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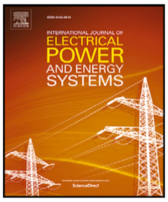

Interactions between electricity and hydrogen markets: A bi-level equilibrium approach

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ABSTRACT

Energy systems increasingly rely on the synergistic operations of the electricity and hydrogen markets pursuing decarbonization. In this context, it is necessary to develop tools capable of representing the interactions between these two markets to understand the role of hydrogen as an energy vector. This paper introduces a bi-level optimization model that captures the interactions between the electricity and hydrogen markets, positioning hydrogen generators as strategic electricity price makers in the power market. The model can be efficiently solved and applied to real-world scenarios by reformulating it as a Mixed Integer Linear Program. The case studies analyze spot market behaviors when hydrogen generators are modeled as price makers in the electricity market. First, single-period simulations reveal the effects of price-making, and next, a year-long simulation assesses broader implications. The findings demonstrate that conventional modeling assumptions, such as the price-taker hydrogen generators in the electricity market and constant production cost hypothesis, lead to non-optimal hydrogen generation strategies that raise electricity prices while reducing the profit of hydrogen generators and the hydrogen market social welfare. These results highlight the need for models that accurately reflect the interdependencies between these two energy markets.

1. Introduction

Globally major economies are making significant efforts towards establishing themselves within the hydrogen economy, recognizing its potential to penetrate energy systems and contribute to decarbonization efforts. The United States has committed $9.5 billion to its Clean Hydrogen Strategy, targeting the production of 10 million tons (MT) of clean hydrogen annually by 2030 [1]. Similarly, China's objectives stretch to an annual capacity of 100–200k tons of renewable hydrogen over the next decade. South Korea, focusing on dominating the Fuel Cell Electric Vehicle (FCEV) market, has plans to produce 3.9MT of hydrogen annually by 2030, backed by approximately $3 billion in investment. Japan and Canada are also notable contenders, with Japan aiming to produce 3MT of clean hydrogen annually by 2030 under its Basic Hydrogen Strategy, and Canada's strategy envisioning it as a leading clean hydrogen producer with an annual output of 20MT by 2050, priced competitively at $1–$3.5/kg [2]. In Europe, the objective scales with the European Union doubling its clean hydrogen usage target to 20MT annually by 2030, while the UK aims to develop a 5 GW hydrogen production capacity by the same year through a £240 million investment from the Net Zero Hydrogen Fund [3]. Germany, Portugal, Spain, and France have all articulated national strategies focusing on expanding their electrolysis capacities to meet the future demand for clean hydrogen, with funding allocations ranging from €1.5 billion to €9 billion to support the development of infrastructure and technology needed to achieve these targets [2].

The growth of the hydrogen sector as an energy vector is closely intertwined with the electricity system. Successful integration of hydrogen could significantly increase electricity demand. Without coordinated efforts, this surge may destabilize the electricity market and inflate prices. Conversely, with strategic alignment, hydrogen could provide flexibility to the electricity system, enhancing supply security and preventing curtailments [4,5]. Although recent studies address some of these interactions, there remains a need for models able to capture the strategic decision-making of hydrogen generators, particularly given the interdependence between these markets. This paper focuses on two key aspects: (1) positioning power-to-gas agents as price makers in the electricity market and (2) the impact of privileged information granted to hydrogen generators. Positioning hydrogen generators as price makers in the electricity market, suggests that electricity demand for hydrogen production could increase electricity prices, coupling the two markets. Additionally, granting privileged information to power-to-gas agents implies that these agents understand their influence on

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Nomenclature

Indices

b	Other hydrogen generators.
h	Power-to-gas agents.
j	Electricity generators.
l	Electricity demands.
m	Hydrogen demands.
t	Time periods.

Parameters

A_g	Slope of the willingness-to-pay curve for power-to-gas agent g.
$\alpha_{j,t}$	Electricity generation cost for generator j at time t.
$\beta_{l,t}$	Electricity demand willingness to pay for consumer l at time t.
η_g	Efficiency of electrolyzers for power-to-gas agent g.
B_m	Willingness to pay for hydrogen demand m.
C_b	Production cost of other hydrogen generators b.
$D_{l,t}$	Maximum electricity demand by consumer l at time t.
$E_{m,t}$	Maximum hydrogen demand by consumer m at time t.
H_b	Maximum hydrogen production by other hydrogen generators b.
H_g	Maximum hydrogen production by power-to-gas agent g.
M	Big-M constant for linearization.
$Q_{j,t}$	Maximum electricity generation by generator j at time t.

Continuous Variables

$e_{m,t}$	Hydrogen demand satisfied for consumer m at time t.
$h_{b,t}$	Hydrogen production by other hydrogen generators b at time t.
$h_{g,t}$	Hydrogen generated via electrolysis by power-to-gas agent g at time t.
$k_{g,t}$	Electricity bought by power-to-gas agent g at time t.
$x_{g,t}$	Willingness-to-pay bid of power-to-gas agent g in the electricity market at time t.
$c_{b,t}$	Hydrogen production cost for other hydrogen generators b at time t.
$c_{g,t}$	Hydrogen production cost for power-to-gas agent g at time t.
$d_{l,t}$	Electricity demand satisfied for consumer l at time t.
$q_{j,t}$	Electricity generated by producer j at time t.

Binary Variables

$b^{\phi}_{j,t}$	Binary variable for complementarity condition linearization for generator j at time t.
$b^{\pi}_{l,t}$	Binary variable for complementarity condition linearization for consumer l at time t.
$b^{\psi}_{j,t}$	Binary variable for complementarity condition linearization for generator j at time t.
$b^{\xi}_{l,t}$	Binary variable for complementarity condition linearization for consumer l at time t.

Dual Variables

$\phi_{j,t}$	Dual variable for lower bound on electricity generation by generator j at time t.
$\psi_{j,t}$	Dual variable for upper bound on electricity generation by generator j at time t.
$\pi_{l,t}$	Dual variable for lower bound on electricity demand by consumer l at time t.
$\xi_{l,t}$	Dual variable for upper bound on electricity demand by consumer l at time t.
λ_t	Electricity balance dual variable at time t. Electricity price.
μ_t	Hydrogen balance dual variable at time t. Hydrogen price.

electricity prices, leading to an imperfect electricity market and enabling them to bid strategically to maximize social welfare in the hydrogen market.

Previous investigations into the hydrogen market have underscored its significance in upcoming energy systems, with studies ranging from policy implications [6] to technical reviews [4,7–11]. These works significantly contribute to understanding hydrogen's potential as a key energy vector. However, they primarily focus on descriptive analysis, technological assessments, and small-scale operations, overlooking the economic and operational interactions between hydrogen production and the electricity market.

Some modeling efforts consider the hydrogen cost independently to the hydrogen production, including cost minimization strategies [12]; profits maximization for renewable energy plants [13,14]; power, natural gas, and hydrogen coupled models [15]; investments decision-making [16]; and considerations of hydrogen production within existing electricity market frameworks [17]. These models are solved efficiently, allowing for highly detailed representations that contribute to understanding hydrogen integration into the energy sector. However, in our paper, we opted for a different approach. We chose to forgo more complex technical constraints to represent hydrogen producers as strategic price-makers in the electricity market.

When it comes to the details of market behavior, a theoretical discussion about clearing mechanisms and auctioning theory applied to energy trading is done in [18]. Delving into the mathematical programming, [19] explores energy markets as complementarity and equilibrium problems, addressing economic concepts such as the relation between market clearing and market equilibrium and presents bi-level models. Advancing this exploration, [20] lays out the theoretical foundations of bi-level problems applied to power systems and the main techniques for solving bi-level games. Moreover, [21] provides a deeper discussion of the mathematical structures, applications and solving techniques for bi-level problems. These studies set the theoretical foundations for our research.

