Assesing the Role of Fuel Cell Vehicles in the Iberia Energy Transition

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Abstract— The mobility sector is expected to significantly impact the power system by deploying battery electric vehicles (BEV) and fuel cell vehicles (FCEV). This work improves CEVESA, a market model for the long-term planning and operation of the Iberian Electricity Market, by modelling FCEV as an alternative to BEV and internal combustion vehicles (ICEV), and its impact on the H_2 demand and storage. The mobility and H_2 economy models interact with the power system through the electricity needs and price. CEVESA is then applied to estimate potential expansion paths of ICEV, BEV and FCEV mobility alternatives considering the total system costs and the EU decarbonization strategy. The findings suggest that if FCEVs technology matures, it could rival BEVs, offering greater system flexibility via electrolyzers and extended driving ranges for users.

Index Terms— Electricity market model; electric, fuel cell and combustion vehicles; H_2 economy.

I. INTRODUCTION

The mobility sector in the EU is evolving rapidly due to global emission policies and local regulations [1], such as low-emission zones, which restrict the use of internal combustion engine vehicles (ICEVs) in urban areas. This has led to the rise of low-emission alternatives like battery electric (BEV) and fuel cell electric vehicles (FCEVs), which rely heavily on electricity supply. Thus, the transition to these vehicles will have a substantial impact on the power system, both directly and indirectly.

Several studies have explored the expansion of alternative mobility options, particularly focusing on their interactions with the power system. For instance, in [2] a cost-benefit analysis is conducted in Germany from 2015-2050 comparing FCEVs to ICEVs, accounting for various cost scenarios and H_2 production emissions. It concluded that CO2 prices in the range of 50-60 €/tCO2 in 2050 would make FCEVs an economically viable option. A life cycle analysis (LCA) for the EU comparing FCEVs, BEVs, ICEVs, hybrid electric vehicles (HEVs), and compressed natural gas (CNG) vehicles found that replacing ICEVs with BEVs could be both environmentally sound and economically profitable, particularly for short-range driving. For long-range driving, HEVs and CNG vehicles still presented better alternatives. In [3], the evolution of total cost of ownership (TCO) in the UK from 2010 to 2050 for various vehicle types (ICEV, BEV, FCEV, HEV, and CNG) is analyzed through a LCA that includes the costs of deploying the necessary energy and electricity infrastructures. To prevent overly optimistic projections where only the most profitable technology progresses, the study imposes predefined evolution paths on each technology. It suggests that for FCEVs to achieve significant market penetration by 2050, their deployment must have started by 2015 (noting that the study was published in 2015). The authors anticipate that by 2025, the costs of the various propulsion technologies will converge, provided that large-scale manufacturing begins by 2020. After 2025, however, they argue that uncertainties in market development and technological advancements will make it difficult to predict which technology will dominate. The work in [4], which is more closely related to the current study, examines the evolution of different mobility technologies in the EU from 2020 to 2050, with a focus on FCEVs. This study employs a soft-linking approach to simulate the evolution of the European power sector and model the behavior of key market agents (e.g., authorities, infrastructure providers, vehicle manufacturers, and users). It concludes that FCEVs could see significant growth by 2030, when green H_2 production may become more cost-competitive than grey H_2 (produced from natural gas). The study emphasizes the importance of energy policies to promote FCEVs, with a particular focus on research and development (R&D) until 2024, followed by direct subsidies for purchasing and refueling FCEVs and the development of necessary infrastructures. The forecast predicts an FCEV penetration of 26% in Europe by 2050 with active policies, compared to just 16% without such interventions. A non-linear behavioral model based on System Dynamics is used to simulate social and psychological factors influencing buyer decisions. However, the analysis of the power system is simplified with low-resolution representative periods and does not differentiate between vehicle fleets with varying usage patterns.

This paper expands the CEVESA model [5] by incorporating FCEVs into its assessment of mobility alternatives (FCEV, BEV, ICEV) in Spain and Portugal. CEVESA links transport with the Iberian electricity market, analyzing vehicle fleets, charging strategies, and H2 demand from electrolysis. The study evaluates potential power system impacts and alignment with EU decarbonization goals through case studies. The next section details the updated model, followed by case studies in Section III and conclusions in Section IV.

II. PROPOSED MIXED LINEAR INTEGER MODEL

This section presents the proposed model formulation, in where Capital and Greek letters denote parameters, while lowercase letters represent variables.

A. Main assumptions

(i) A centralized cost-minimization approach optimizes power and transport costs, including fuel, maintenance, and investment.

(ii) Only electrolytic H_2 is considered, with one electrolyzer and storage system per price zone. H_2 costs vary by production time and can be consumed or stored.

(iii) H_2 demand includes external uses and FCEV consumption.

(iv) Electrolyzers are reversible, enabling electricity generation from stored H_2.

(v) Mobility options include ICEVs, BEVs, and FCEVs, with optimized vehicle shares.

(vi) All FCEVs have the same tank capacity and consumption, with fixed quantity refueling.

