Applied Energy 374 (2024) 123966

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Multi-energy balancing services provision from a hybrid power plant: PV, battery, and hydrogen technologies

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ARTICLE INFO

Keywords:
Battery storage
Photovoltaic plant
Hydrogen
Hydrogen storage
Electrolyzer
Fuel cell
Electricity balancing
Gas balancing
Hydrogen network

ABSTRACT

Hydrogen technologies have gained momentum in recent years in the context of achieving fully renewable energy systems. Apart from the ability of electrolyzers and fuel cells to consume and generate green energy, the latest research on their technical characteristics also promotes them as providers of balancing services in both power and gas (either hydrogen or natural gas) systems. The balancing services provision is a highly uncertain process and is not scheduled in advance, however, due to signed contracts and rules, the provision of these services to the TSO is not considered as a deviation from the agreed schedule. Contrary to battery storage, whose operation only affects the power system power flows, the operation of power-to-hydrogen and hydrogen-to-power units in one system (e.g. power system) has an impact on the other system (e.g. gas) as well. Because of that, the unscheduled balancing services provision to one TSO will cause an imbalance towards the TSO in the other system. This impact remains unexplored in the available literature.

In this paper, we propose a model of a PV-battery-hydrogen power plant participating in both the power and gas (hydrogen) system markets while acting as a provider of balancing services and the responsible party of its own balancing group in both systems as well. We analyze how considering the influence that energy-conversion units simultaneously have on both observed systems affects the realized profit of the power plant and we show that neglecting this impact increases the total imbalance costs of the power plant, and consequently reduces its overall profit.

1. Introduction

1.1. Background and motivation

Conventionally, electric power and gas systems operate with a single interconnector – gas-fired power plants. Nonetheless, with climate deterioration, arrival of the pandemic, and the war in Europe, integration of newer and carbon-free energy systems is becoming more important than ever [1]. In response, renewable hydrogen emerges as the most promising solution. Hydrogen is mostly used in oil, chemical, and iron industry, however, almost all of its current production relies on fossil fuels. Strategies aimed at mitigating climate change tend to replace the hydrogen produced from fossil fuels with renewable hydrogen and integrate it into sectors where it is still seldomly used, such as the transport, the heating or the power system. For example, hydrogen can be used as a fuel for hydrogen power plants or for heating commercial buildings and households [2].

1.2. Creation and integration of the hydrogen system

Considering the current underdevelopment of the hydrogen market and infrastructure, the European Union has made a series of recommendations to simplify hydrogen integration [3]. These suggestions, such as enabling access to the gas wholesale markets for renewable types of gases, are considered in the research community as well. Paper [4] presented a model where a power-to-gas plant purchases electricity in the day-ahead market to operate an electrolyzer. The produced hydrogen is then stored and used either for charging hydrogen vehicles or converted into synthetic methane and sold in the gas day-ahead market. Another type of renewable gas — synthetic natural gas, produced from cheap electricity and, ultimately, sold in the gas day-ahead market, was discussed in [5]. The proposed model aims to minimize gas load consumption costs, reduce storage operating expenditures, and assess the economic viability of power-to-gas storage under various market conditions, incorporating a short-term gas demand forecaster for improved coordination. Likewise, the authors in [6] presented a

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https://doi.org/10.1016/j.apenergy.2024.123966
Received 10 January 2024; Received in revised form 19 March 2024; Accepted 17 July 2024
Available online 1 August 2024

Nomenclature

Abbreviations

aFRR	Automatic Frequency Restoration Reserve
BC	Balancing Capacity
BE	Balancing Energy
BG	Balancing Group
BS	Battery Storage
DA	Day-Ahead
EL	Electrolyzer
ENTSO-E	European Network of Transmission System Operators for Electricity
FC	Fuel Cell
FCR	Frequency Containment Reserve
HT	Hydrogen Tank
IS	Imbalance Settlement
mFRR	Manual Frequency Restoration Reserve
OS	Other System
PV	Photovoltaics
TSO	Transmission System Operator

Binary Variables

x_t^{b}	Binary variable restricting simultaneous battery storage charging and discharging in time period t
$x_t^{d,b}$	Binary variable restricting simultaneous increase of battery storage charging and reduction of discharging for downward reserve provision in time period t
$x_t^{d,ht}$	Binary variable restricting simultaneous increase of hydrogen tank charging and reduction of discharging for downward reserve provision in time period t
$x_t^{el,fc}$	Binary variable restricting simultaneous operation of the electrolyzer and fuel cell in time period t
x_t^{ht}	Binary variable restricting simultaneous hydrogen tank charging and discharging in time period t
$x_t^{u,b}$	Binary variable restricting simultaneous battery storage charging reduction and increase of discharging for upward reserve provision in time period t
$x_t^{u,ht}$	Binary variable restricting simultaneous hydrogen tank charging reduction and increase of discharging for upward reserve provision in time period t

Free Variables

$\theta^{bc,\{p,g\}}$	Power/gas BC profit (€)
$\theta_s^{be,\{p,g\}}$	Power/gas BE profit/cost (€)
$\theta^{da,\{p,g\}}$	Power/gas DA profit/cost (€)
θ^{ht}	Hydrogen tank compression DA power cost (€)
$\theta^{is,\{p,g\}}$	Power/gas IS profit/cost (€)
$h_t^{da,g}$	Total hydrogen traded in the gas DA in time period t (MW)
$p_t^{da,p}$	Total power traded in the power DA in time period t (MW)

Parameters

Δt	Time period length (h)
η^{ch}	Charging efficiency of the battery storage (%)
η^{dis}	Disharging efficiency of the battery storage (%)
$\eta^{el,f}$	Fixed part of the electrolyzer efficiency curve (%)
η^{el}	Variable part of the electrolyzer efficiency curve (%)
$\eta^{fc,f}$	Fixed part of the fuel cell efficiency curve (%)
η^{fc}	Variable part of the fuel cell efficiency curve (%)
η^{ht}	Compression efficiency of the hydrogen tank (%)
$\lambda_t^{da,\{p,g\}}$	Power/gas DA market price in time period t (€/MWh)
$\mu_d^{\{s,l\}}$	Imbalance price for BG surplus/shortage in gas system on day d (€/MWh)
$\mu_d^{\{u,d\},be}$	Upward/downward BE price in the gas system on day d (€/MWh)
$\mu_t^{\{u,d\},bc}$	Upward/downward BC price in the gas system in time period t (€/MW)
$\rho_t^{\{s,l\}}$	Imbalance price for BG surplus/shortage in power system in time period t (€/MWh)
$\rho_t^{\{u,d\},bc}$	Upward/downward BC price in the power system in time period t (€/MW)
$\rho_t^{\{u,d\},be}$	Upward/downward BE price in the power system in time period t (€/MWh)
H^{ht}	Installed hydrogen tank power (MW)
$M_{t,s}^{\{u,d\}}$	Portion of activation of upward/downward BC in the gas system (%)
$P_{t,s}^{\{s,l\},pv}$	Surplus/shortage in PV production (MWh)
P^{b}	Installed power of the battery storage (MW)
$P^{el,min}$	Minimum operational power of the electrolyzer (MW)
P^{el}	Installed power of the electrolyzer (MW)
$P^{fc,min}$	Minimum operational power of the fuel cell (MW)
P^{fc}	Installed power of the fuel cell (MW)
$P_t^{for,pv}$	Forecasted production of PV (MW)
$R_{t,s}^{\{u,d\}}$	Portion of activation of upward/downward BC in the power system (%)
S^{bs}	Battery storage capacity (MWh)
S^{ht}	Hydrogen tank capacity (MWh)

method for a coordinated operation of the electricity and the natural gas systems, which resulted in production of the electricity-based renewable gas available for gas grid injection. The excess renewable energy was used to produce hydrogen, which was then injected into multiple gas grid locations. The authors also proposed a method for tracking the hydrogen share in the gas mixture in order to respect the given limitations recommended by the agencies in [3].

Many papers assume that the hydrogen system and market already exist, and analyze different impacts of such markets on the operation and profit of the power plants, market prices, etc. In [7], a hybrid plant participated in the electricity and hydrogen markets aiming to maximize its profit through performing price arbitrage. The profit with

Positive Variables

$b^{l,g}_{d,s}$	Gas imbalance shortage from power balancing on day d and in scenario s (MWh)
$b^{l,pv}_{t,s}$	Power imbalance shortage from the PV overforecast in time period t and scenario s (MWh)
$b^{l,p}_{t,s}$	Power imbalance shortage from gas balancing in time period t and scenario s (MWh)
$b^{s,g}_{d,s}$	Gas imbalance surplus from power balancing on day d and in scenario s (MWh)
$b^{s,pv}_{t,s}$	Power imbalance surplus from the PV underforecast in time period t and scenario s (MWh)
$b^{s,p}_{t,s}$	Power imbalance surplus from gas balancing in time period t and scenario s (MWh)
$d^{\{u,d\}}_{t,s}$	OS reserve allocated for upward/downward imbalances arising from gas system in time period t and in scenario s (MWh)
$d^{\{u,d\}}_{t}$	OS reserve allocated for upward/downward imbalances arising from gas system in time period t (MWh)
$d^{\{i,r\},ch}_{t,s}$	Battery storage charging increase/reduction reserved to balance the downward/upward imbalances arising from gas system in time period t and scenario s (MWh)
$d^{\{i,r\},dis}_{t,s}$	Battery storage discharging increase/reduction reserved to balance the upward/downward imbalances arising from gas system in time period t and scenario s (MWh)
$d^{\{i,r\},ch}_{t}$	Battery storage charging increase/reduction reserved to balance the downward/upward imbalances arising from gas system in time period t (MWh)
$d^{\{i,r\},dis}_{t}$	Battery storage discharging increase/reduction reserved to balance the upward/downward imbalances arising from gas system in time period t (MWh)
$f^{\{u,d\}}_{t,s}$	PV reserve allocated for PV over-/under-forecast in time period t and in scenario s (MWh)
$f^{\{u,d\}}_{t}$	PV reserve allocated for PV over-/under-forecast in time period t (MWh)
$f^{\{i,r\},ch}_{t,s}$	Battery storage charging increase/reduction reserved to balance the PV under-/over-forecast in time period t and scenario s (MWh)
$f^{\{i,r\},dis}_{t,s}$	Battery storage discharging increase/reduction reserved to balance the PV over-/under-forecast in time period t and scenario s (MWh)
$f^{\{i,r\},el}_{t,s}$	Electrolyzer power consumption increase/reduction reserved to balance the PV under-/over-forecast in time period t and scenario s (MWh)
$f^{\{i,r\},fc}_{t,s}$	Fuel cell power generation increase/reduction reserved to balance the PV over-/down-forecast in time period t and scenario s (MWh)
$f^{\{i,r\},ch}_{t}$	Battery storage charging increase/reduction reserved to balance the PV under-/over-forecast in time period t (MWh)
$f^{\{i,r\},dis}_{t}$	Battery storage discharging increase/reduction reserved to balance the PV over-/under-forecast in time period t (MWh)
$f^{\{i,r\},el}_{t}$	Electrolyzer power consumption increase/reduction reserved to balance the PV under-/over-forecast in time period t (MWh)
$f^{\{i,r\},fc}_{t}$	Fuel cell power generation increase/reduction reserved to balance the PV over-/down-forecast in time period t (MWh)
$h^{\{ch,dis\}}_{t}$	Hydrogen charged/discharged to/from the hydrogen tank in time period t (MW)
$h^{\{el,fc\}}_{t}$	Hydrogen generated/consumed by the electrolyzer/fuel cell in time period t (MW)
$h^{\{i,r\},ch}_{t}$	Total hydrogen tank charging increase/reduction potential in time period t (MW)
$h^{\{i,r\},dis}_{t}$	Total hydrogen tank discharging increase/reduction potential in time period t (MW)
$l^{\{u,d\}}_{t,s}$	Hydrogen capacity reserved for upward/downward imbalances arising from power system in time period t and in scenario s (MWh)
$l^{\{u,d\}}_{t}$	Hydrogen capacity reserved for upward/downward imbalances arising from power system in time period t (MWh)
$l^{\{i,r\},ch}_{t,s}$	Hydrogen tank charging reduction/increase reserved to balance the upward/downward imbalances arising from power system in time period t and scenario s (MWh)
$l^{\{i,r\},dis}_{t,s}$	Hydrogen tank discharging increase/reduction reserved to balance the upward/downward imbalances arising from power system in time period t and scenario s (MWh)
$l^{\{i,r\},ch}_{t}$	Hydrogen tank charging increase/reduction reserved to balance the downward/upward imbalances arising from power system in time period t (MWh)
$l^{\{i,r\},dis}_{t}$	Hydrogen tank discharging increase/reduction reserved to balance the upward/downward imbalances arising from power system in time period t (MWh)
$m^{\{u,d\}}_{t}$	Upward/downward gas TSO reserve sold in the gas BC on day d (MW)
$m^{\{i,r\},ch}_{t}$	Hydrogen tank charging increase/reduction reserved for the downward/upward gas BC in time period t (MW)