Applying a bi-level program, Ref. [22] introduces an innovative model that maximizes the profit of a gas-fired unit constrained by the operation of electricity and gas markets. This model has elements in common with our proposal, such as using bi-level optimization to calculate electricity and gas market prices as the dual of the respective balance constraints. However, there is no direct coupling between the gas and the electricity markets since both are represented in the lower level. Moreover, hydrogen has an extra interaction where production cost depends on electricity price.

Regarding hydrogen bi-level programs, [23] models the investment decisions in the hydrogen market addressing hydrogen's complementary role to electricity. The study proposes an electricity-hydrogen-integrated energy system model utilizing a bi-level mixed-integer program. In this case the model does not associate the cost of producing hydrogen with the electricity pricing.

Another bi-level program applied to hydrogen, Ref. [24], ventures into optimizing hydrogen production through grid-connected electrolyzer systems, taking a significant step towards incorporating price considerations. In contrast to our proposal, this bi-level model is integrated into a multi-stage framework which estimates electricity prices with a machine learning algorithm rather than endogenously in the optimization problem as propossed in this paper.

Another application of bi-level programming to hydrogen modeling is found in Ref. [25], exploring the operational decisions of a Virtual Power Plant (VPP) in the electricity and hydrogen market. It considers the hydrogen and electricity prices as the dual variable of balance constraints to calculate the profit of the VPP, as we do. However, it does not use this information to calculate hydrogen generation costs.

Efforts to model integrated electricity, hydrogen, and gas sectors have implemented more complex mathematical structures such as a three-level model [26]; however, even in this case, the electricity price is not used to determine hydrogen cost as is considered in this paper.

Other optimization techniques have successfully modeled the equilibrium between the electricity and hydrogen markets under various competition assumptions. For instance, [27] formulates a Mixed Complementarity Problem (MCP) to determine the equilibrium point among electricity and hydrogen market participants, assuming perfect competition. Similarly, [28] extends an MCP approach by incorporating subsidy mechanisms between the electricity and hydrogen markets. Furthermore, [29] reformulates a Variational inequalities problem (VI) to analyze interactions between the electricity and hydrogen markets under perfect competition and Cournot Oligopoly hypotheses. A common feature of these studies is their reliance on the electricity market clearing price to calculate hydrogen costs, a method also adopted in this work. However, a key distinction lies in the underlying assumptions. While [27,28] assume perfect competition, and [29] explores both perfect competition and Cournot oligopoly under predefined demand curves (enabling single-level reformulation), our model introduces imperfect competition through Stackelber equilibrium in the electricity market seeking to identify potential participation strategies for power-to-gas agents within the electricity market.

Table 1 positions our paper within the literature. The column "Model Motivation" indicates the primary objective of each model. The next column, "Hydrogen Market", specifies whether any type of market clearing is modeled for hydrogen bids. As observed, it is common for hydrogen markets not to be fully represented; in such cases, models typically focus on a subsystem, such as a single electrolyzer or a virtual power plant (VPP) with electrolysis capacity. The following column, "Electricity Market", performs a similar function for the electricity market. The column "Model Type" refers to the formulation of the model, indicating whether it is an Mixed Complementarity Problem (MCP), a Bi-level model or a variational inequalities problem (VI). The "Electricity Market Equilibrium Type" column, when applicable, identifies whether the market is represented as a perfect competition or an imperfect equilibrium, such as a Cournot or Stackelberg equilibrium. Finally, the "Hydrogen Cost Calculation" column is checked if the hydrogen cost is derived from electricity market clearing using the dual value of the balance constraint. If it is not checked, this indicates that the hydrogen cost is determined using alternative methods, such as an exogenous electricity price series or a neural network [30].

Our model, as shown in Table 1, represents both markets using a Stackelberg equilibrium. This means that power-to-gas agents bids in the electricity market are made strategically to maximize the net social welfare of the hydrogen market. Furthermore, the cost of producing hydrogen is derived from the electricity price, which is obtained through the electricity market clearing process.

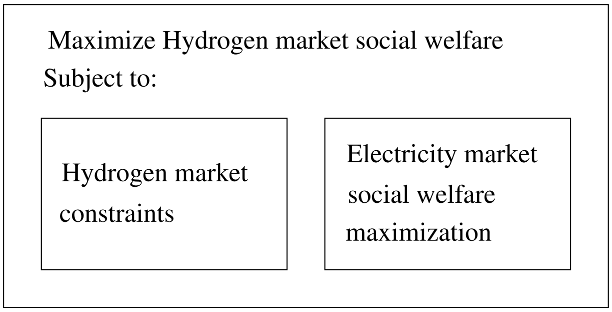

Fig. 1. Bi-level model structure.

In essence, while the extant literature provides an understanding of hydrogen and electricity markets in a wide variety of situations, our work extends this knowledge by presenting a bi-level optimization model that encapsulates coupling interactions when hydrogen generators exert market power in the electricity market. This contributes to the literature highlighting potential market interactions that may emerge in forthcoming energy systems.

This paper is divided into four sections. Section 2 describes the problem of coupled hydrogen and electricity markets clearing, presents the theoretical basis of the mathematical model, introduces the bi-level formulation, and reformulates it as a single-level optimization problem. Section 3 first introduce a set of single-period case studies which are used to isolate and explain relevant model solutions; secondly, it runs and compare the results of a year horizon scenario against prevalent assumptions in the literature; and thirdly, it asserts computational performance. Finally, Section 4 discusses findings and future works.

2. Mathematical model overview

This section presents a bi-level optimization model that represents the interdependent electricity and hydrogen markets clearings, capturing the impact of electrolysis-based hydrogen production on electricity and hydrogen prices and demands. The model includes power-to-gas agents, which buy electricity on the electricity market to produce hydrogen via electrolysis and sell it on the hydrogen market; other hydrogen generators, which sell hydrogen on the electricity market not generated by electrolysis; hydrogen demands, which buy hydrogen at the hydrogen market; electricity generators, which sell electricity in the electricity market; and electricity demands, which buy electricity at the electricity market. In the formulation, the market participants are identified with the sets of index h, b, m, j, and l for the power-to-gas agents, other hydrogen generators, hydrogen demands, electricity generators, and electricity demands, respectively.

The structure of the bi-level problem is illustrated in Fig. 1. This model is useful for policymakers and market operators to understand the consequences of introducing large amounts of hydrogen generated through electrolysis into the electricity market. It can also aid in long-term planning and provide insights into how hydrogen producers might strategically participate in the electricity market. Additionally, simulations using this model may be valuable for hydrogen producers in decision-making support and the development of bidding strategies, as well as for investors in the electricity market to evaluate scenarios with high hydrogen penetration. The lower level represents the electricity market clearing maximizing the social welfare. Decision variables for each time period t are electricity generation $q_{j,t}$ and satisfied demand $d_{l,t}$ of generators and demands, whose bids are defined by a production cost ($\alpha_{j,t}$) and a maximum quantity ($Q_{j,t}$) for hydrogen generators and a buying price ($\beta_{l,t}$) and a maximum quantity ($D_{l,t}$) for demands. In this

Table 1
Comparison of hydrogen models.

