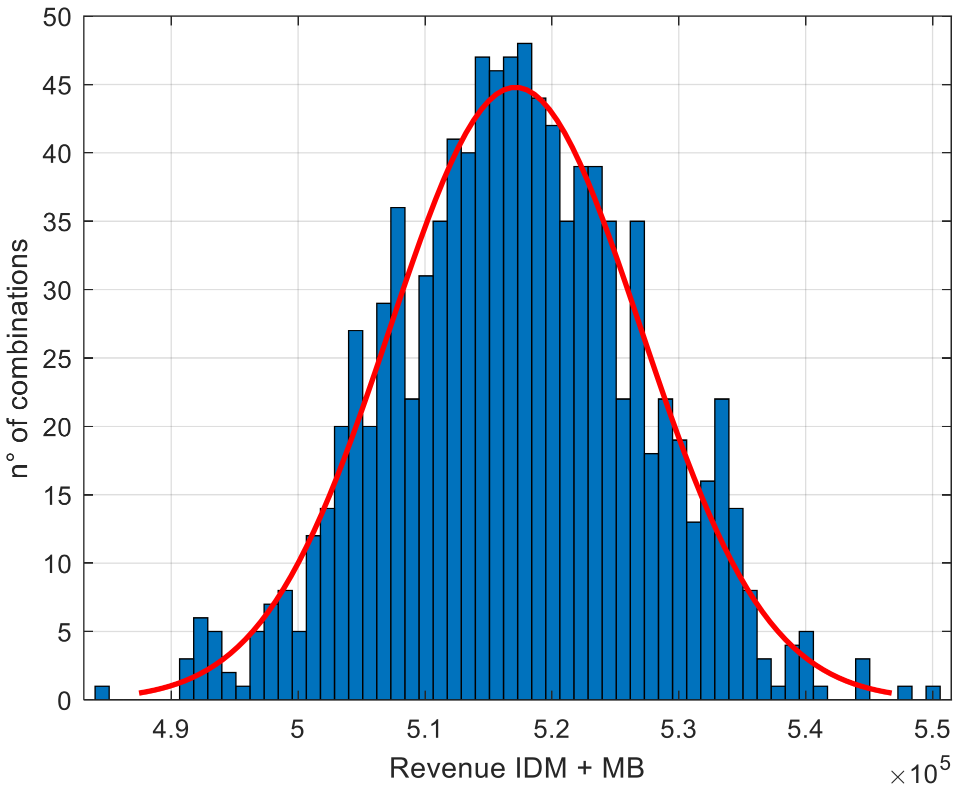

Figure 4.17: Gaussian distribution in case of 40% of accepted offers in scenario VI of the modified model.

The MB result decreases with the percentage of bids not accepted while the result of IDM stays the same (submission and acceptance are instantaneous), thus, the sum IDM + MB is only affected by the decrease in MB. It is possible to find a percentage that makes the proposed new model inconvenient since the IDM result is (always) a cost while this is (always) a revenue in the original model (Table 4.1). Looking at Table 4.3, it is enough that 33% of the bids submitted on MB with the proposed method are accepted, with a lower percentage it is convenient to use the original model while for a higher percentage the proposed method leads to a higher revenue. Figure 4.18 shows the revenue from the sum of the IDM and MB markets as the percentage of accepted bids changes, the intersection represents the trade-off.