the integration of the hydrogen market was increased compared to trading only in the electricity day-ahead market. Similar conclusions were drawn in [8], which claimed an increase in profit of 2.74 times when the hydrogen market is included in the trading process. Furthermore, according to [9], it seems that the integration of hydrogen technologies can reduce the electricity price volatility. Still, only a

$m_t^{\{i,r\},dis}$	Hydrogen tank discharging increase/reduction reserved for the upward/downward gas BC in time period t (MW)
n_t^l	Power shortage from gas TSO balancing in time period t (MW)
n_t^s	Power surplus from gas TSO balancing in time period t (MW)
$n_t^{\{i,r\},el}$	Electrolyzer power consumption increase/reduction reserved for the upward/downward gas BC in time period t (MW)
$n_t^{\{i,r\},fc}$	Fuel cell power generation increase/reduction reserved for the downward/upward gas BC in time period t (MW)
$p_t^{\{ch,dis\}}$	Power charged/discharged to/from the battery storage in time period t (MW)
$p_t^{\{el,fc\}}$	Power consumed/generated by the electrolyzer/fuel cell in time period t (MW)
$p_t^{\{i,r\},ch}$	Total battery storage charging increase/reduction potential in time period t (MW)
$p_t^{\{i,r\},dis}$	Total battery storage discharging increase/reduction potential in time period t (MW)
$p_t^{\{i,r\},el}$	Total electrolyzer power consumption increase/reduction potential in time period t (MW)
$p_t^{\{i,r\},fc}$	Total fuel cell power generation increase/reduction potential in time period t (MW)
$r_t^{\{u,d\}}$	Upward/downward power TSO reserve sold in the BC market in time period t (MW)
$r_t^{\{i,r\},ch}$	Battery storage charging increase/reduction reserved for downward/upward power BC in time period t (MW)
$r_t^{\{i,r\},dis}$	Battery storage discharging increase/reduction reserved for upward/downward power BC in time period t (MW)
$r_t^{\{i,r\},el}$	Electrolyzer power consumption increase/reduction reserved for downward/upward power BC in time period t (MW)
$r_t^{\{i,r\},fc}$	Fuel cell power generation increase/reduction reserved for upward/downward power BC in time period t (MW)
$soe_{t,s}$	State of energy of the battery storage in time period t and scenario s (MWh)
$soh_{t,s}$	State of hydrogen in the hydrogen storage in time period t and scenario s (MWh)
$v_{t,s}^l$	Gas shortage from PV balancing in time period t and scenario s (MWh)
v_t^l	Gas shortage from PV balancing in time period t (MWh)
$v_{t,s}^s$	Gas surplus from PV balancing in time period t and scenario s (MWh)
v_t^s	Gas surplus from PV balancing in time period t (MWh)
w_t^l	Gas shortage from power TSO balancing in time period t (MW)
w_t^s	Gas surplus from power TSO balancing in time period t (MW)

decrease in the investment costs or an increase in the CO_2 emission costs will make power-to-gas technologies more attractive to investors. The authors in [10,11] demonstrated that cooperation between the electric power and hydrogen systems might also serve to mitigate deviations in variable renewable sources' production, such as wind or PV.

1.3. Reserve provision to the power system

Power generation from uncontrollable renewable sources, i.e. wind and PV, is growing rapidly, causing a decrease in controllable, dominantly fossil-fuel-powered, power units. This means that the power system gradually loses its capability to maintain the generation-consumption balance. New technologies are necessary to bridge the gap and provide additional flexibility (ancillary services) to the power system. Battery storage emerged as one of the solutions ready to react quickly and provide ancillary services to the system. Providing such services contributes to the return on investment in battery storage. According to [12], even below-average prices for providing automatic frequency restoration reserve (aFRR) ensure a significant increase in profit for the battery storage owner. Offering frequency containment reserve (FCR), which requires an even faster response, can make an investment in battery storage highly profitable under the current market regulations in some European countries, e.g. Denmark and Germany [13].

Energy-conversion units, such as electrolyzers and fuel cells, also show useful characteristics for maintaining the power system balance. According to the ENTSO-E report [14], electrolyzers are capable of providing a whole range of frequency reserves — from FCR to slower reserves such as aFRR or mFRR, given that they can increase their operating power to maximum in a matter of seconds. Though, it is important to take into account what types of electrolyzers are used and what are their current states of operation (switched off, standby, in operation).

Many research papers that consider reserve provision using energy-conversion units focus on hydrogen refilling stations, pointing out that reserve provision can increase the overall profit for the station owners [15–17]. Recently, the focus slightly moved from the hydrogen refilling stations to the power-to-hydrogen plants providing reserves to the power system operator [18–23]. All these papers modeled participation in the day-ahead markets and the provision of one reserve type in the power system, with the exception of [23], participating in *three* reserve markets (FCR, aFRR, and mFRR). As with the fueling stations, FCR and aFRR provision contribute to higher profits for the power plant and reduced hydrogen marginal price compared to the case without the reserve market participation. However, highest revenues can be achieved by selling the remaining hydrogen in the hydrogen market, after fulfilling the local demand.

1.4. Research gap and contribution

Although various papers demonstrated how reserve provision to the power system operator by using hydrogen technologies results in higher return rates, none of the papers, to the best of our knowledge, considered that these units can balance the gas system as well. When it comes to technical capabilities for the provision of this service, there should be no obstacle since the deviations in the gas system are corrected at a lower frequency (within a day or monthly), so the power-to-hydrogen units should be able to provide balancing services in that system as well.

Another deficiency in the existing literature is the absence of an analysis of the impact of the reserve provision by energy-conversion units in one system (e.g. electric power) on another system (e.g. gas), since the operation of such unit in one system will also affect the flows in the other system.

Therefore, the main scientific contribution is the design of a novel operational model for a PV-battery-hydrogen plant for multi-energy multi-service market participation considering all technical limits and costs, along with a detailed analysis of the imbalance implications across different energy systems. The model and the analysis take into account:

- Two energy systems: electrical power and gas system (assuming total shift from natural gas to renewable hydrogen).
- Provision of several services to those systems: day-ahead trading/scheduling, imbalance settlement, balancing services provision to balancing groups (BG) and transmission system operators (TSOs).
- Modeling of the balancing services activations and PV generation as uncertain parameters through scenario-based stochastic optimization approach using real historic data.
- Explicit consideration of the impact of the balancing services activations in one system on another's imbalance settlement and the effect of the imbalance correction.
- Transfer of imbalances from one system to another due to imbalance price difference and different imbalance settlement periods (1 h vs 1 day).

The primary focus of this paper is to introduce a comprehensive operational model of a hybrid power plant rather than studying its dimensioning and investment profitability. We argue that the initial step in constructing a high-quality investment (or dimensioning) model is to establish an accurate and reliable operational model. To validate this operational model, we selected arbitrary but mutually comparable capacities for the units within the hybrid power plant. While the dimensioning of the units presented herein represents just one use case, the model itself is applicable to any other capacities of the hybrid power plant units.

Moreover, to reduce complexity, our study concentrates on the day-ahead markets, and aFRR balancing capacity and energy markets, but it can be extended to other markets and services such as the intraday, the FCR, and the mFRR markets. It is essential to note that this operational model can be used for all decentralized energy markets where users are considered as balancing responsible parties and can provide balancing services. In the paper we showcase results using the Croatian markets as the case study, but the model remains valid for other use cases (countries) as well.

1.5. Paper structure

Section 2 provides details on the hybrid power plant, the services it can provide, and the markets it can participate in. It also explains how the operation of energy-conversion units might unwillingly affect both systems simultaneously. Section 3 presents a mathematical model of the hybrid plant, including all market and technical constraints. Section 4 provides information about the input data used to gather the results discussed in Section 5. A summary of the presented work, its limitations, and future research plans are given in Section 6.

2. Modeling framework

2.1. Plant description

The hybrid plant in this paper refers to a single facility and a single market player composed of the following units:

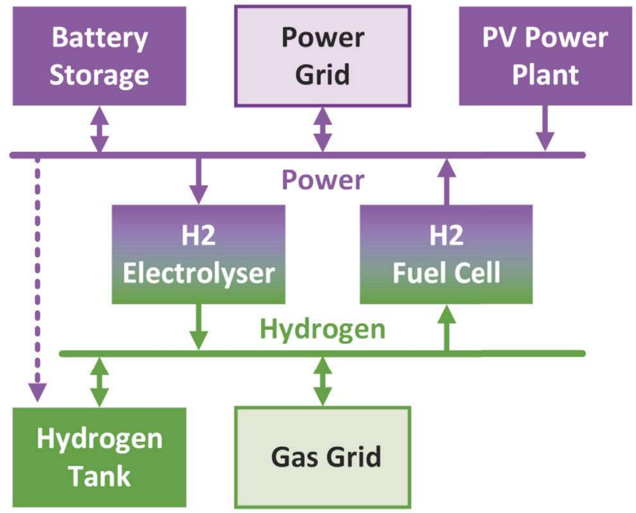

Fig. 1. Illustration of the interactions of individual units of the hybrid power plant with the power system and the (natural or hydrogen) gas system (Full Case in Section 5.1.2).

- PV power plant with uncertain generation,
- Energy converting technologies:
  - Electrolyzer, i.e. a power-to-hydrogen unit,
  - Fuel Cell, i.e. a hydrogen-to-power unit,
- Storage facilities:
  - Battery storage connected to the power bus,
  - Hydrogen tank connected to the gas bus,

An illustration of the hybrid plant is given in Fig. 1. The plant's capacity is considered sufficiently small not to be able to alter the prices in both the electricity and the gas (hydrogen) markets, thus the hybrid plant is considered to be a price taker in both markets.