Ref.	Model motivation	Hydrogen market	Electricity market	Model type	Electricity market equilibrium type	Hydrogen cost calculation
[31]	Analyze seasonal hydrogen storage in small energy systems with dynamic electrolyzer characteristics.	✗	✗	Bi-level		✗
[32]	Enhance reliability of supply–demand balance and minimize carbon emissions in a integrated energy systems with hydrogen.	✗	✗	Bi-level		✗
[33]	Economically and environmentally optimize microgrid with a hydrogen storage system operations under renewable energy uncertainty.	✗	✗	Bi-level		✗
[34]	Optimize multi-type energy storage for low-carbon systems and hydrogen usage.	✗	✗	Bi-level		✗
[35]	Optimize electricity, heat, and hydrogen systems under wind uncertainty and hydrogen utilization.	✗	✗	Bi-level		✗
[36]	Optimize investments in shared hydrogen storage for cost efficiency and performance.	✗	✗	Bi-level		✗
[37]	Develop efficient methods to optimize hydrogen supply chains with multiple objectives.	✗	✗	Bi-level		✗
[38]	Enable high renewable energy integration, optimize investments, and reduce hydrogen supply costs.	✗	✗	Bi-level		✗
[39]	Optimize hydrogen retail operations under uncertainties in demand and renewable energy.	✗	✗	Bi-level		✗
[30]	Optimize hydrogen-electricity systems with electricity price prediction and hydrogen's dual role.	✗	✗	Bi-level		✗
[40]	Optimize energy management and pricing for service providers, improving economic and environmental outcomes.	✗	✗	Bi-level		✗
[41]	Strategically optimize energy storage systems in energy and reserve markets under wind and grid uncertainties.	✗	✓	Bi-level	Stackelberg	✓
[25]	Improve profitability of virtual power plants with waste-to-energy and renewable energy integration.	✓	✓	Bi-level	Stackelberg	✗
[27]	Evaluates Power-to-Gas investment in a competitive electricity and gas market	✓	✓	MCP	Nash	✓
[28]	Analyze the impact of hydrogen support mechanisms on hydrogen, electricity, and emission markets	✓	✓	MCP	Nash	✓
[29]	Analyze the interaction between hydrogen and electricity markets under Perfect competition.	✓	✓	VI	Nash	✓
[29]	Analyze the interaction between hydrogen and electricity markets under Perfect competition..	✓	✓	VI	Cournot	✓
Our model	Analyze the interaction between hydrogen and electricity markets when hydrogen market players strategically participate in the electricity market.	✓	✓	Bi-level	Stackelberg	✓

context, power-to-gas agents participate as an extra electricity demand $k_{g,t}$. Analogously, the upper level represents the market clearing of the hydrogen market where decision variables are hydrogen generated via electrolysis $h_{g,t}$, other hydrogen productions $h_{b,t}$ and satisfied hydrogen demand $e_{m,t}$. In the bi-level framework, two new variables are necessary: $x_{g,t}$, which defines the bid of power-to-gas agents in the electricity market and the dual variable of the electricity balance λ_t, which defines electricity price and, therefore, affects hydrogen production cost.

This formulation relies on several assumptions. As a consequence of using a bi-level framework, it is first assumed that hydrogen market participants set their decision variables initially (upper-level), followed by the response of the electricity market (lower-level), reflecting the real-world scenario where power-to-gas agents participate in the electricity market. Second, it is assumed that the upper-level participants, i.e., those in the hydrogen market, fully anticipate the lower-level reaction (electricity market clearing) to their bids. Although this is a strong assumption, the model provides valuable insights into the potential interactions between the hydrogen and electricity markets. It especially useful in low-uncertainty scenarios and when we consider that demand elasticity is larger in the hydrogen market than in the electricity one, what makes the electricity market behavior comparatively more predictable. The empirical evidence shows that electricity demand elasticity is low [42] while studies suggest that hydrogen demand elasticity might be higher [43], especially in the long term, as the market matures and alternative energy sources remain available. Besides, it is useful for analyzing the strategic bidding behavior of hydrogen producers and evaluating the value of information in energy markets. Moreover, the model could be extended by incorporating uncertainty in the electricity market bids, resulting in a representation more adequate for systems with a high level of uncertainty in which power-to-gas agents would consider a range of possible outcomes when making their decisions.

Other assumptions in the model, that are common in the context of energy markets, include single-bus modeling and linear production costs in the hydrogen and electricity markets. These simplifications are taken for the sake of simplicity and without loss of generality. Considering a multiple-node network and transport losses of electricity and hydrogen would increase the problem size and computational time while complicating the acquisition of a realistic dataset. On the other hand, while electricity market bids could be represented as quadratic functions without significantly increasing computational complexity, modeling hydrogen market bids with quadratic functions would result in a mixed-integer quadratic programming (MIQP) problem after reformulation, rather than the mixed-integer linear programming (MILP) problem obtained with the presented approach. To achieve an efficient trade-off between data requirements, computational complexity, and realism constant bids are assumed for all market participants except for the demand bids of hydrogen generators in the electricity market where quadratic bids are used.

Regarding the technical operation of hydrogen agents, several important simplifications are made. Hydrogen is assumed to be generated with constant efficiency, regardless of the load on the electrolyzers. Additionally, ramp constraints, start-up dynamics, and transport losses are neglected. These simplifications are reasonable from a medium-term market analysis perspective and have been made deliberately to focus on the effects of coupling the two markets, which would persist regardless of these considerations. Furthermore, since these restrictions relate to the upper-level problem, they could be incorporated directly without altering the reformulation of the model.

Another relevant assumption is the simultaneous clearing of hydrogen and electricity markets. This simplification is made to make the results more tractable. The formulation section outlines the changes that would be necessary to account for different clearing periods, such as daily dispatches in the hydrogen market combined with quarter-hour balancing intervals in the electricity market. Regarding the pricing, the electricity and the hydrogen prices are obtained as the dual variables of their respective balance equations.

As described before, the electricity market clearing is represented as a social welfare maximization problem. Ref. [19] shows that the social welfare maximization in the electricity market solution is equivalent to a Nash equilibrium where, assuming perfect competition, power generators decide production aiming to maximize profit while power demands decide demand quantity maximizing demand utility. Analogously, despite non-linearities caused by the bi-level structure, the upper level hydrogen market social welfare maximization problem corresponds to a market equilibrium under perfect competition. Therefore, the model presented herein can be formulated in four different ways: (I) as a single leader single follower problem if both levels are presented in the social welfare optimization form; (II) as a Mathematical Model with Equilibrium Constraints (MPEC) (Single leader multiple followers), if the upper level is presented as an optimization problem and the lower level is presented as an equilibrium problem; (III) as a multiple leader single follower if the upper level is presented as an equilibrium problem and the lower level is presented as an optimization problem; (IV) or as an Equilibrium Problem with Equilibrium constraints (EPEC) (multiple leaders multiple followers) if both levels are presented as an equilibrium problem. These equivalences are notable, since by solving a single-leader-single-follower problem the model is obtaining the results of more complex problems which market participants can use to estimate their profit/demand utility and decide on participating strategies.

Therefore, the formulation presented in this model reaches a Stackelberg equilibrium between the hydrogen and electricity market addressing social welfare. However, due to the equivalences mentioned, solutions can be interpreted as different types of market equilibrium. (I) Analyzing both markets separately, there is a perfect hydrogen market and an imperfect electricity market where the power-to-gas agents have complete knowledge over the other electricity market participants, which assumes perfect competition. (II) There is a Stackelberg equilibrium between the power-to-gas agents addressing profit maximization and the agents of the electricity market addressing profit/utility maximization. (III) As well, the upper level solution presents a Generalised Nash Equilibrium between the hydrogen market participants, and (IV) for the fixed bids of the upper level there is a Nash Equilibrium between the participants of the electricity market. See [20] for more details about these types of equilibriums.

2.1. Lower level: Electricity market

2.1.1. Objective function

The objective function (1) to be minimized represents the negative social welfare in the electricity market, accounting for generation costs against demand utility including the specific demand utilities associated with hydrogen generators.

$$\min_{k_{g,t},q_{j,t},d_{l,t}} \sum_j q_{j,t}\alpha_{j,t} - \sum_l d_{l,t}\beta_{l,t} - \sum_g k_{g,t}\left(x_{g,t} + \frac{1}{2}k_{g,t}A_g\right) \tag{1}$$

In this expression the variables $q_{j,t}$ are the electricity generated by producer j at time period t, $d_{l,t}$ the satisfied demand of electricity by consumer l at time t and $k_{g,t}$ the electricity bought in the electricity market by the power-to-gas agents. $\alpha_{j,t}$ and $\beta_{l,t}$ are the electricity generation cost and the electricity willingness to pay (also known as demand price), respectively. The willingness to pay is modeled as constant for each participants, except for power-to-gas agents, where it is defined as a linear function of quantity by the slope A_g and the intercept $x_{g,t}$. The rationale for this representation is detailed in Section 2.2.