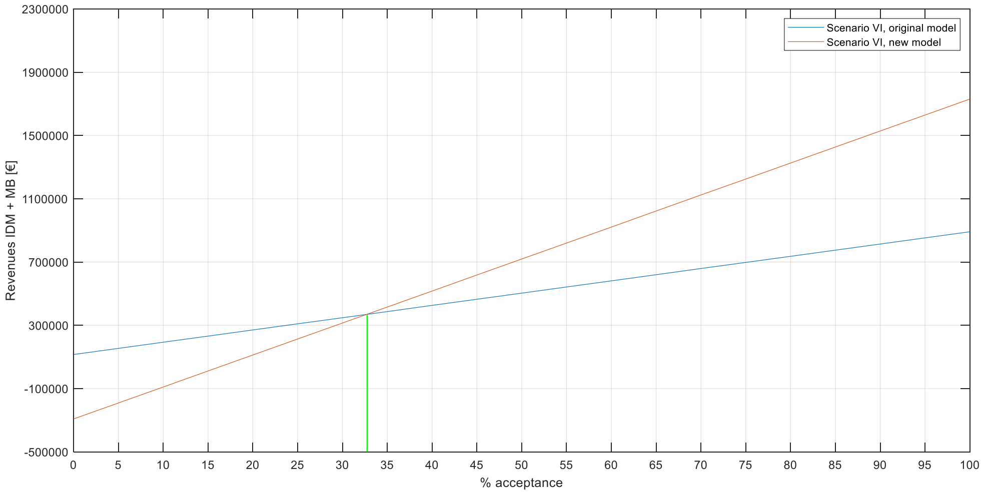

Figure 4.18: Revenues from the sum of the IDM and MB markets as the % of accepted offers made on MB changes.

Table 4.3: Social cost IDM + MB with different percentages of acceptance of offers in scenario VI for both models.

	Social cost IDM + MB [€], Scenario VI	
% Offers accepted	New Model	Original Model
100	1730183,32	891382,17
95	1629147,19	852595,68
90	1528300,14	813725,18
85	1427044,42	775020,39
80	1325891,78	736137,13
75	1224518,71	697512,68
70	1123985,85	659021,64
65	1022539,92	619813,59
60	920851,38	580858,27
55	819925,69	542298,00
50	719108,45	503304,85
45	618140,22	464703,74
40	516524,56	425989,03
35	415519,96	386744,02
33	**375744,38**	**371099,82**
30	314515,35	347840,60
25	213476,72	309436,70
20	112376,26	270670,64
15	11341,64	231697,60
10	-90158,59	231697,60
5	-190978,11	193093,01
0	-291955,80	115438,16

Chapter 5

5 Conclusions

The model performs an hourly simulation of an aggregate unit composed of PV and Power-to-gas that is necessary to assess both the potential of value stacking, understood as progressive market integration, and of cross-market arbitrage. The simulation implements a multi-period and multi-stage optimization on the entire year and is based on empirical market data for Italy. As mentioned in Chapter 3, the developed model is derived from an earlier model to which modifications have been introduced to deal with the concept of cross-market arbitrage. In particular, the starting model has been revisited to execute the intraday and balancing markets in an integrated manner inside the same optimization stage; thus, they are no longer independent as they were in the original model, but they are optimized together. Four scenarios characterized by increasing integration in markets have been considered, and it has been proven that, for these scenarios, the modifications lead to significant economic improvements considering the totality of interactions with markets.

Despite an apparent economic loss at the end of the intraday market in all scenarios, at the end of the balancing market there is a sensational gain exceeding those of the original scenarios by as much as +160% (as in scenario VI). This results in an economic benefit from the combination of these two markets of about +90%. These gains are due to the creation of a purposeful baseline in the intraday market to take maximum advantage of the balancing market session. This is possible because it has been considered on having a P2G that is able to move both production and absorption, thus making it possible to position in the desired way in the market at any time. Overall, when all the contributions from the interaction with the different markets are added together, there is an increase in revenues ranging from +25% for scenario IX to +40% in scenarios VII and VIII.

The application of the unlimited passive balance characterizing scenario IX is possible when a few large operators, who hold a very large share of electricity generation, are able to predict when the TSO has overproduction needs. In fact, having many power plants at their disposal and knowing exactly what is going on in each individual plant, they are able to understand that if one of their own plants goes out for maintenance, then there will be problems in the grid somehow managing to "predict the future." So, they know very well that, during those maintenance hours, Terna will be in trouble and will very gladly welcome the overproduction that these large plants can provide them. So, providing this service becomes a premium for these large operators.
It is clear that the gain related to the imbalance management (1324 k€) of scenario IX is not projectable over the entire life of the plant because it is based on the fact that there are those precise imbalance charges. If all operators implemented this strategy, there would no longer be that precise imbalance charge but perhaps the opposite. Since price varies according to how all traders position themselves within markets, if all traders behaved the same way then the market would adjust and there would be no more room for arbitrage; in other words, if all traders were price-makers, prices would adapt. So, this technique works exclusively if those who implement it are the only ones, or among the few, who can anticipate and exploit situations that arise in the market.

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