A RES (PV) power plant produces uncertain amounts of electricity. It is accompanied by a hydrogen-converting technology to increase the value of renewable energy and to diversify its participating markets. PV is the only unit within the hybrid power plant with stochastic output, meaning it can cause imbalances. Storage technology is added for balancing/security reasons in the first place, and secondary to increase the value of renewable energy. The hybrid power plant can be connected to the electric power and the gas system, either natural gas or hydrogen grid. Our assumption is that in the next couple of years, such plants can be used to decarbonize the natural gas grids, but in the long term the gas grids will fully convert to hydrogen grids. The only difference between the natural gas and the hydrogen connection is that the plant cannot take gas from the former one (it can only inject into it). On the other hand, when connected to future the hydrogen grid, it can both extract and inject hydrogen. The rest of the paper uses the term *gas* for hydrogen gas, however, practically the same mathematical formulations for the two systems can be used, apart from omitting the hydrogen withdrawal constraint in the case of the natural gas grid connection.

2.2. Markets and services

The paper focuses on the European market structure. The hydrogen markets, which are still undeveloped, are assumed to have the same structure as the existing natural gas markets. The plant has the following interactions with both the power and hydrogen systems:

- Wholesale day-ahead markets,
- Imbalance settlement,

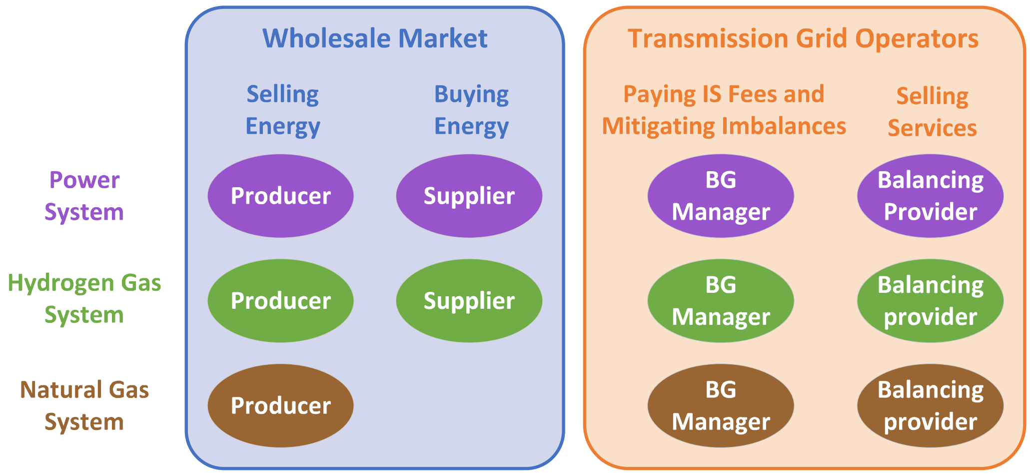

Fig. 2. Different roles the observed plant can take as market participant and service provider.

- BG balancing services,
- TSO balancing services.

2.2.1. Wholesale day-ahead markets (DA)

These are the reference price-setting markets in Europe for both power and natural gas. Their gate closures are one day before the delivery and the accepted bids/asks are considered obligatory schedules towards the power and natural gas TSOs. The same principle is assumed for the hydrogen DA market. The plant can act at both demand and supply sides in the power and hydrogen DA markets, while in the natural gas market, it can only sell gas.

2.2.2. Imbalance settlement (IS)

Each market participant should keep its energy realizations as close as possible to its DA schedules. Each market participant must be a part of a BG that is responsible for its imbalances towards the TSO. In this paper, the power plant acts as a manager of its own BG. If imbalances occur, they are penalized by the TSOs through imbalance prices. The power system balancing is on an hourly resolution, while the gas system (both natural gas and hydrogen) calculates imbalances on daily resolution. Two causes of imbalances are considered for the hybrid power plant in this paper (neglecting units' failures and technical imperfections):

(i) uncertain PV generation — the only unit that can cause imbalances due to its unpredictability, later in the text the term *PV imbalance* stands for these imbalances,
(ii) uncertain provision of balancing services in other systems (OS — Other System) — provision of balancing services in one energy system, e.g. power, causes issues in the other system, e.g. hydrogen, later in the text the term *OS imbalance* stands for these imbalances.

2.2.3. BG balancing services

Each BG can reserve part of its flexible capacity to reduce imbalances, i.e. deviation from its net market position. In this aspect, the BG manager provides balancing services to its BG members. This paper assumes the distinction among the BG balancing services based on their cause:

(i) PV reserve and PV activation — reserved capacity and activated energy to cover for imbalances stemming from uncertain PV generation,
(ii) OS reserve and OS activation — reserved capacity and activated energy to cover for imbalances stemming from balancing services provision in other systems.

2.2.4. TSO balancing services

Even with the BG managers trying to mitigate imbalances, the imbalances in the system still occur. To keep the grids balanced, TSOs use balancing markets where balancing service providers sell their flexibility. In the power system, two balancing markets exist: balancing capacity (BC) and balancing energy (BE) markets. The first one is used to reserve sufficient capacity for future balancing needs, while the second one is used to provide the balancing energy when needed. For gas balancing (both natural and hydrogen gas) the same structure is employed but on the daily resolution. In the rest of the paper the term *TSO reserve* refers to provision of capacity in the balancing capacity market, while the term *TSO activation* refers to provision of services in the balancing energy market. All the plant's interactions and roles are depicted in Fig. 2.

Fig. 3 shows a simplified hybrid power plant where only two units (electrolyzer and fuel cell) are shown with all the interactions with the power and gas (either hydrogen or natural gas) system. The point of this figure is to zoom in the interactions between the plant and the external systems. Fig. 3 indicates that the hybrid plant can interact with the two systems as follows: submit its DA market bids (brown arrows), pay for imbalances (blue arrows), provide balancing services to its own BG (orange arrows) and to the TSOs (gray arrows). Total volumes of the power plant (variables) correspond to its interaction with the two systems and they must be distributed among all units within the hybrid power plant.

2.3. Challenges

Two issues can emerge from uncertainties related to the PV output and the balancing services provision in the other energy system: (i) violation of the technical boundaries, and (ii) imbalanced positions after the delivery.

For example, the power TSO reserve activation on the power side using a converting technology, i.e. an electrolyzer or a fuel cell, directly causes different hydrogen flows. They can cause hydrogen technical limits to be reached (if not modeled properly) and stop the provision of the agreed reserve. Furthermore, those changes in hydrogen flows can create imbalance and penalties towards the gas TSO (either hydrogen or natural gas), even if the technical limits are obeyed. Analogously, the gas balancing services provision can create the same effects on power limits and imbalance towards the power TSO.

In this paper, the effect on technical limits is explicitly modeled, while the focus is on the investigation of the cross-energy system imbalance effects. In Fig. 3, the light red curves (marked with number 1.) visualize the impact of power balancing services provision on the

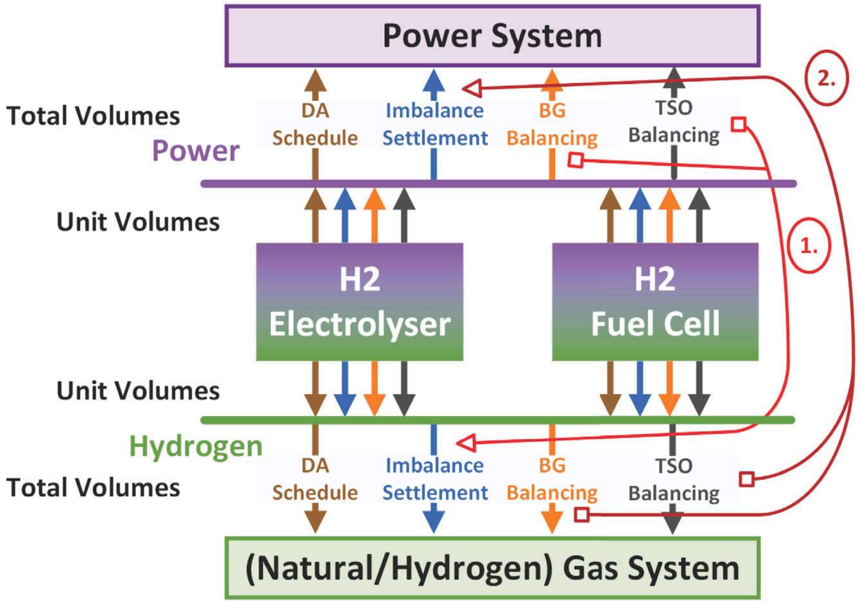

Fig. 3. Illustration of interactions of energy-conversion units with the power and the gas systems with detailed display of market interactions (Simple Case in Section 5.1.2).

gas side, while the dark red curves (number 2.) visualize the gas balancing impact on the power side.

Ignoring the possibility of inducing imbalance in one system by using the energy-converting technologies for balancing the other system can create unexpected costs for the hybrid plant. The model in this paper can effectively solve these issues since those imbalances are explicitly considered (imbalance cost-mitigating effect). Furthermore, the imbalance from one energy system can be directly transferred to the other, mitigating the imbalances in both systems (imbalance netting effect) or exploiting the imbalance price difference between the two systems (imbalance arbitrage effect).

3. Mathematical model

The model presented in this section is a mixed-integer problem where the plant is a price-taker in all markets with deterministic prices. The uncertain parameters modeled using scenarios are the PV output and the TSO reserve activation in both systems.

3.1. Objective function

Objective function (1) maximizes the profit made in the power and gas DA ($\theta^{\mathrm{da,p}}$, $\theta^{\mathrm{da,g}}$), BC ($\theta^{\mathrm{bc,p}}$, $\theta^{\mathrm{bc,g}}$), BE ($\theta_s^{\mathrm{be,p}}$, $\theta_s^{\mathrm{be,g}}$), and IS ($\theta_s^{\mathrm{is,p}}$, $\theta_s^{\mathrm{is,g}}$) markets. Note that the BE and IS variables are modeled as stochastic parameters using activation scenarios s. Additionally, the objective function considers costs related to the power consumption of the hydrogen tank compression (θ^{ht}). The DA, BE and IS profit/losses are calculated on the hourly resolution for the power system and the daily resolution for the gas system.

Profits/losses in the DA markets are calculated using Eqs. (2)–(3), where electrical energy volumes $p_t^{\mathrm{da,p}} \cdot \Delta t$ are sold/purchased at prices $\lambda_t^{\mathrm{da,p}}$ and gas volumes $p_t^{\mathrm{da,g}} \cdot \Delta t$ are sold/purchased at prices $\lambda_d^{\mathrm{da,g}}$. Profits from the BC markets are calculated in Eqs. (4)–(5), where BC volumes for upward (r_t^{u}) and downward (r_t^{d}) directions in the power system are sold at power BC prices ($\rho_t^{\mathrm{u,bc}}$, $\rho_t^{\mathrm{d,bc}}$), while the ones in the gas system (m_t^{u}, m_t^{d}) are sold at the gas BC prices ($\mu_t^{\mathrm{u,bc}}$, $\mu_t^{\mathrm{d,bc}}$). Finally, the BE market profit/losses are calculated in Eqs. (6)–(7) at BE prices where $\rho_t^{\mathrm{u,be}}$ and $\rho_t^{\mathrm{d,be}}$ denote the prices for upward and downward activations in the power system, while $\mu_d^{\mathrm{u,be}}$ and $\mu_d^{\mathrm{d,be}}$ stand for their equivalent values in the gas system. The BE volumes are calculated as BC volumes multiplied with the average activation ratio and timestep duration as follows:

- $r^{\mathrm{u}_t} \cdot R \cdot \Delta t$, for upward power system BE,
- $r_t^{\mathrm{d}} \cdot R \cdot \Delta t$, for downward power system BE,
- $m_t^{\mathrm{u}} \cdot M \cdot \Delta t$, for upward gas system BE,
- $m_t^{\mathrm{d}} \cdot M \cdot \Delta t$, for downward gas system BE.