2.1.2. Constraints and variables

The electricity market balance (2) ensures that the total electricity generation equals the total demand. Where the dual variable λ_t corresponds to the electricity price.

$$\sum_j q_{j,t} = \sum_g k_{g,t} + \sum_l d_{l,t} \;:\; \lambda_t \tag{2}$$

Finally, the bounds on electricity generation and demand are set by (3) to (4) where $\phi_{j,t}, \psi_{j,t}, \pi_{l,t}$ and $\xi_{l,t}$ represents the dual variables of the constraints.

$$0 \le q_{j,t} \le Q_{j,t} \;:\; \phi_{j,t}, \psi_{j,t} \tag{3}$$

$$0 \le d_{l,t} \le D_{l,t} \;:\; \pi_{l,t}, \xi_{l,t} \tag{4}$$

2.2. Upper level: Hydrogen market

2.2.1. Objective function

The objective function to be minimized is defined in (5).

$$\min_{h_{g,t},x_{g,t},e_{m,t}} \sum_{g,t} c_{g,t} + \sum_{b,t} c_{b,t} - \sum_{m,t} e_{m,t}B_m \tag{5}$$

This function represents the negative social welfare as the operation costs against the demand utility. It captures the hydrogen production costs of power-to-gas agents $c_{g,t}$ and other hydrogen generators $c_{b,t}$, and the hydrogen demand utility as the fulfilled quantity $e_{m,t}$ times the willingness to pay B_m.

2.2.2. Constraints

The total hydrogen production by power-to-gas agents is given by (6), where $k_{g,t}$ is the electricity bought in the electricity market to generate hydrogen and η_g the electrolyzers efficiency.

$$h_{g,t} = k_{g,t}\eta_g \tag{6}$$

The hydrogen production cost is given by (7) and (8) where λ_t is the electricity market price at every time step t and C_b the production cost of every other hydrogen technology h_b.

$$c_{g,t} = k_{g,t}\lambda_t \tag{7}$$

$$c_{b,t} = h_{b,t}C_b \tag{8}$$

It is worth mentioning here that the model assumes that all electricity for hydrogen production is bought in the electricity market since this study focuses on the coupled market equilibrium. Power purchase agreements (PPAs) can be included directly by accounting for the PPA quantity in (6) and price in (7).

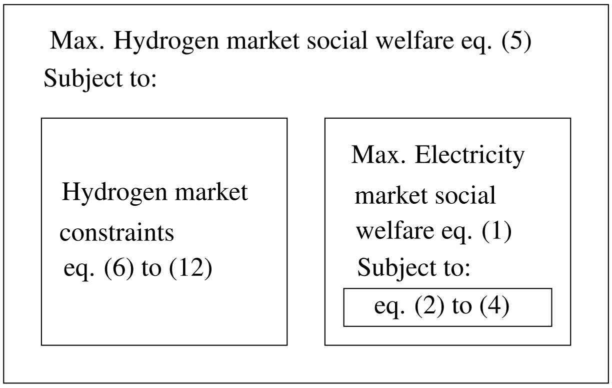

Fig. 2. Bi-level model structure with equations reference.

The market balance is ensured through (9), guaranteeing that the total hydrogen supply equals the demand. The dual variable μ_t represents the hydrogen market price.

$$\sum_g h_{g,t} + \sum_b h_{b,t} = \sum_m e_{m,t} \; : \; \mu_t \tag{9}$$

Note that the balance assumes the clearing of the hydrogen and electricity markets at the same time. However, this formulation could be easily generalised to different clearing periods in both markets by using distinct time sets at each level and aggregating the shorter period in (9). This approach would be useful to represent daily dispatches in the hydrogen market or quarter-hour balances in the electricity market, for example.

Bounds on hydrogen production and demand are defined as:

$$0 \le h_{g,t} \le H_g \tag{10}$$

$$0 \le h_{b,t} \le H_b \tag{11}$$

$$0 \le e_{m,t} \le E_{m,t} \tag{12}$$

In this level, the electricity used to produce hydrogen $k_{g,t}$ is not an unconstrained variable since it is set in the electricity market (lower level). Nevertheless, this level decides the variable x_{gt}, which characterizes the willingness to pay of power-to-gas agents bids in the electricity market. Eq. (13) defines the bids as a linear willingness to pay for power-to-gas agents where A_g are the parameters defining the slopes of the demand curves and $x_{g,t}$ the intercepts. Since the upper level has perfect knowledge over the lower level $x_{g,t}$, it is enough to define the price-quantity bid of power-to-gas agents in the electricity market. The use of a linear willingness to pay simplifies bids into a single decision variable x_{gt}. Employing a constant willingness to pay would require the model to simultaneously determine willingness to pay and maximum production quantity as two separate decision variables. Note that the value of the parameter A_g is instrumental since x_{gt} will adjust accordingly to obtain the optimal hydrogen production regardless of the A_g input value.

$$x_{g,t} + k_{g,t}A_g \tag{13}$$

2.2.3. Bi-level problem formulation

The complete bi-level formulation is defined by the objective function (5) constrained by the hydrogen market constraints, (6) to (12) and the lower level problem and (1) to (4) (see Fig. 2).

2.3. MILP reformulation

Bi-level models are not trivial to solve. This section presents an approach that converts the bi-level model into a single-level Mixed Integer Linear Program (MILP) using the single-level reformulation presented by Fortuny-Amat and McCarl [44] and exploiting specific problem characteristics to eliminate bilineal terms associated with the hydrogen cost.

Firstly, the bi-level is reformulated as a single-level problem, and secondly, the hydrogen cost is linearized, obtaining a MILP.

2.3.1. Single-level reformulation

The reformulation begins by integrating the lower level problem (1)–(4) into the upper level problem as the Karush–Kuhn–Tucker (KKT) conditions, resulting in a Mathematical Problem with Complementarity Constraints (MPCC) [44]. The KKT stationarity conditions for the model are specified by (14) to (16).

$$\frac{\partial \mathcal{L}}{\partial q_{j,t}} = \alpha_{j,t} - \lambda_t - \phi_{j,t} + \psi_{j,t} = 0 \tag{14}$$

$$\frac{\partial \mathcal{L}}{\partial d_{l,t}} = -\beta_{l,t} + \lambda_t - \pi_{l,t} + \xi_{l,t} = 0 \tag{15}$$

$$\frac{\partial \mathcal{L}}{\partial k_{g,t}} = -x_{g,t} - A_g k_{g,t} + \lambda_t = 0 \tag{16}$$

Primal and dual feasibility conditions of the KKT are enforced by incorporating lower level constraints into the upper level and ensuring dual variables for inequalities are non-negative, respectively. Complementary slackness conditions are encapsulated by (17) to (20). Here the symbol $\perp$ means that two terms must be orthogonal, ensuring their product must be zero.

$$0 \le q_{j,t} \perp \phi_{j,t} > 0 \tag{17}$$

$$Q_{j,t} \ge q_{j,t} \perp \psi_{j,t} > 0 \tag{18}$$

$$0 \le d_{l,t} \perp \pi_{l,t} > 0 \tag{19}$$

$$D_{l,t} \ge d_{l,t} \perp \xi_{l,t} > 0 \tag{20}$$

Subsequently, the MPCC is transformed into a Mixed Integer Non-Linear Program (MINLP) using the Big M approach. The transformation entails modeling the primal, dual, and complementarity KKT conditions with a set of constraints and a binary variable. For example, the expression (17) is replaced with (21) to (24) where $b^{\phi}_{j,t}$ represents the binary variable associated with the dual variable $\phi_{j,t}$.

$$q_{j,t} \ge 0 \tag{21}$$

$$\phi_{j,t} \ge 0 \tag{22}$$

$$q_{j,t} \le M b^{\phi}_{j,t} \tag{23}$$

$$\phi_{j,t} \le M(1 - b^{\phi}_{j,t}) \tag{24}$$

2.3.2. Hydrogen cost linearization

The bi-linear term used to calculate the hydrogen cost in (7) as the product of electricity price λ and hydrogen production h_g can be linearized using problem structure and duality theory. Given the upper level's complete knowledge over the lower level, power-to-gas agents are always marginal in the electricity market when they buy electricity; therefore, if $k_{g,t} > 0$ (25) is true.