$$\max_{\Xi} \ \theta^{\mathrm{da,p}} + \theta^{\mathrm{da,g}} + \theta^{\mathrm{bc,p}} + \theta^{\mathrm{bc,g}} + \sum_s (\theta_s^{\mathrm{be,p}} + \theta_s^{\mathrm{be,g}} + \theta_s^{\mathrm{is,p}} + \theta_s^{\mathrm{is,g}}) - \theta^{\mathrm{ht}} \tag{1}$$

$$\theta^{\mathrm{da,p}} = \sum_t p_t^{\mathrm{da,p}} \cdot \Delta t \cdot \lambda_t^{\mathrm{da,p}} \tag{2}$$

$$\theta^{\mathrm{da,g}} = \sum_d \lambda_d^{\mathrm{da,g}} \cdot \sum_t^d h_t^{\mathrm{da,g}} \cdot \Delta t \tag{3}$$

$$\theta^{\mathrm{bc,p}} = \sum_t (r_t^{\mathrm{u}} \cdot \rho_t^{\mathrm{u,bc}} + r_t^{\mathrm{d}} \cdot \rho_t^{\mathrm{d,bc}}) \tag{4}$$

$$\theta^{\mathrm{bc,g}} = \sum_t (m_t^{\mathrm{u}} \cdot \mu_t^{\mathrm{u,bc}} + m_t^{\mathrm{d}} \cdot \mu_t^{\mathrm{d,bc}}) \tag{5}$$

$$\theta_s^{\mathrm{be,p}} = \Delta t \cdot \sum_t (R_{t,s}^{\mathrm{u}} \cdot r_t^{\mathrm{u}} \cdot \rho_t^{\mathrm{u,be}} - R_{t,s}^{\mathrm{d}} \cdot r_t^{\mathrm{d}} \cdot \rho_t^{\mathrm{d,be}}), \quad \forall s \tag{6}$$

$$\theta_s^{\mathrm{be,g}} = \Delta t \cdot (\sum_d \mu_d^{\mathrm{u,be}} \cdot \sum_t^d M_{t,s}^{\mathrm{u}} \cdot m_t^{\mathrm{u}} - \mu_d^{\mathrm{d,be}} \cdot \sum_t^d M_{t,s}^{\mathrm{d}} \cdot m_t^{\mathrm{d}}) \tag{7}$$

Profits/losses from the power and gas IS mechanisms are calculated in Eqs. (8)–(9), where imbalance volumes are represented as:

- $b_t^{\mathrm{s,pv}}$ for the surplus in PV production in the power system,
- $b_t^{\mathrm{l,pv}}$ for the lack in PV production in the power system,
- $b_t^{\mathrm{s,p}}$ for the surplus in the power system caused by gas TSO reserve activation,
- $b_t^{\mathrm{l,p}}$ for the lack in the power system caused by gas TSO reserve activation,
- $b_d^{\mathrm{s,g}}$ for the surplus in the gas system caused by power TSO reserve activation,
- $b_d^{\mathrm{l,g}}$ for the lack in the gas system caused by power TSO reserve activation,

These volumes are then sold or purchased at prices ρ_t^{s} and ρ_t^{l} for the surpluses and lacks in the power system, or at prices μ_d^{s} and μ_d^{l} for their gas system counterparts.

$$\theta_s^{\text{is,p}} = \sum_t \Delta t \cdot [\rho_t^{\text{s}} \cdot (b_{t,s}^{\text{s,pv}} + b_{t,s}^{\text{s,p}}) - \rho_t^{\text{l}} \cdot (b_{t,s}^{\text{l,pv}} + b_{t,s}^{\text{l,p}})] \tag{8}$$

$$\theta_s^{\text{is,g}} = \sum_d (\mu_d^{\text{s}} \cdot b_{d,s}^{\text{s,g}} - \mu_d^{\text{l}} \cdot b_{d,s}^{\text{l,g}}), \quad \forall s \tag{9}$$

To operate hydrogen compressors to charge the hydrogen tank, electrical power must be provided either in the DA market or from the PV, the battery, or the fuel cell, as modeled in Eq. (10), where $\eta_t^{\text{ht}} \cdot h_t^{\text{ch}} \cdot \Delta t$ is the required power linearly depending (η_t^{ht}) on the compressed hydrogen volume $h_t^{\text{ch}} \cdot \Delta t$.

$$\theta^{\text{ht}} = \sum_t \eta^{\text{ht}} \cdot h_t^{\text{ch}} \cdot \Delta t \cdot \lambda_t^{\text{da,p}} \tag{10}$$

3.2. Total imbalance volumes

Equations in this subsection calculate the total imbalance volumes in power, (11)–(14), and gas, (17)–(22), systems.

Power imbalances arise from PV forecast errors in Eqs. (11) and (12), and reserve activations in the gas system in Eqs. (13)–(14). Note that the hydrogen tank's increased ($l_t^{\text{i,ch}}$) or reduced ($l_t^{\text{r,ch}}$) charging for balancing reasons also incurs slight imbalance in the power system due to unplanned compression requirements. Eqs. (11) and (12) allow imbalance corrections using variables $f_{\text{t,s}}^{\text{d}}$ and $f_{\text{t,s}}^{\text{u}}$. Eqs. (13) and (14) allow correction of power imbalances arising from reserve activations in the gas system using variables $d_{\text{t,s}}^{\text{d}}$ and $d_{\text{t,s}}^{\text{u}}$.

$$P_{t,s}^{\text{s,pv}} - f_{t,s}^{\text{d}} = b_{t,s}^{\text{s,pv}}, \quad \forall t, s \tag{11}$$

$$P_{t,s}^{\text{l,pv}} - f_{t,s}^{\text{u}} = b_{t,s}^{\text{l,pv}}, \quad \forall t, s \tag{12}$$

$$M_{t,s}^{\text{d}} \cdot n_t^{\text{s}} + \eta^{\text{ht}} \cdot l_{t,s}^{\text{i,ch}} - d_{t,s}^{\text{d}} = b_{t,s}^{\text{s,p}}, \quad \forall t, s \tag{13}$$

$$M_{t,s}^{\text{u}} \cdot n_t^{\text{l}} + \eta^{\text{ht}} \cdot l_{t,s}^{\text{r,ch}} - d_{t,s}^{\text{u}} = b_{t,s}^{\text{l,p}}, \quad \forall t, s \tag{14}$$

Total power imbalance volumes caused by the upward (n_t^s) and the downward (n_t^l) reserve activations in the gas system are calculated in Eqs. (15) and (16). These imbalances can be caused by:

- an increase in power consumption of the electrolyzer ($n_t^{\text{i,el}}$),
- a reduction in power consumption of the electrolyzer ($n_t^{\text{r,el}}$),
- an increase in power generation of the fuel cell ($n_t^{\text{i,fc}}$),
- a reduction in power generation of the fuel cell ($n_t^{\text{r,fc}}$),
- an increase in charging of the hydrogen tank due to compression requirements for gas balancing reasons ($m_t^{\text{i,ch}}$),
- a reduction in charging of the hydrogen tank due to compression requirements for gas balancing reasons ($m_t^{\text{r,ch}}$).

Note that the variables $n_t^{\text{i,el}}$, $n_t^{\text{r,el}}$, $n_t^{\text{i,fc}}$, and $n_t^{\text{r,fc}}$ are defined as power flow variables.[1]

$$n_t^{\text{s}} = n_t^{\text{r,el}} + n_t^{\text{i,fc}} + \eta^{\text{ht}} \cdot m_t^{\text{r,ch}}, \quad \forall t \tag{15}$$

$$n_t^{\text{l}} = n_t^{\text{i,el}} + n_t^{\text{r,fc}} + \eta^{\text{ht}} \cdot m_t^{\text{i,ch}}, \quad \forall t \tag{16}$$

Eqs. (17) and (18) allow for the correction of gas imbalances arising from reserve activations in the power system using variables $l_{\text{t,s}}^{\text{d}}$ and $l_{\text{t,s}}^{\text{u}}$. They are analogous to the power Eqs. (13) and (14). Imbalances in the gas system are calculated on a daily resolution.

$$\sum_t^d \Delta t \cdot (R_{t,s}^{\text{d}} \cdot w_t^{\text{s}} + v_{t,s}^{\text{s}} - l_{t,s}^{\text{d}}) = b_{d,s}^{\text{s,g}}, \quad \forall d, s \tag{17}$$

[1] By multiplication with η^{el} and η^{fc} they are transformed into hydrogen flow variables.

$$\sum_t^d \Delta t \cdot (R_{t,s}^{\text{u}} \cdot w_t^{\text{l}} + v_{t,s}^{\text{l}} - l_{t,s}^{\text{u}}) = b_{d,s}^{\text{l,g}}, \quad \forall d, s \tag{18}$$

Hydrogen Eqs. (19)–(22) are analogous to power Eqs. (15)–(16), where total gas imbalance volumes caused by the power TSO (w_t^{s}, w_t^{l}) and PV reserve activations (v_t^{s}, v_t^{l}) are calculated. These imbalances can be caused by:

- an increase in hydrogen generation from the fuel cell for power TSO balancing reasons ($\eta^{\text{fc}} \cdot r_t^{\text{i,fc}}$),
- a reduction in hydrogen generation from the fuel cell for power TSO balancing reasons ($\eta^{\text{fc}} \cdot r_t^{\text{r,fc}}$),
- an increase in hydrogen consumption from the electrolyzer for power TSO balancing reasons ($\eta^{\text{el}} \cdot r_t^{\text{i,el}}$),
- a reduction in hydrogen consumption from the electrolyzer for power TSO balancing reasons ($\eta^{\text{el}} \cdot r_t^{\text{r,el}}$),
- an increase in hydrogen generation from the fuel cell for PV balancing reasons ($\eta^{\text{fc}} \cdot f_{t,s}^{\text{i,fc}}$),
- a reduction in hydrogen generation from the fuel cell for PV balancing reasons ($\eta^{\text{fc}} \cdot f_{t,s}^{\text{r,fc}}$),
- an increase in hydrogen consumption from the electrolyzer for PV balancing reasons ($\eta^{\text{el}} \cdot f_{t,s}^{\text{i,el}}$),
- a reduction in hydrogen consumption from the electrolyzer for PV balancing reasons ($\eta^{\text{el}} \cdot f_{t,s}^{\text{r,el}}$).

$$w_t^l = \eta^{\text{el}} \cdot r_t^{\text{r,el}} + \eta^{\text{fc}} \cdot r_t^{\text{i,fc}}, \quad \forall t \tag{19}$$

$$v_{t,s}^l = \eta^{\text{el}} \cdot f_{t,s}^{\text{r,el}} + \eta^{\text{fc}} \cdot f_{t,s}^{\text{i,fc}}, \quad \forall t, s \tag{20}$$

$$w_t^s = \eta^{\text{el}} \cdot r_t^{\text{i,el}} + \eta^{\text{fc}} \cdot r_t^{\text{r,fc}}, \quad \forall t \tag{21}$$

$$v_{t,s}^s = \eta^{\text{el}} \cdot f_{t,s}^{\text{i,el}} + \eta^{\text{fc}} \cdot f_{t,s}^{\text{r,fc}}, \quad \forall t, s \tag{22}$$

3.3. Distribution of total volumes to individual units

Total volumes are the final volumes submitted by the hybrid plant to different markets. These overall volumes are then allocated to individual units, as visualized in Fig. 3. Eqs. (23)–(34) distribute the total trading volumes in different markets to individual units.

The DA market traded volumes in the power system ($p_t^{\text{da,p}}$) and in the gas system ($h_t^{\text{da,g}}$) are defined in (23) and (24). Both busbars contain storage (battery storage and hydrogen tank) charging/discharging variables (p_t^{ch}, p_t^{dis}, h_t^{ch}, and h_t^{dis}) and the energy-conversion variables related to the electrolyzer and the fuel cell (p_t^{el}, p_t^{fc}, h_t^{el}, and h_t^{fc}). Note the opposite signs for the electrolyzer and the fuel call variables in the power and hydrogen system (e.g. the electrolyzer consuming power in the power system translates to generation of hydrogen in the hydrogen system). Additionally, the power busbar contains the forecasted PV generation parameter ($P_t^{\text{for,pv}}$).

$$p_t^{\text{da,p}} = p_t^{\text{dis}} - p_t^{\text{ch}} - p_t^{\text{el}} + p_t^{\text{fc}} + P_t^{\text{for,pv}} \quad \forall t \tag{23}$$

$$h_t^{\text{da,g}} = h_t^{\text{dis}} - h_t^{\text{ch}} + h_t^{\text{el}} - h_t^{\text{fc}} \quad \forall t \tag{24}$$

Total power system reserve volumes in the up (r_t^{u}, $f_{t,s}^{\text{u}}$, $d_{t,s}^{\text{u}}$) and down (r_t^{d}, $f_{t,s}^{\text{d}}$, $d_{t,s}^{\text{d}}$) directions are defined in (25)–(30). TSO reserves (r_t^{u} and r_t^{d}) are sold in the balancing capacity market to the power TSO. PV reserves ($f_{t,s}^{\text{u}}$ and $f_{t,s}^{\text{d}}$) are used to minimize the PV forecast imbalances, while power OS reserves ($d_{t,s}^{\text{u}}$ and $d_{t,s}^{\text{d}}$) are used to minimize imbalances stemming from reserve activations in the gas system. TSO and PV reserves can be provided by all three flexible units by:

- increasing the charging power of the battery storage ($r_t^{\text{i,ch}}$, $f_{t,s}^{\text{i,ch}}$),
- reducing the charging power of the battery storage ($r_t^{\text{r,ch}}$, $f_{t,s}^{\text{r,ch}}$),
- increasing the discharging power of the battery storage ($r_t^{\text{i,dis}}$, $f_{t,s}^{\text{i,dis}}$),

- reducing the discharging power of the battery storage ($r_t^{\rm r,dis}$, $f_{t,s}^{\rm r,dis}$),
- increasing power consumption of the electrolyzer ($r_t^{\rm i,el}$, $f_{t,s}^{\rm i,el}$),
- reducing power consumption of the electrolyzer ($r_t^{\rm r,el}$, $f_{t,s}^{\rm r,el}$),
- increasing power generation of the fuel cell ($r_t^{\rm i,fc}$, $f_{t,s}^{\rm i,fc}$),
- reducing power generation of the fuel cell ($r_t^{\rm r,fc}$, $f_{t,s}^{\rm r,fc}$).

Note the opposite meaning of the increase-reduction variables, e.g. for the battery storage — reduction of charging provides the upward reserve to the power TSO, while reduction of discharging provides the downward reserve to the power TSO. On the other hand, power OS reserve to reduce the imbalances induced by the gas TSO activation can only be allocated to battery storage, since the electrolyzer and fuel cell are the units that create imbalances in the first place, see (27) and (30).

$$r_t^{\rm u} = r_t^{\rm r,ch} + r_t^{\rm i,dis} + r_t^{\rm r,el} + r_t^{\rm i,fc}, \quad \forall t \tag{25}$$

$$f_{t,s}^{\rm u} = f_{t,s}^{\rm r,ch} + f_{t,s}^{\rm i,dis} + f_{t,s}^{\rm r,el} + f_{t,s}^{\rm i,fc}, \quad \forall t, s \tag{26}$$

$$d_{t,s}^{\rm u} = d_{t,s}^{\rm r,ch} + d_{t,s}^{\rm i,dis}, \quad \forall t, s \tag{27}$$

$$r_t^{\rm d} = r_t^{\rm r,dis} + r_t^{\rm i,ch} + r_t^{\rm i,el} + r_t^{\rm r,fc}, \quad \forall t \tag{28}$$

$$f_{t,s}^{\rm d} = f_{t,s}^{\rm r,dis} + f_{t,s}^{\rm i,ch} + f_{t,s}^{\rm i,el} + f_{t,s}^{\rm r,fc}, \quad \forall t, s \tag{29}$$

$$d_{t,s}^{\rm d} = d_{t,s}^{\rm r,dis} + d_{t,s}^{\rm i,ch} \quad \forall t, s \tag{30}$$

Hydrogen Eqs. (31)–(34) are analogous to power Eqs. (25)–(30). Gas TSO reserves ($m_t^{\rm u}$ and $m_t^{\rm d}$) can be provided by:

- an increase of charging the hydrogen tank ($m_t^{\rm i,ch}$),
- an reduction of charging the hydrogen tank ($m_t^{\rm r,ch}$),
- an increase of discharging the hydrogen tank ($m_t^{\rm i,dis}$),
- an reduction of discharging the hydrogen tank ($m_t^{\rm r,dis}$),
- increase of hydrogen consumption by the fuel cell ($\eta^{\rm fc} \cdot n_t^{\rm i,fc}$),
- reduction of hydrogen consumption by the fuel cell ($\eta^{\rm fc} \cdot n_t^{\rm r,fc}$),
- increase of hydrogen generation by the electrolyzer ($\eta^{\rm el} \cdot n_t^{\rm i,el}$),
- reduction of hydrogen generation by the electrolyzer ($\eta^{\rm el} \cdot n_t^{\rm r,el}$).

Linear transformation coefficients $\eta^{\rm el}$ and $\eta^{\rm fc}$ are used here to transform power consumption/generation of the electrolyzer/fuel cell to hydrogen generation/consumption. Gas OS reserve to reduce the imbalances induced by the power TSO activation ($l_{t,s}^{\rm u}$ and $l_{t,s}^{\rm d}$) can only be allocated to the hydrogen tank since the electrolyzer and fuel cell are units that create the imbalances in the first place as in (32) and (34).

$$m_t^d = m_t^{\rm i,ch} + m_t^{\rm r,dis} + \eta^{\rm el} \cdot n_t^{\rm r,el} + \eta^{\rm fc} \cdot n_t^{\rm i,fc}, \ \forall t \tag{31}$$

$$l_{t,s}^d = l_{t,s}^{\rm i,ch} + l_{t,s}^{\rm r,dis}, \quad \forall t, s \tag{32}$$

$$m_t^u = m_t^{\rm r,ch} + m_t^{\rm i,dis} + \eta^{\rm el} \cdot n_t^{\rm i,el} + \eta^{\rm fc} \cdot n_t^{\rm r,fc}, \ \forall t \tag{33}$$

$$l_{t,s}^u = l_{t,s}^{\rm r,ch} + l_{t,s}^{\rm i,dis}, \quad \forall t, s \tag{34}$$

TSO reserves in both systems (variables r and m) are activated externally based on the TSO signal. Their reserved capacity is the same in each scenario, which is why they do not contain the index s. On the other hand, the PV and OS reserves (variables f, d, and l) are activated internally and can be adjusted to each scenario, thus they contain index s.

3.4. Coordination of the units' market and physical variables

Each unit's market participation or service provision must be incorporated into their physical boundaries, which is given through (36)–(47). For variables defined per scenario (f, d, and l) the highest value must be extracted to adequately define the units' physical boundaries in all scenarios, as in (35).

$$\begin{aligned}&\{ f_{t,s}^{\rm i,ch}, f_{t,s}^{\rm r,ch}, f_{t,s}^{\rm i,dis}, f_{t,s}^{\rm r,dis}, d_{t,s}^{\rm i,ch}, d_{t,s}^{\rm r,ch}, d_{t,s}^{\rm i,dis}, d_{t,s}^{\rm r,dis},\\ &f_{t,s}^{\rm i,el}, f_{t,s}^{\rm r,el}, f_{t,s}^{\rm i,fc}, f_{t,s}^{\rm r,fc}, l_{t,s}^{\rm i,ch}, l_{t,s}^{\rm r,ch}, l_{t,s}^{\rm i,dis}, l_{t,s}^{\rm r,dis}\}\\ &\leq \{ f_t^{\rm i,ch}, f_t^{\rm r,ch}, f_t^{\rm i,dis}, f_t^{\rm r,dis}, d_t^{\rm i,ch}, d_t^{\rm r,ch}, d_t^{\rm i,dis}, d_t^{\rm r,dis},\\ &f_t^{\rm i,el}, f_t^{\rm r,el}, f_t^{\rm i,fc}, f_t^{\rm r,fc}, l_t^{\rm i,ch}, l_t^{\rm r,ch}, l_t^{\rm i,dis}, l_t^{\rm r,dis}\}, \quad \forall t, s\end{aligned} \tag{35}$$

To provide different power balancing services (power TSO/PV/OS reserves), battery storage can increase or reduce its charging and discharging ($p_t^{\rm i,ch}$, $p_t^{\rm r,ch}$, $p_t^{\rm i,dis}$, and $p_t^{\rm r,dis}$), as in (36)–(39). Similarly, the electrolyzer and fuel cell can increase or reduce their consumption and generation ($p_t^{\rm i,el}$, $p_t^{\rm r,el}$, $p_t^{\rm i,fc}$, and $p_t^{\rm r,fc}$), as in (40)–(43), to provide balancing services to the power and gas TSO and to balance the PV production. Analogously to the battery storage, the hydrogen tank can provide different gas balancing services (TSO and OS reserves) through an increase or reduction of its charging and discharging power ($h_t^{\rm i,ch}$, $h_t^{\rm r,ch}$, $h_t^{\rm i,dis}$, and $h_t^{\rm r,dis}$), as in (44)–(47).

$$r_t^{\rm i,ch} + f_t^{\rm i,ch} + d_t^{\rm i,ch} = p_t^{\rm i,ch}, \quad \forall t \tag{36}$$

$$r_t^{\rm r,ch} + f_t^{\rm r,ch} + d_t^{\rm r,ch} = p_t^{\rm r,ch}, \quad \forall t \tag{37}$$

$$r_t^{\rm i,dis} + f_t^{\rm i,dis} + d_t^{\rm i,dis} = p_t^{\rm i,dis}, \quad \forall t \tag{38}$$

$$r_t^{\rm r,dis} + f_t^{\rm r,dis} + d_t^{\rm r,dis} = p_t^{\rm r,dis}, \quad \forall t \tag{39}$$

$$r_t^{\rm i,el} + f_t^{\rm i,el} + n_t^{\rm i,el} = p_t^{\rm i,el}, \quad \forall t \tag{40}$$

$$r_t^{\rm r,el} + f_t^{\rm r,el} + n_t^{\rm r,el} = p_t^{\rm r,el}, \quad \forall t \tag{41}$$

$$r_t^{\rm i,fc} + f_t^{\rm i,fc} + n_t^{\rm i,fc} = p_t^{\rm i,fc}, \quad \forall t \tag{42}$$

$$r_t^{\rm r,fc} + f_t^{\rm r,fc} + n_t^{\rm r,fc} = p_t^{\rm r,fc}, \quad \forall t \tag{43}$$

$$m_t^{\rm i,ch} + l_t^{\rm i,ch} = h_t^{\rm i,ch}, \quad \forall t \tag{44}$$

$$m_t^{\rm r,ch} + l_t^{\rm r,ch} = h_t^{\rm r,ch}, \quad \forall t \tag{45}$$

$$m_t^{\rm i,dis} + l_t^{\rm i,dis} = h_t^{\rm i,dis}, \quad \forall t \tag{46}$$

$$m_t^{\rm r,dis} + l_t^{\rm r,dis} = h_t^{\rm r,dis}, \quad \forall t \tag{47}$$