$$\lambda_t = x_{g,t} + k_{g,t}A_g \quad \forall g \tag{25}$$

Multiplying both terms by electricity production, (26) is obtained and satisfied whether $k_{g,t} > 0$ or $k_{g,t} = 0$.

$$\sum_{g,t} c_{g,t} = \sum_{g,t} \lambda_t k_{g,t} = \sum_{g,t} k_{g,t}(x_{g,t} + k_{g,t}A_g) \quad \forall g, \forall t \tag{26}$$

From duality theory, the lower level objective function at optimal equals its dual objective function, (27).

$$\sum_{j,t} q_{j,t}\alpha_{j,t} - \sum_{l,t} d_{l,t}\beta_{l,t} - \sum_{g} k_{g,t}\left(x_{g,t} + \frac{k_{g,t}A_g}{2}\right) = \sum_{g,t} \frac{k_{g,t}A_g}{2} - \sum_{j,t} \psi_{j,t}Q_{j,t} - \sum_{l,t} \xi_{l,t}D_{l,t} \tag{27}$$

Thus, the hydrogen cost is linearized as (28).

$$\sum_{g,t} c_{g,t} = \sum_{j,t} q_{j,t}\alpha_{j,t} - \sum_{l,t} d_{l,t}\beta_{l,t} + \sum_{j,t} \psi_{j,t} Q_{j,t} + \sum_{l,t} \xi_{l,t} D_{l,t} \tag{28}$$

The reformulated MINLP, by substituting hydrogen costs sum at (5) with the linearized form (28), becomes a solvable MILP using standard MIP solvers. In this reformulation, the objective function remains the negative hydrogen market social welfare and the set of decision variables includes the upper level decision variables $(h_{g,t}, x_{g,t}, e_{m,t})$, the lower level decision variables $(k_{g,t}, q_{j,t}, d_{l,t})$, the dual variables of the lower level problem $(\lambda_t, \phi_{j,t}, \psi_{j,t}, \pi_{l,t}, \xi_{l,t})$, and the binary variables necessary for the reformulation of each inequality constraint $(b^{\phi}_{j,t}, b^{\psi}_{j,t}, b^{\pi}_{l,t}, b^{\xi}_{l,t})$.

3. Case study

The first part of this section, 3.1, presents a set of case studies and sensitivity analyses within a single time period, exploring interactions between the electricity market and the hydrogen market. This analysis aids in understanding the impact of representing hydrogen producers as price makers in the electricity market through the bi-level model. The second part, 3.2, extends over a one-year horizon, aiming to comprehend the effects of the isolated phenomena discussed previously in a more realistic scenario by comparing the outcomes of the bi-level model with those obtained applying the most prevalent hypotheses in the literature.

All the cases were executed using the reformulated MILP model described in Section 2.3. It was implemented in GAMS Studio 1.11.3 and solved using GUROBI on a Windows 11 PC equipped with 64.0 GB of RAM and an Intel(R) Core(TM) i7-8700 CPU @ 3.20 GHz. For the Annual-horizon case study, spanning 8760 h, the solving time was 47 s.

3.1. Single-period cases

This section analyses the results for single-period cases to illustrate how the model represents the interaction of the two markets.

In the simulations presented in this section, the electricity market includes of three generation bids and three demand bids. The generation bids are characterized by the parameters α_j and Q_j which can be found in Table 2. The demand bids are described by β_l and D_l, listed in Table 3. The market clearing with no hydrogen bids is shown in Fig. 3.

In this stylized cases, the hydrogen market includes a single power-to-gas agent with enough capacity to satisfy the whole demand $H_g = 30$ MWh and a electricity willingness to pay slope of $A_g = 0.1$ €/MWh (assuming a perfect efficiency $\eta_g = 1$ to simplify the interpretability of the results without loss of generality) and one hydrogen demand characterized by a demand quantity of $E_m = 30$ MWh and willingness to pay $B_m = 4$ €/MWh. Note that although there is just one generator, the formulation maximizes social welfare, which is equivalent to perfect competition for the case with several generators. Hence, the results and strategic decisions are generalizable to situations involving more participants.

Table 2
Electricity market generation bids.

	Generation cost α_j €/MWh	Capacity Q_j MW
Generation 1	1	20
Generation 2	3	5
Generation 3	6	9

Table 3
Electricity market demand bids.

	Willingness to pay β_l €/MWh	Capacity D_l MW
Demand 1	2	5
Demand 2	4	7
Demand 3	5	10

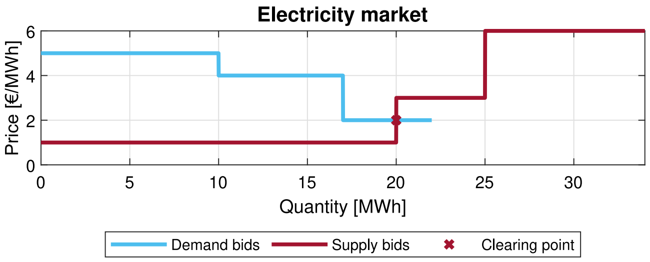

Fig. 3. Single-period case: electricity market clearing without electrolyzers demand.

3.1.1. Hydrogen and electricity markets clearing

Fig. 4 shows the clearing for the hydrogen and electricity markets. In the hydrogen market, there is only one demand block and one supply block, which results in the demand and supply curves not intersecting. However, the clearing point is marked with a cross. This point represents the maximum production level that consumers are willing to pay for and that the power-to-gas agents are willing to produce at the marginal cost of hydrogen. The input parameters determine the hydrogen market price-quantity demand block, while the power-to-gas agent bid (supply) depends on the electricity market clearing. The hydrogen generator strategically sets the value of the bid characterization x_g to purchase the maximum amount of electricity possible without exceeding the threshold that would activate a more expensive generator increasing electricity cost and thus decreasing market hydrogen social welfare. This reflects the Stackelberg game approach where electrolyzers leverage their market knowledge to optimize their electricity purchase while influencing the market clearing.

In Fig. 4, as well as in the other electricity market clearing figures presented in this paper, it can be observed that modeling the bids of hydrogen generators as a linear function yields the same outcome as modeling them with a constant willingness to pay and a maximum quantity, but with one variable less.

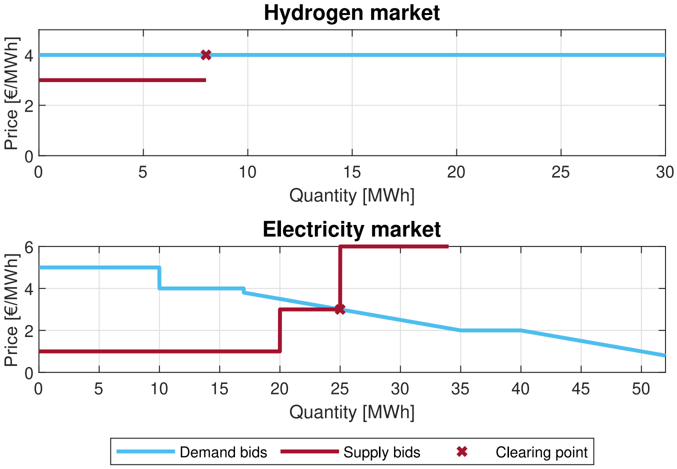

Fig. 4. Single-period case 1: Hydrogen and electricity markets clearings.

In Fig. 4 and every electricity market figure presented in this paper, hydrogen generator bids are modeled as linear functions. As explained in Section 2.2, this linear representation obtains the same result as using a constant willingness to pay and a maximum quantity, but with one variable less per bid.

3.1.2. Analysis of the power-to-gas agents' bids on electricity market

Given the prior results, to accurately interpret the behavior of power-to-gas agents, it is crucial to understand the role of the upper level variable x_g, which characterizes the bidding strategy of power-to-gas agents in the electricity market. For this analysis, the bi-level problem was decomposed into the upper and lower levels and solved sequentially for a set of fixed values of x_g. Initially, the electricity market outcomes were determined with these fixed values, followed by integration of the resulting electricity price λ and quantity k_g into the hydrogen market model.