3.5. Units' physical constraints

Each of the technical units needs to obey its power and energy (in the case of battery storage and hydrogen tank) limits, as given in (48)–(77). Battery storage and hydrogen tank cannot simultaneously charge and discharge and their output power must always be below their installed powers ($P^{\rm b}$, $H^{\rm ht}$), as in (48)–(51). The same applies for the electrolyzer and fuel cell operation with their upper boundaries $P^{\rm el,max}$ and $P^{\rm fc,max}$, as in (52)–(55). Additionally, their operation must be above their minimum stable output ($P^{\rm el,min}$ and $P^{\rm fc,min}$). Eqs. (56) and (57) represent linearized energy transformation equations for the electrolyzer and the fuel cell. Efficiency terms $\eta^{\rm el}$ and $\eta^{\rm fc}$ represent variable terms depending on consumed ($p_t^{\rm el}$) or generated power ($p_t^{\rm fc}$), while $\eta^{\rm elf}$ and $\eta^{\rm fcf}$ represent fixed terms denoting whether the electrolyzer or fuel cell is operational or not.

$$p_t^{\rm ch} \leq x_t^{\rm b} \cdot P^{\rm b}, \quad \forall t \tag{48}$$

$$p_t^{\rm dis} \leq (1 - x_t^{\rm b}) \cdot P^{\rm b}, \quad \forall t \tag{49}$$

$$h_t^{\rm ch} \leq x_t^{\rm ht} \cdot H^{\rm ht}, \quad \forall t, \tag{50}$$

$$h_t^{\rm dis} \leq (1 - x_t^{\rm ht}) \cdot H^{\rm ht}, \quad \forall t, \tag{51}$$

$$p_t^{\rm el} \geq P^{\rm el,min} \cdot x_t^{\rm el,fc}, \quad \forall t \tag{52}$$

$$p_t^{\rm el} \leq P^{\rm el} \cdot x_t^{\rm el,fc}, \quad \forall t \tag{53}$$

$$p_t^{\rm fc} \geq P^{\rm fc,min} \cdot (1 - x_t^{\rm el,fc}), \quad \forall t \tag{54}$$

$$p_t^{\rm fc} \leq P^{\rm fc} \cdot (1 - x_t^{\rm el,fc}), \quad \forall t \tag{55}$$

$$h_t^{el} = \eta^{\rm el} \cdot p_t^{\rm el} + \eta^{\rm elf} \cdot P^{\rm el} \cdot x_t^{\rm el,fc}, \quad \forall t \tag{56}$$

$$h_t^{fc} = \eta^{\rm fc} \cdot p_t^{\rm fc} + \eta^{\rm fcf} \cdot P^{\rm fc} \cdot (1 - x_t^{\rm el,fc}), \quad \forall t \tag{57}$$

Provision of balancing services for all units is defined relative to the DA market schedules, as in (58)–(73). Eqs. (58)–(63) define the boundaries of battery storage, while Eqs. (64)–(69) define boundaries of the hydrogen tank, which force the realistic order of balancing schedules, e.g. if the battery storage or the hydrogen tank is already scheduled to charge in the DA market with its maximum power, then, in order to provide the upward service, it must first schedule the reduction of its charging amount and only then can it increase the discharging. Eqs. (70)–(73) define balancing limits for the electrolyzer and the fuel cell. Note that we do not assume shutting down or starting up the electrolyzer or the fuel cell for balancing purposes, hence only linear transformation coefficients in constraints (19)–(22), (31), and (33).

$$p_t^{\mathrm{r,ch}} \le p_t^{\mathrm{ch}}, \quad \forall t \tag{58}$$

$$p_t^{\mathrm{ch}} - p_t^{\mathrm{r,ch}} \le x_t^{\mathrm{u,b}} \cdot P^{\mathrm{b}}, \quad \forall t \tag{59}$$

$$p_t^{\mathrm{i,dis}} \le (1 - x_t^{\mathrm{u,b}}) \cdot P^{\mathrm{b}} - p_t^{\mathrm{dis}}, \quad \forall t \tag{60}$$

$$p_t^{\mathrm{r,dis}} \le p_t^{\mathrm{dis}}, \quad \forall t \tag{61}$$

$$p_t^{\mathrm{dis}} - p_t^{\mathrm{r,dis}} \le x_t^{\mathrm{d,b}} \cdot P^{\mathrm{b}}, \quad \forall t \tag{62}$$

$$p_t^{\mathrm{i,ch}} \le (1 - x_t^{\mathrm{d,b}}) \cdot P^{\mathrm{b}} - p_t^{\mathrm{ch}}, \quad \forall t \tag{63}$$

$$h_t^{\mathrm{r,ch}} \le h_t^{\mathrm{ch}}, \quad \forall t \tag{64}$$

$$h_t^{\mathrm{ch}} - h_t^{\mathrm{r,ch}} \le x_t^{\mathrm{u,ht}} \cdot H^{\mathrm{ht}}, \quad \forall t \tag{65}$$

$$h_t^{\mathrm{i,dis}} \le (1 - x_t^{\mathrm{u,ht}}) \cdot H^{\mathrm{ht}} - h_t^{\mathrm{dis}}, \quad \forall t \tag{66}$$

$$h_t^{\mathrm{r,dis}} \le h_t^{\mathrm{dis}}, \quad \forall t \tag{67}$$

$$h_t^{\mathrm{dis}} - h_t^{\mathrm{r,dis}} \le x_t^{\mathrm{d,ht}} \cdot H^{\mathrm{ht}}, \quad \forall t \tag{68}$$

$$h_t^{\mathrm{i,ch}} \le (1 - x_t^{\mathrm{d,ht}}) \cdot H^{\mathrm{ht}} - h_t^{\mathrm{ch}}, \quad \forall t \tag{69}$$

$$p_t^{\mathrm{r,el}} \le p_t^{\mathrm{el}} - P^{\mathrm{el,min}} \cdot x_t^{\mathrm{el,fc}}, \quad \forall t \tag{70}$$

$$p_t^{\mathrm{i,el}} \le P^{\mathrm{el,max}} \cdot x_t^{\mathrm{el,fc}} - p_t^{\mathrm{el}}, \quad \forall t \tag{71}$$

$$p_t^{\mathrm{r,fc}} \le p_t^{\mathrm{fc}} - P^{\mathrm{fc,min}} \cdot (1 - x_t^{\mathrm{el,fc}}), \quad \forall t \tag{72}$$

$$p_t^{\mathrm{i,fc}} \le P^{\mathrm{fc,max}} \cdot (1 - x_t^{\mathrm{el,fc}}) - p_t^{\mathrm{fc}}, \quad \forall t \tag{73}$$

Apart from their power limits, battery storage and hydrogen tank also have their energy limits, as in (74)–(77). Eqs. (74) and (76) calculate state of energy of each storage using the real activation values (different for each scenario) for all balancing services. The battery state of energy and the hydrogen tank state of hydrogen must at all times be in between their minimal and maximal limits as stated in constraints (75) and (77).

$$\begin{aligned} soe_{t,s} = {} & soe_{t-1,s} + (p_t^{\mathrm{ch}} - R_{t,s}^{\mathrm{u}} \cdot r_t^{\mathrm{r,ch}} - f_{t,s}^{\mathrm{r,ch}} - d_{t,s}^{\mathrm{r,ch}} \\ & + R_{t,s}^{\mathrm{d}} \cdot r_t^{\mathrm{i,ch}} + f_{t,s}^{\mathrm{i,ch}} + d_{t,s}^{\mathrm{i,ch}}) \cdot \eta^{\mathrm{ch}} \cdot \Delta t \\ & - (p_t^{\mathrm{dis}} - R_{t,s}^{\mathrm{d}} \cdot r_t^{\mathrm{r,dis}} - f_{t,s}^{\mathrm{r,dis}} - d_{t,s}^{\mathrm{r,dis}} \\ & + R_{t,s}^{\mathrm{u}} \cdot r_t^{\mathrm{i,dis}} + f_{t,s}^{\mathrm{i,dis}} + d_{t,s}^{\mathrm{i,dis}}) \cdot \Delta t / \eta^{\mathrm{dis}}, \quad \forall t, s \end{aligned} \tag{74}$$

$$0 \le soe_{t,s} \le S^{\mathrm{bs}}, \quad \forall t, s \tag{75}$$

$$\begin{aligned} soh_{t,s} = {} & soh_{t-1,s} + (h_t^{\mathrm{ch}} - M_{t,s}^{\mathrm{u}} \cdot m_t^{\mathrm{r,ch}} - l_{t,s}^{\mathrm{r,ch}} \\ & + M_{t,s}^{\mathrm{d}} \cdot m_t^{\mathrm{i,ch}} + l_{t,s}^{\mathrm{i,ch}}) \cdot \Delta t - (h_t^{\mathrm{dis}} - M_{t,s}^{\mathrm{d}} \cdot m_t^{\mathrm{r,dis}} \\ & - l_{t,s}^{\mathrm{r,dis}} + M_{t,s}^{\mathrm{u}} \cdot m_t^{\mathrm{i,dis}} + l_{t,s}^{\mathrm{i,dis}}) \cdot \Delta t, \quad \forall t \end{aligned} \tag{76}$$

$$0 \le soh_{t,s} \le S^{\mathrm{ht}}, \quad \forall t, s \tag{77}$$

4. Input data and scenarios

4.1. Scalar input data

The capacity of the PV plant is 100 MW, the hourly data for PV forecasts are taken from a location in the Southern Croatia, while the scenarios are generated using the tool from [24]. The battery storage, the electrolyzer and the fuel cell have installed electrical power of 25, 35, and 11 MW. If these rated powers are observed as units of power in hydrogen, the electrolyzer and the fuel cell have installed hydrogen power of 25 MW each. Hydrogen tank's charging/discharging hydrogen limits are 25 MW. Energy capacity of the battery storage is 200 MWh (8-hour discharge), while its hydrogen system counterpart is 4200 MWh (7-day discharge). Charging and discharging efficiencies of the lithium-ion battery storage are both set to 92% [25]. The electrolyzer and the fuel cell converting efficiencies are modeled as linearly decreasing from their technical minima ($P^{\mathrm{el,min}}$, $P^{\mathrm{fc,min}}$) to their installed power capacities ($P^{\mathrm{el,max}}$, $P^{\mathrm{fc,max}}$). The electrolyzer's efficiency at its maximum power is equal to 70% and at its minimum power to 80%. For the fuel cell, these values range from 32% at maximum power to 41% at minimum power. The electrolyzer efficiency coefficients η^{el} and η^{elf} take values 0.689 and 0.011, while the fuel cell efficiencies η^{fc} and η^{fcf} are 2.386 and −0.114 [26].

At the hydrogen gas bus, the pressures must be harmonized either through compressors (from lower to higher pressure) or through pressure regulators (from higher to lower pressure). Increasing the pressure requires additional electricity consumption for the compressor operation and its efficiency depends on the inlet and outlet pressure levels. Decreasing the pressures entails only negligible energy losses and we assume this process to be perfectly efficient.