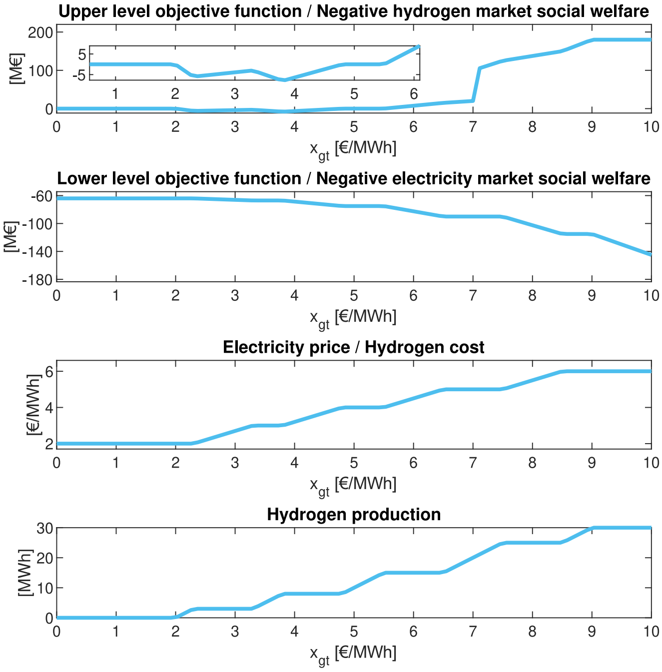

Fig. 5. Single-period case 2: Sensitivity to power-to-gas agents electricity bids characterization x_g.

Fig. 5 presents the dependence of the market outcomes on x_g. Since it characterizes the gas to power agents bid, for a constant slope A_g, the higher the x_g value is, the higher the electricity willingness to pay by the hydrogen generators is. The results identify two saturation points affecting the upper level objective function, the electricity price, and the hydrogen production. For x_g values below 2 €/MWh, the bid from the power-to-gas agent is not competitive against the prevailing electricity market price, which results in zero hydrogen production. Conversely, when x_g exceeds 9 €/MWh, the electrolyzers are producing at maximum capacity, rendering any further increase in x_g inconsequential to the electricity market clearing (Fig. 6). The lower level objective function is only saturated for x_g values below 2 €/MWh since for values of x_g greater than 9 €/MWh the utility of the demand term keeps growing unboundedly. In the upper level objective function graph, two minima can be observed, a local minimum at the point $x_g = 2.03$ €/MWh with a social welfare of the hydrogen market of 5.99 M€ and the solution to the bi-level optimization problem, the absolute minimum, at $x_g = 3.16$ €/MWh, with a social welfare of 7.34 M€.

When the bi-level model is solved, x_g can freely adapt its value to achieve optimal hydrogen production. Therefore, the value of the parameter A_g does not influence the optimal solution as long as it remains greater than zero (unless it is set excessively small or large, which could lead to numerical errors).

3.1.3. *Sensitivity analysis on hydrogen willingness to pay*

This section presents a sensitivity analysis of the hydrogen willingness to pay B_m while keeping the hydrogen demand quantity constant at $E_m = 30$ MWh, as in the preceding cases. The focus here is on how variations in B_m affect hydrogen market outcomes, precisely the hydrogen production quantity and costs, which depend on electricity prices.

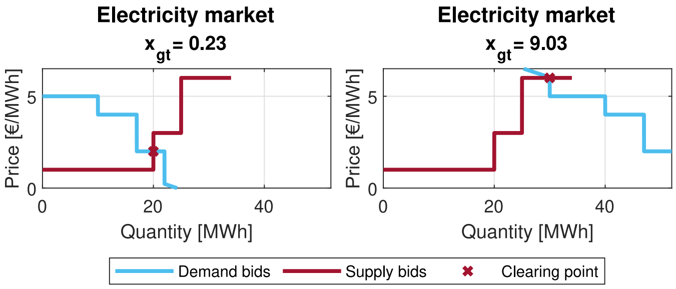

Fig. 6. Single-period case 2: electricity market clearing for extreme x_g values.

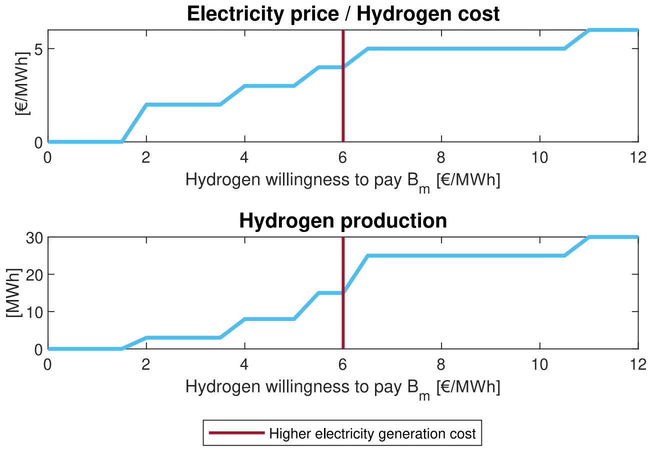

Fig. 7. Single-period case 3: Variations in hydrogen price and production in response to the hydrogen willingness to pay B_m values from 0 to 12 €/MWh.

Fig. 7 shows the relationship between the hydrogen willingness to pay and the resulting market outcome. An increase in B_m leads to a rise in the hydrogen produced and its associated production cost. Notably, the optimal hydrogen market solution does not necessarily maximize the hydrogen production at a cost below the hydrogen demand willingness to pay, otherwise, hydrogen generators would be producing at full capacity for hydrogen willingness to pay over the higher electricity generation cost (red line in Fig. 7, 6 €/MWh), which is the maximum hydrogen generation cost the model can obtain (assuming a perfect efficiency $\eta_g = 1$). For example, when the hydrogen willingness to pay is set to $B_m = 9$ €/MWh, the hydrogen production is below 30 MWh, although producing this quantity will never raise the hydrogen generation cost over 6 €/MWh. This is a critical distinction from electricity market behaviors and requires explicit clarification.

Increasing hydrogen production can escalate the electricity cost, elevating the overall production expenses for hydrogen. This might lead to reduced social welfare and power-to-gas agents' profits, leading to a situation where hydrogen generators need to be aware of their impact on electricity costs to maximize profits. This awareness contrasts with the electricity market operation, where higher output from generators cannot increase the operational costs of those already in service.

To highlight and identify this effect throughout our paper, we introduce the term “cost maker” to describe hydrogen generation units capable of influencing the generation costs for every power-to-gas unit by altering their output. Consequently, every hydrogen generation unit that behaves as a price maker in the electricity market also acts as a cost maker for electricity-based hydrogen.

Fig. 8 illustrates various market clearing instances for hydrogen and electricity, varying the hydrogen willingness to pay B_m. The power-to-gas agent adjusts x_g to optimize electricity bids, from no production at $B_m = 0$ €/MWh to full capacity at $B_m = 11$ €/MWh. Notably, when B_m covers hydrogen costs, production may remain below demand, such as in the fourth-row case, indicating again that increased production can reduce electrolyzers' profits, highlighting the cost-making consequences.