Currently available large-scale commercial hydrogen tanks have pressures 240–1000 bar. Gas transmission grid in Croatia has pressure levels of 50, 75, and 100 bar. In this paper, we assume a 350 bar hydrogen tank and a connection to the 50 bar hydrogen gas grid. Therefore to store hydrogen in the hydrogen tank (to charge it) a compression from 50 to 350 bar is required and the assumed energy loss for this process is 4% of the charged hydrogen energy. This value was taken from paper [26] as the difference between compressed energy to HHV in % (for multi-stage compression as the closest to reality) at 35 MPa/350 bar (≈8%) and at 5 MPa/50 bar (≈4%) which is 4%. This efficiency leads to electrical power of the hydrogen compressor of around 1 MW ($25\ \mathrm{MW} \cdot 0,04$).

4.2. Time-series input data

The power DA market prices are taken from the Croatian Power Exchange for 2021, while the natural gas DA market prices are from the Central European Gas Hub for the same year. For the hydrogen DA market price, the corresponding hub still does not exit. Hence, Hydex — green hydrogen index, was used as the DA hydrogen market price, as this is currently the closest data that exist in Europe.

Power BE prices are defined according to the prices currently used in Croatia for aFRR balancing energy price [27] and are fixed to: 40% higher than power DA market prices for the upward direction (e.g. $\rho_t^{\mathrm{u,be}} = 1.4 \cdot \lambda_t^{\mathrm{da,p}}$) and 40% lower than the DA market prices for the downward direction ($\rho_t^{\mathrm{d,be}} = 0.6 \cdot \lambda_t^{\mathrm{da,p}}$). The natural gas BE prices are not regulatory fixed as aFRR in the power sector, but their value is commonly in the range of $\pm 40\%$ of the natural gas DA market price in Croatia [28,29]. For hydrogen gas BE no data is available yet, so the same principle as for the natural gas BE prices is assumed. Power and gas IS prices are modeled using the same fixed amounts as the BE market prices, since this is the method currently valid in Croatia [29,30].

4.3. Scenario-based input data

We use eight scenarios that incorporate three sources of uncertainties: TSO activations in the power and gas systems, as well as the realized PV production. Power BE scenarios are constructed based on the real Croatian power system balancing 15-minute activations from 2021 [31]. The 15-minute activations are summed to hourly resolution as the timestep used in this paper is one hour. Gas BE scenarios are constructed based on the actual Croatian gas system BE daily activations from 2021 [32]. Daily activations are converted to hourly in a way that all hours in a specific day have the same value. Contrary to the power BE activations, where activation can be in the range from 0 to 1, in the gas system we assume only full activations, i.e. $M_{t,s}^{\mathrm{d}}$ is either 0 or 1. In the power system, the ratio of activation

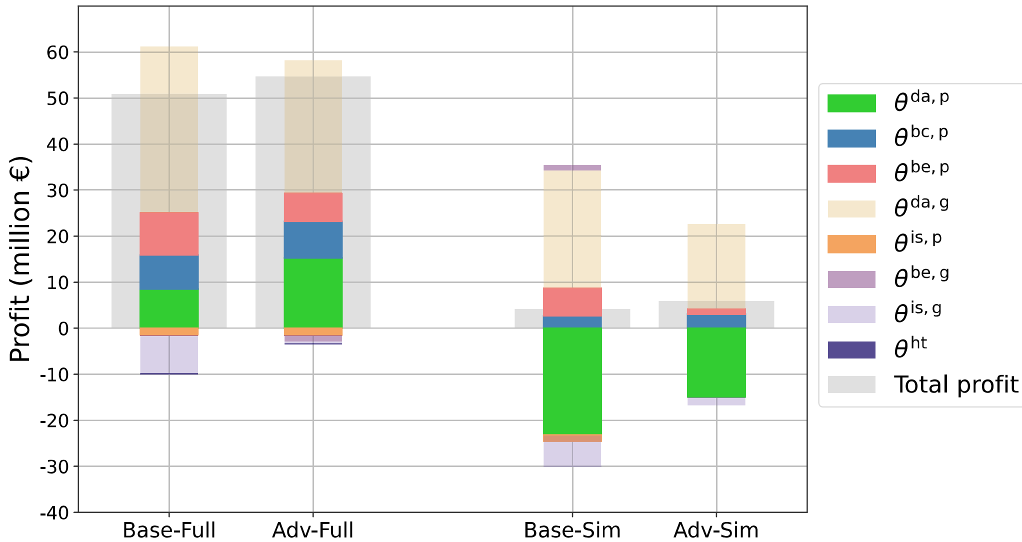

Fig. 4. Comparison of neglecting the imbalance cost from deviations caused by the other system and adding them afterward, ex-post, (Base) and considering them in the optimization process (Adv). Both models are applied to two configurations of a hybrid power plant described in chapter 5.1.2.

for individual power plants in Croatia is determined by the ratio of the total balancing energy to the balancing capacity, ranging from 0 to 1. However, in the gas system, where there is no balancing capacity, only balancing energy is used to determine the imbalance direction, assuming full provision if an imbalance exists, adhering to the current gas system balancing practices where providers are activated in full power to achieve the system balance. The BE scenarios in the hydrogen system are the same as the ones in the natural gas system.

5. Results and discussion

A hybrid power plant can bid in power and gas DA markets, while also providing balancing services to power and gas TSOs (TSO reserves and activations). In the power system, balancing services are offered by the battery storage, electrolyzer and fuel cell, while in the gas system by the energy-conversion units and by the hydrogen tank. Since the power plant is considered responsible for its own imbalances (PV and OS) in both systems, it must arrange its operation to minimize potential IS costs. It can even provide balancing services to its own BG (PV/OS reserve and activation) to mitigate these imbalances. Those balancing services can be provided either by the battery storage or by the hydrogen tank, depending on the observed system.

5.1. Models and configurations cases

5.1.1. Two models

To determine the importance of including the imbalance while scheduling the hybrid power plant operation, two models are introduced: the baseline model and the advanced one. The baseline model assumes that the operation of the electrolyzer and the fuel cell in one system will not affect the other one and, therefore, does not include the associated imbalance costs (omitted constraint (9) and variables $b_{t,s}^{s,p}$ and $b_{t,s}^{l,p}$ in (8)). Consequently, the only imbalances that this BG can be held accountable for in the baseline model are the PV imbalances. In contrast to the baseline model, the advanced model, described in Section 3, considers the impact of providing balancing services in one system on the other system, with the units connecting both systems. Accordingly, in the power system the plant is susceptible to both PV and OS imbalances, while in the gas system, only the latter is considered.

5.1.2. Two configuration cases

The simulations for both models described above are performed for two configuration cases of the hybrid power plant: (1) full plant including all elements, as shown in Fig. 1 and (2) simple plant including only H_2 energy-conversion technologies, as shown in Fig. 3. In Fig. 4 the first configuration is referred to as 'Full' and the second one as 'Sim'. The point of having these two cases is to investigate if neglecting OS imbalances has a different impact on different plant configurations. Note that the simple case includes only OS imbalances without the means to cover them, while the full case includes both the OS and the PV imbalances as well as the means to cover them (using the battery storage and the hydrogen tank). For brevity, we use the simple case only to demonstrate the financial value and do not present detailed operational breakdown for this configuration.

5.2. The financial value of explicit OS imbalance modeling

The comparison of profits, costs, and revenues using the baseline and the advanced models under the full and the simple power plant case is shown in Fig. 4. The profit of the baseline model includes the costs of OS imbalances *ex-post*, i.e. they are not explicitly modeled but are added after the operation scheduling is done. On the other hand, the profit of the advanced model considers the costs of OS imbalances *ex-ante* through the model itself. The gray bars in Fig. 4 represent the total profit, while the colored bars represent the composition of those profits considering all the revenues and costs. In this subsection, we focus only on total profits and total imbalance costs for both models and both configurations.

5.2.1. Full configuration case

In the baseline model, the total profit is 51.15 million € (the first gray bar in Fig. 4). However, when imbalances are *ex-ante* considered in the advanced model, the profit increases to 54.69 million € (second gray bar in Fig. 4), this amounts to 6.90% of profit increase. In the baseline model, the plant does not have the incentive to keep an eye on the potential financial impact of OS imbalances that it might have in reality. Whereas in the advanced model, the plant can better schedule itself to minimize the potential costs that can come from OS imbalances. In this case, the total IS costs (including both gas and power IS costs — light purple and orange bars in Fig. 4) decrease from 9.47 million € in the baseline model to 1.80 million € in the advanced model. However, the whole decrease happens in the gas system, while, on the other hand, the power system recorded a small increase in the cost of 2.07%.

Table 1
Average reserved power in the power and the gas system in MW (electrical power for the power system; hydrogen power for the gas system).

	BASELINE						ADVANCED						
	POWER SYSTEM						POWER SYSTEM						
	TSO			PV			TSO			PV			OS
	BS	EL	FC	BS	EL	FC	BS	EL	FC	BS	EL	FC	BS
up	24.98	20.17	0.68	0.21	1.19	0.11	24.80	16.64	0.06	0.53	0.12	0.00	0.01
dw	20.58	1.76	0.07	1.18	0.00	0.00	20.48	12.30	0.14	1.06	0.19	0.03	0.04
	GAS SYSTEM						GAS SYSTEM						
	TSO			PV			TSO			PV			OS
	HT	EL	FC	BS	EL	FC	HT	EL	FC	BS	EL	FC	HT
up	10.35	2.15	0.02	–	–	–	10.12	0.00	0.00	–	–	–	1.84
dw	18.73	0.00	0.00	–	–	–	17.43	0.05	0.06	–	–	–	1.58

5.2.2. Simple configuration case

In the baseline model, the total profit is 4.15 million € (the third gray bar in Fig. 4). However, when imbalances are considered *ex-ante* in the advanced model, the profit increases to 5.90 million € (the fourth gray bar in Fig. 4). The reasoning for the increase in profit is the same as in the Full case: the plant can better schedule itself to minimize the potential costs stemming from the OS imbalances. In this case, the total IS costs (including both the gas and the power IS costs) decrease from 8.10 million € in the baseline model to 1.79 million € in the advanced model. The main part of this 78% decrease occurs in the gas system, while the rest is observed in the power system, resulting in no power IS costs.

In relative terms, the profit increase impact is much higher in Simple ('Sim') case than in the Full case: the profit increase from the baseline to the advanced model is 42.19%. There are several reasons for this. The first one is that the profit level in absolute terms is much lower compared to the Full case, thus much more susceptible to imbalance costs. The second one is that the Simple case does not have the battery storage and the hydrogen tank to provide BG balancing, meaning that all imbalances must be financially settled. The third one is: there is no possibility to annul the imbalances at the BG level by combining them with the PV imbalances (following the logic: the larger the BG group, the easier to maintain balance).

5.3. Profit breakdown change with explicit OS imbalance modeling

In this subsection we focus on the profit breakdown of both models but only for the Full configuration case which is shown as the first two colored bars in Fig. 4.

5.3.1. The baseline model

41.05% of the profit comes from the power system, while the rest comes from the gas system. In the gas system, only the DA trading brings revenue — 36.15 million €, while the BE provision results in an average cost of 0.29 million € over all considered scenarios. In the power system, the revenue is split almost evenly between the DA trading (8.53 million €), BC (7.33 million €) and BE provision (9.19 million € on average). The imbalance caused by deviations in PV production results in an average cost of 0.28 million €, while the cost of hydrogen tank operation is 0.29 million €. The power and gas OS imbalance costs are calculated *ex-post* and are equal to 1.18 million € and 8.01 million €, respectively.