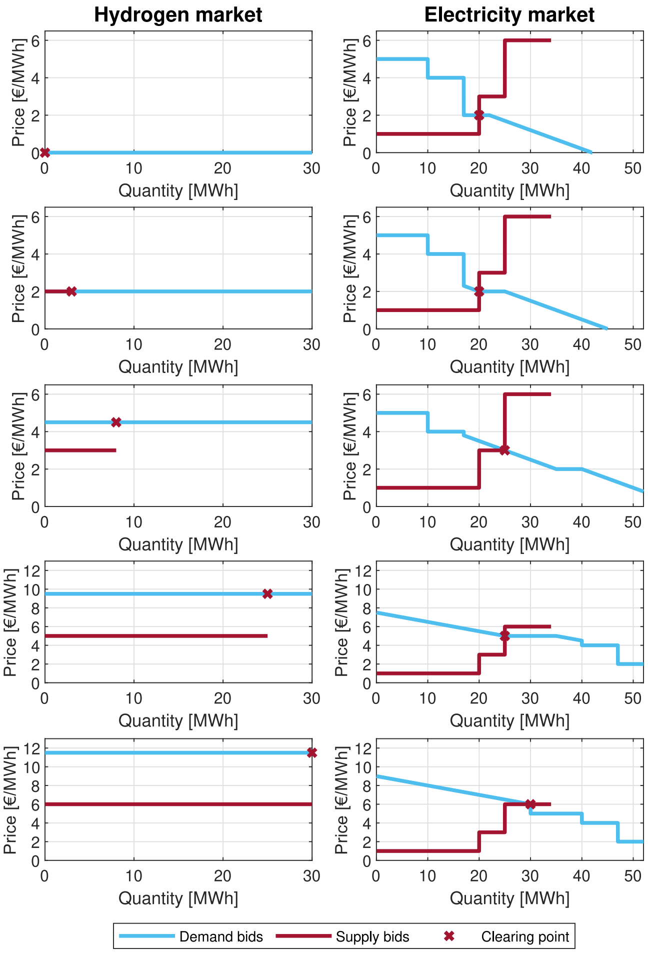

Fig. 8. Single-period case 3: Hydrogen and electricity market clearings for B_m values of 0, 2, 4.5, 9, and 12 €/MWh.

3.1.4. *Hydrogen market clearing as a price-taker*

The earlier cases illustrate the outcomes of the bi-level model introduced in this paper. It is also illustrative to calculate the results of the case 3.1.1 using a single-level price-taker model for the hydrogen market. Here, the electricity market is not cleared, and the model from Section 2.2 is solved with the electricity price fixed at 2 €/MWh, the clearing price indicated in Fig. 3.

The results indicate a hydrogen production of 30 MWh, fulfilling all the demand the generators can meet. This occurs because the willingness to pay for hydrogen is higher than the electricity price (which equals hydrogen production cost since electrolyzers are assumer perfectly efficient).

This case study points out that hydrogen production at a time step is reduced to a binary decision with price-taker models. The generators either produce at the minimum value between hydrogen demand and generation capacity when the willingness to pay for hydrogen equals or exceeds the electricity price times efficiency, or no hydrogen is produced.

Compared to the bi-level model, the price-taker simulation results in higher hydrogen generation (30 MWh in the price-taker versus 8 MWh in the bi-level) while assuming lower electricity prices (2 €/MWh versus 3 €/MWh). This discrepancy arises because the price-taker simulation does not account for the increase in electricity demand in the electricity market. Such differences are expected to also happen over more extended time horizon simulations, leading to underestimations of electricity prices and, consequently, unrealistic social welfare outcomes in the hydrogen market.

Table 4
Electricity market generation parameters.

	Generation bid €/MWh	Capacity GW
Non-renewable 1	70	13
Non-renewable 2	100	13
Nuclear	0	9.7
Bio	8.5	9.7
Solar 1	1	8.5
Solar 2	0.5	8.5
Solar 3	1.7	8.5
Solar 4	2	8.5
Wind 1	1.2	8.5
Wind 2	1	3.8
Wind 3	3	3.8
Wind 4	4	1

3.2. *Annual-horizon case study*

This section analyses the hydrogen and electricity generation output within a realistic scenario, evaluating the use of the bi-level model against simpler alternatives. It analyses the effects of these modeling decisions on generation profits, demand utility, and overall social welfare within the hydrogen and electricity markets.

The scenario input data is defined in Section 3.2.1, which corresponds to a year-long period based on the Spanish targets for 2030.

The solution of the bi-level model, referred to as the Bi-level case, is compared to the prevalent assumptions in the literature: price taking and fixed production cost for electrolysis-based hydrogen. While the Bi-level case is solved as explained in Section 2.3, the two alternative cases, the Fixed Cost and the Price Taker, are computed using the hydrogen market model presented in Section 2.2 and considering the electricity price λ_t an input parameter, therefore, the electricity market is not clear and results such as social welfare or generation are not computed in this two modelings. For the Fixed Cost case, a constant hydrogen production cost is applied, whereas, in the Price Taker case, time-variant costs depend on an exogenously calculated electricity prices series.

The analysis of results is structured in two stages. First, Section 3.2.2 performs a direct comparison of outcomes across the Bi-level, Fixed Cost, and Price Taker cases to understand how the hydrogen market clearing is solved by each model. Second, in Section 3.2.3, these results are reassessed within an operational context. This involves updating the electricity price by clearing the electricity market (as described in Section 2.1) with the necessary electricity demand by power-to-gas agents to meet the hydrogen production calculated in the first stage. Subsequently, the hydrogen market costs, profits, demand utilities, and social welfare are recalculated for the hydrogen productions decided in the first stage with the updated electricity prices.

3.2.1. *Input data specification*

The study employs a data set based on the Spanish National Plan of Energy and Climate (PNIEC) for 2030 [45] to ensure realistic simulations.

The electricity market data is encapsulated in Table 4 for generators, encompassing generation bids and capacities and Table 5 for demand, including willingness to pay and quantities. The generation mix features renewable and non-renewable sources, with solar and wind profiles based on the 2018 MIBEL dataset [46] and other sources assumed to have constant capacities over time periods based on [45]. Demand is categorized into residential, industrial, services, and transportation sectors, with variability in residential consumption and constancy over time in other demands.

The hydrogen market delineated in Tables 6 and 7 introduces three hydrogen production methods: alkaline (AEC), Proton exchange membrane (PEMEC), and other (OTR). Demand within this market is segmented into time-variant (HDEM1, HDEM2) and steady (HDEM3,

Table 5
Electricity market demand parameters.

	Time profile	Willingness to pay €/MWh	Capacity GW
Residential	Time variant	200	12
Domestic 1	Constant	5	2.9
Domestic 2	Constant	83	6.7
Services	Constant	7	8.1
Transport 1	Constant	8	0.6
Transport 2	Constant	73	1.5

Table 6
Hydrogen market generation parameters.

Technology	Generation bid €/MWh	Capacity GW	Efficiency H_2 MWh/MWh
AEC	–	1	0.7
PEMEC	–	1	0.65
OTR	50	2	–

Table 7
Hydrogen market demand parameters.

	Time profile	Willingness to pay €/MWh	Capacity GW
HDEM1	Time variant	3	0.3
HDEM2	Time variant	33	0.9
HDEM3	Constant	50	1.2
HDEM4	Constant	5	0.3

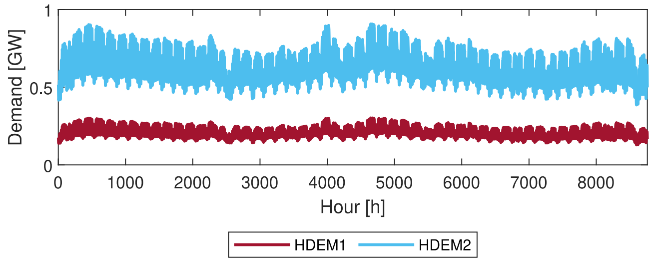

Fig. 9. Hydrogen demand hourly profiles.

Table 8
Annual simulation summary: Bi-level vs. Price taker vs. Fixed cost.

	Units	Bi-level	Price taker	Fixed cost
Hydrogen social welfare	k€	−330.75	−341.88	−205.61
Electricity social welfare	M€	−20.65		
AEC production	GWh	7.04	7.20	8.76
PEMEC production	GWh	3.71	4.02	.258
OTR production	GWh	0.06	0.97	0
H2 production	GWh	10.82	11.22	11.34
AEC profit	k€	88.49	84.83	87.55
PEMEC profit	k€	23.46	24.09	21.25
OTR profit	€	0	0	0
Demand utility	k€	218.79	232.95	96.79

HDEM4) demands, with the time-variant profiles illustrated in Fig. 9. The capacities of hydrogen are based on the expected hydrogen consumption in Spain in 2030 according to [45] while the segmentation into four entities is arbitrary.

The Price Taker case derives hydrogen production cost as the efficiency times the electricity price obtained from a simulation of the electricity market model presented in Section 2.1 (lower level without hydrogen production) with the inputs defined in this section. In the Fixed Cost case, AEC and PEMEC operation costs are set at 23 €/MWh and 24.7 €/MWh, respectively, which averages the costs of these technologies in the Price Taker simulation.

3.2.2. *Models results*

Table 8 presents the outcomes of the price maker bi-level case, the Price Taker case and the Fixed Cost case. The first two rows describe the objective functions at each level, which compute negative social welfare. Note that the electricity market is only cleared on the bi-level case; therefore, the electricity market social welfare in the price taker and fixed cost cases is not computed. The subsequent three rows detail the production outputs of different hydrogen technologies, aggregated in the fourth row. The final rows present the profit and demand utility of hydrogen market participants.

Results show that the Price Taker model yields an overestimation of hydrogen production and social welfare as a consequence of neglecting the impact of hydrogen production on electricity prices. This oversight leads to inflated profits for generators and higher values for demand utilities compared to the bi-level model outcomes.

Conversely, the Fixed Costs case leads to reduced hydrogen production, reduced profits, and lower demand utilities. This primarily occurs because the Fixed Cost model does not take advantage of periods of low electricity pricing, missing opportunities to fulfill hydrogen demand at costs below the fixed hydrogen production cost.

In all cases, the profit for other hydrogen technologies is zero, as when producing hydrogen, it is always a marginal technology that sells at production cost.

3.2.3. *Decision-making outcomes*

To evaluate the consequences of decision making using these three models, the electricity market is cleared “a posteriori” including the electricity demand by the power-to-gas agents necessary to produce the hydrogen shown in Table 8 and consequently the hydrogen market cost, profits, demand utilities and objective functions are recalculated with the updated electricity prices. Table 9 shows the results of these calculations- in addition to the rows in the previous table- this table includes the hydrogen average price, the average hydrogen production cost, and electricity market outputs. The average price is the average of the hourly electricity price weighted with the hourly production.

The results of the Price Taker and Fixed Cost cases show decreased hydrogen social welfare, elevated electricity prices, and lower profits for gas-to-power agents than initially anticipated from the model execution. The bi-level model’s results match those from its execution since a strength of the bi-level model is considering hydrogen generation’s impact on the electricity market.

The results presented in Table 9 are a consequence of overlooking the cost maker role of power-to-gas agents in the Price Taker and Fixed

Table 9
Reevaluated market outputs: Bi-level vs. Price taker vs. Fixed cost.

	Units	Bi-level	Price taker	Fixed cost
Hydrogen social welfare	k€	−330.75	−287.03	−150.92
Electricity social welfare	M€	−20.65	−20.68	−20.68
AEC production	GWh	7.04	7.20	8.76
PEMEC production	GWh	3.71	4.02	2.58
OTR production	GWh	0.063	0.97	0
H2 production	GWh	10.82	11.2	11.34
Electricity generation	GWh	220.93	221.60	220.39
Electricity average cost	€/MWh	2.93	3.05	3.56
Electricity average price	€/MWh	11.29	13.54	14.35
H_2 average cost	€/MWh	5.4	12.98	28.23
H_2 average price	€/MWh	15.75	17.41	33
AEC profit	k€	88.49	42.68	40.43
PEMEC profit	k€	23.46	11.39	13.69
OTR profit	€	0	0	0
Demand utility	k€	218.79	232.95	96.79

Cost cases. When both simplified models calculate optimal hydrogen production without accounting for its impact on electricity prices, the overall cost of generating electricity-based hydrogen increases, reducing both the social welfare of the hydrogen market and the profits of hydrogen generators.

The effects of these simplified models on the electricity market results are also notable. Among the three cases, the Bi-level model achieves the lowest electricity prices and costs while maintaining similar levels of social welfare associated with electricity generation. The Price Taker model fails to leverage price valleys, increasing prices. In the Fixed Cost case, fluctuations in electricity prices – peaks and valleys – are not even evaluated. This is evident when analyzing the average electricity prices: without hydrogen production, the average price is 11.50 €/MWh. When hydrogen production is included in the clearing, this price drops to 11.29 €/MWh if decisions are made using the bi-level model. Conversely, if generation is scheduled using the Price Taker or Fixed Cost models, the average electricity price increases to 12.54 €/MWh and 14.35 €/MWh, respectively.

It is also noticeable that there is an increase in demand utility alongside decreased production profit for the Price Taker cases. In the electricity market models, where costs and willingness to pay are fixed and the electricity price is calculated as the dual of the balance, non-optimal production can either reduce demand utility without affecting generation profit, diminish generation profit without impacting demand utility, or decrease both. However, in the hydrogen market model where power-to-gas agents are cost makers, the profit function gains an extra degree of freedom (hydrogen cost), which allows for a reduction in profits while increasing demand utility. Consequently, as observed in Section 3.1.3, there are situations where it is more profitable for power-to-gas agents to reduce production rather than increase electricity price/hydrogen cost. A strength of the bi-level model is that it successfully considers these situations.

In summary, the findings identify the consequences of overlooking the interplay between hydrogen production and electricity pricing. Depending on the simplifications applied and their parameters (specifically electricity prices), results can either overestimate or underestimate hydrogen production and electricity prices, leading to unrealistic social welfare in the hydrogen market and questioning the accuracy and interpretation of price-taker models for large-scale hydrogen production.

4. Conclusion

This study presents a bi-level optimization model that captures the interdependencies between the electricity and hydrogen markets. It models hydrogen clearing as an upper level problem constrained by the electricity market clearing at the lower level. The results highlight the impact of electrolysis-based hydrogen production on market interactions.

A study of single-period cases identifies bidding patterns in the electricity market by hydrogen producers as a consequence of modeling hydrogen generators as strategic price makers on the electricity market, introducing the term cost maker to address those hydrogen generators that can influence the operation cost of other hydrogen producers by varying their output. A year-long simulation reveals the importance of considering the reciprocal influences between the hydrogen and the electricity market. This emphasizes the value of developing price-taker models for large-scale electricity-based hydrogen production to improve real-world representation. The proposed bi-level model addresses this need, and the MILP reformulation enables practical application to real-world scenarios by improving computational efficiency.

The results of this paper suggest that a hydrogen industry with sufficient electrolysis capacity might influence electricity market prices. This possibility raises several important questions that future research should address. Among the most interesting are the following: under what conditions could the hydrogen market exert market power over electricity markets, how should antitrust regulations adapt to a coupled electricity-hydrogen sector, and what measures could hydrogen consumers take to protect themselves?

Finally, the research calls for a more nuanced modeling of hydrogen production within electricity markets. Future studies should broaden the model to consider uncertainty, regional regulation, storage technologies, and operation constraints such as ramps and non-linear efficiencies, contributing to the representation of integrated energy systems.

CRediT authorship contribution statement

Luis Jesús Fernández: Writing – original draft, Resources, Formal analysis, Conceptualization, Writing – review & editing, Methodology, Software, Project administration, Investigation, Data curation. **Efraim Centeno:** Writing – review & editing, Project administration, Formal analysis, Supervision, Conceptualization. **Sonja Wogrin:** Supervision, Writing – review & editing.

Ethical considerations

The authors confirm that this research complies with ethical standards and that all necessary permissions and approvals have been obtained, where applicable.

Declaration of competing interest

The author declare that he has no conflict of interest in relation to my submission, which he has submitted for review and possible publication.

The author confirm that there are no financial, personal, or professional affiliations or relationships that could be seen as influencing the research or its interpretation.

Data availability

All data generated or analyzed during this study are included in the manuscript. Additional data, if required, will be made available upon reasonable request.

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