5.3.2. The advanced model

Unlike in the baseline model, the total profit in the advanced model is almost equally split between the gas and the power system. Again, the entire profit in the gas system comes from the DA trading, which gained revenue of 28.94 million €. Providing BE and IS in the gas system resulted in costs — 1.45 million € and 0.32 million €, respectively, which is the consequence of dominantly providing down reserve. In the power system, trading in the DA market brings around 15.26 million € (55%), almost double compared to the baseline. Almost 7.97 million € (29%) comes from providing BC and around 6.03 € (22%) from providing BE. The IS cost in the power system equals 1.48 million €, out of which 1.47 million € (81.66% of total power and gas imbalances) goes to PV imbalances, which is more than 5 times higher than in the baseline model. The rest, 0.01 million €, belongs to the power OS imbalances. Hydrogen tank operation in the advanced case results in a cost of 0.25 million €.

5.3.3. Emphasizing the differences

One of the main differences when integrating the explicit OS imbalance constraints is that the plant increases its power system DA revenues while decreasing the gas DA revenues. It also increases the BE provision cost in the gas system and decreases the BE revenue in the power system. Thereby, the total imbalance costs are reduced, mostly due to a reduction of the gas OS imbalance cost. This decrease is obtained at the expense of an increase in the PV imbalance cost as well, since correcting the PV deviations directly causes an imbalance in the gas system. Thus, although the power OS imbalance cost is also reduced in the advanced model, the overall power imbalance cost in the power system (PV + OS imbalance) is slightly increased.

5.4. Change in the TSO balancing provision

The average offered BC by each unit in both systems is given in Table 1. The left-hand side lists the results of the baseline model, while the right-hand side of the advanced model.

5.4.1. The baseline model

The average upward capacity reserved for the power TSO amounts to 45.83 MW, out of which 54.5% comes from the battery storage, 44.0% from the electrolyzer, and only 1.5% from the fuel cell. For the downward direction, 22.41 MW of capacity is reserved on average. Most of it is covered by the battery storage (91.8%) and the rest by the electrolyzer (7.9%) and the fuel cell (0.3%). The total average capacity reserved for PV balancing in the upward direction is 1.51 MW, from which 78.7% by the electrolyzer, 14.0% by the battery storage, and 7.3% by the fuel cell. In the downward direction, all balancing is performed by the battery storage alone. In the gas system, on the other hand, units only provide balancing services to the TSO, with an average of 12.50 MW in the upward direction and 18.73 MW in the downward direction. The upward reserve is mostly provided by the hydrogen tank (82.67%) and the rest is offered by the electrolyzer (17.17%) and the fuel cell (0.16%). The downward reserve is entirely supplied by the hydrogen tank.

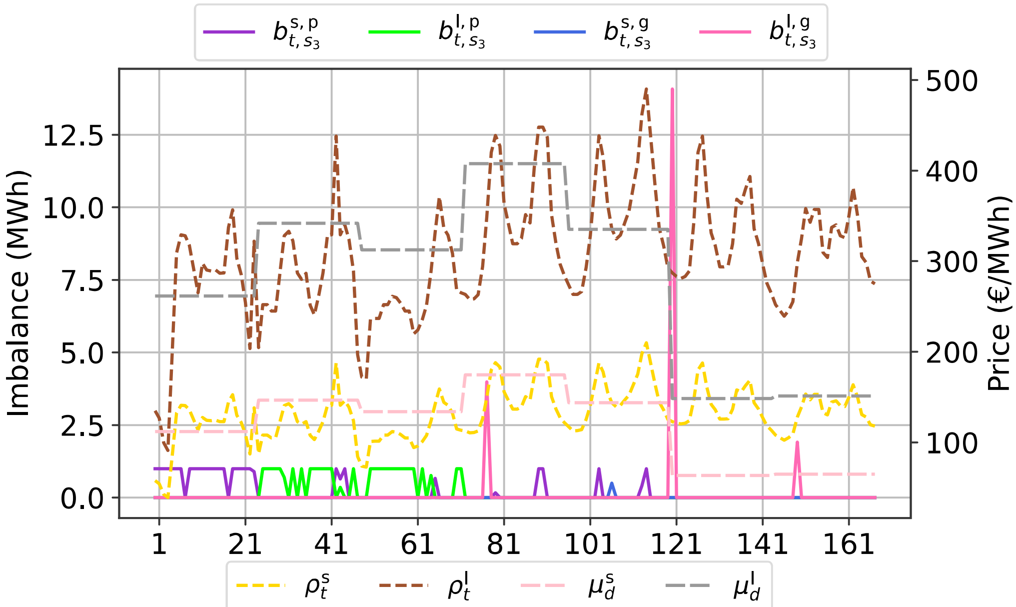

Fig. 5. Power and gas imbalances (full lines) vs imbalance prices (dotted) for week 41 in the year 2021, scenario 3.

5.4.2. The advanced model

The total offered power for the TSO BC in the upward direction reduces to 41.5 MW, due to a 17.5% reduction of the BC offered by the electrolyzer. On the contrary, downward BC increases to 32.93 MW, because the electrolyzer increases its offered BC almost 6 times. A similar effect is observed in the case of the fuel cell and PV balancing. The upward BC provided to the gas TSO decreases to 10.12 MW, because both energy-converting units stopped providing this service. On the other side, the downward BC is kept at a similar level as in the baseline model, with 17.54 MW offered on average. Since in the advanced model the battery storage and hydrogen tank can also provide OS balancing, battery storage offers around 10 kW of upward reserve and 40 kW of the downward reserve for imbalances introduced by the gas system. The hydrogen tank reserves 1.84 MW in the upward and 1.58 MW in the downward direction for imbalances caused by the unit operation in the power system. Overall, 64.23 GWh of the power TSO BE is provided in the upward direction and 47.34 GWh in the downward direction. In the gas system, the plant provides 17.55 GWh of the BE in the upward direction and 37.50 GWh in the downward direction. Significantly less BE is delivered for balancing the BG (PV/OS) — 11.90 GWh and 5.57 GWh for surplus and lack in power system, respectively, and 13.87 GWh and 16.12 GWh in the gas system.

5.4.3. Emphasizing the differences

The differences in the BC that the battery storage and hydrogen tank offer to the TSOs are negligible compared to the baseline model and these slight differences are a result of the OS balancing provision. However, the greatest differences appear in the amounts provided by the electrolyzer and the fuel cell. In the advanced model, the reserved BC from these units to both TSOs and its BG in the upward direction is reduced and increased in the downward direction to reduce gas OS imbalance cost. Analogously, in the gas system, the electrolyzer and the fuel cell reduce the offered upward BC to the TSO and increase it in the downward direction to reduce power OS imbalance costs.

5.5. Change in imbalance volumes

5.5.1. The baseline model

There is a total of 23.75 GWh of positive imbalances, out of which 23.69 GWh (99.75%) are PV imbalances and 0.06 GWh (0.25%) are OS imbalances. Total negative power system imbalances equal to 20.59 GWh, with 13.22 GWh (64.21%) from PV and 7.37 GWh (35.79%) from OS. In the gas system, there are 0.25 GWh of positive imbalances and 69.57 GWh of negative imbalances.

5.5.2. The advanced model

With the explicit OS imbalance modeling one would assume that imbalance volumes should be reduced. However, the direction of imbalances is not treated in the same manner. Positive imbalances represent revenue, while negative represent cost for the plant. Therefore, by adding those imbalances into the model, they would change in a manner that the positive imbalances (surplus) will increase, while the negative imbalances (lack) will decrease in both systems. A change in PV imbalances, on the other hand, allows for the OS imbalances to change as described since they are directly connected to the gas OS imbalances. In our case, when comparing the baseline and the advanced models, total positive imbalances in the power system decrease to 23.11 GWh, where the PV imbalances decrease by 3.97% and the OS imbalances increase by 500.00%. In the gas system, positive imbalances increase to 1.49 GWh. In the same comparison, the negative imbalances in the power system increase to 20.9 GWh, with an increase of 55.98% of the PV imbalances and a decrease of 96.20% of the OS imbalances. In the gas system, negative imbalances experience a huge decrease to only 4.06 GWh. This negative imbalance decrease in the gas system is the most significant change compared to the baseline model.

A more thorough look at how the imbalances in both systems are affected by the reserve prices is given in Fig. 5. The purple curve represents a surplus in the power system, while the green curve represents a lack in the power system. The downward gas reserve is worth providing when the price obtained for power surplus (yellow dashed curve) is higher than the price paid for the provided reserve (light pink[2]). On the other hand, upward reserve provision in the gas system can be profitable only if the revenue gained from it (gray dashed price curve[1]) is higher than the cost of the lack of energy in the power system (brown dashed price curve and green full curve).

A similar behavior is observed for surpluses (blue curve) and lacks (pink full curve) in the gas system. The price for gas surplus (light

[2] Since the price is the same for downward reserve provision to the gas TSO and for surplus in the gas system, only the imbalance prices are shown for better visibility and clarity. This applies to the other reserve prices as well.

pink dashed curve) needs to be higher than the price for downward reserve provision to the power TSO (yellow dashed curve[2]) for reserve provision to be profitable. The price for upward reserve provision to the power TSO (brown dashed curve[2]) needs to be higher than the price for lack of energy in the gas system (gray dashed curve) for reserve provision to be profitable.

As expected, battery storage is used to perform hourly arbitrage, while hydrogen tank is used for daily arbitrage, as a result of market structures.

6. Conclusion

This paper analyzed the operation of a hybrid power plant, consisting of a PV, an electrolyzer, a fuel cell, a hydrogen tank, and a battery storage that connects the (natural or hydrogen) gas and the power systems. The plant participates in both DA markets and provides balancing services to both TSOs and its BG. Since the power plant acts as the manager of its BG, it is also responsible for the imbalance that occurs towards both TSOs. Operating energy-conversion units (electrolyzer and fuel cell) in one system (e.g. power) can create changes in power flows in the other system (e.g. gas) and consequently create imbalance. Therefore, this paper inspects how uncertain events like PV production deviations or uncertain TSO reserve activations can affect the profit of the power plant through additional imbalance generation.

With the absence of battery storage and a hydrogen tank in a balancing group, all imbalances necessitate financial settlement. Furthermore, it is shown that a larger balancing group facilitates easier balance maintenance by combining different units' imbalances. On the other hand, the consideration of the influence the operation of connecting units can have on the other system while deciding on the power plant operation increases its profit. While total imbalance costs are reduced when this effect is considered, the decrease in the gas system imbalance costs caused by reserve activations in the power system comes at the expense of increased PV imbalance costs. Therefore, although the power system imbalance costs caused by reserve activations in the gas system decrease, the overall power imbalance cost in the power system sees a slight increase. Reserve provision of a battery storage and a hydrogen tank to both TSOs exhibits negligible differences when considering the influence and when not, while significant variations in the outputs of the electrolyzer and fuel cell are revealed. The upward reserve provision is reduced and the downward reserve provision is increased in both systems, thus, reducing the imbalance cost introduced by the changed power flows in the other observed system.

In our future endeavors, we aim to enhance the precision of modeling uncertainty in the operation of a hybrid power plant. Additionally, constructing an investment model, focusing on optimal dimensioning of units within a hybrid power plant, stands as another potential research direction. Moreover, exploring participation in the intraday market as a means of mitigating imbalances will be incorporated into the future work.

CRediT authorship contribution statement

Nikolina Čović: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Ivan Pavić:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Hrvoje Pandžić:** Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This research was funded in part by the Luxembourg National Research Fund (FNR) and PayPal, PEARL grant reference 13342933/Gilbert FRIDGEN and by the Luxembourg National Research Fund (FNR), grant reference 17742284. For the purpose of open access, and in fulfillment of the obligations arising from the grant agreement, the author has applied a Creative Commons Attribution 4.0 International (CC BY 4.0) license to any Author Accepted Manuscript version arising from this submission.

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