(vii) H_2 storage costs are explicitly modeled, while ICEV fuel storage costs are included in fuel prices.

B. *Objective function*

CEVESA employs a multi-annual simulation horizon to minimize system costs, comprising power sector costs ($cg_{a,z}$), H_2 sector costs ($ch_{a,z}$) and transport sector costs ($ct_{a,z}$):

$$\min \sum_{a,z} \left(cg_{a,z} + ch_{a,z} + ct_{a,z} \right) \tag{1}$$

where a is the index for years and z the zones index.

<u>*Power sector costs*</u> *($cg_{a,z}$):* include variable, start-up, shutdown, emission, and maintenance costs of the generation plants, as detailed in [6], [7] and [8].

<u>*Hydrogen sector costs*</u> *($ch_{a,z}$):* include electrolyser variable costs for both H_2 production and storage:

$$\sum_{h} \left(CH^{VAR}_{a,z} \cdot CHG \cdot h_{h,a,z} + CH^{STO}_{a,z} \cdot sh_{h,a,z} \right) \tag{2}$$

where h is the index for hours, CHG the electricity-to-H_2 conversion rate [tonH$_2$/GWh], $CH^{VAR}_{a,z}$ the electrolyser variable cost [€/MWh] and $CH^{STO}_{a,z}$ the H_2 storage cost [€/tonH$_2$]. The last two are multiplied by the H_2 produced ($h_{h,a,z}$ [tonH$_2$]), and the H_2 stored ($sh_{h,a,z}$ [tonH$_2$]), respectively.

<u>*Transport sector costs*</u> *(ct)*: include the ICEV fossil energy costs for traction, associated emission costs, investment in new vehicles, and maintenance of the existing fleets (similarly to equation (2) of [9]). The vehicle types considered are CEV, BEV and FCEV, indexed by t, while different vehicle fleets are indexed by f:

$$\sum_{h,f} CT^{'ICEV'}_{h,a,f,z} \cdot c_{a,f,z,'ICEV'} + \sum_{f,t} \left(CT^{INV}_{a,t} \cdot nc_{a,f,z,t} + CT^{MNT}_{a,t} \cdot c_{a,f,z,t} \right. \tag{3}$$

- $CT^{'ICEV'}_{h,f,a,z} = \left(CT^{COMB}_{a,z} + C^{E}_{a,z} \cdot E_{f,z} \right) \cdot KM_{h,f,z,'ICEV'} \cdot CON_{a,'ICEV'}$ is the ICEV variable energy cost [€/Kunits].
- $CT^{COMB}_{a,z}$ is the fuel cost [€/L], $C^{E}_{a,z}$ is the CO_2 emissions cost [€/ton CO_2], $E_{f,z}$ represents CO_2 emissions [ton CO_2/L].
- $KM_{h,f,z,'ICEV'}$ is the distance travelled [km] and $CON_{a,'ICEV'}$ is the fuel consumption [L/km].
- $CT^{INV}_{a,t}$ and $CT^{MNT}_{a,t}$ denote investment and maintenance costs [€/Kunits], respectively.
- $c_{a,f,z,t}$ represents the number of vehicles [Kunits], while $nc_{a,f,z,t}$ corresponds to new vehicles [Kunits].

C. *Linking sectors constraints*

Equation (4) links the H_2 produced ($h_{h,a,z}$) to the electricity of the electrolyzer ($deh_{h,a,z}$ [MWh]), considering efficiency $\alpha H_{a,z}$ [%]:

$$deh_{h,a,z} = \frac{h_{h,a,z}}{\alpha H_{a,z}} \cdot CHG \tag{4}$$

The term $deh_{h,a,z}$ must be included as an additional electricity demand in the electricity balance equation (2) of [6]. Equation (5) ensures that H_2 demand (right-hand side) can be met either directly from the electrolyser ($h^{h2}_{h,a,z}$ [tonH$_2$]) or from the H_2 previously stored ($sh^{H2}_{h,a,z}$ [tonH$_2$]):

$$h^{h2}_{h,a,z} + sh^{H2}_{h,a,z} \cdot CHG \cdot \alpha H^{STO}_{a,z} = dt_{h,a,z} + DH_{h,a,z} \tag{5}$$

where $dt_{h,a,z}$ represents FCEV H_2 demand [tonH$_2$], $DH_{h,a,z}$ the non-mobility H_2 demand [tonH$_2$] and $\alpha H^{STO}_{a,z}$ the H_2 storage efficiency [%]. Equation (6) limits total CO_2 emissions in accordance with the EU maximum threshold $GHG^{M}_{a,z}$ [tonCO$_2$] from [10]:

$$\sum_{h} eg_{h,a,z} + \sum_{h,f} \left\{ c_{a,f,z,'ICEV'} \cdot E^{'ICEV'}_{h,a,f,z} \right\} \leq GHG^{M}_{a,z} \tag{6}$$

where $eg_{h,a,z}$ [tonCO$_2$] represents CO_2 power sector emissions (see equation (10) of [6]), and $E^{'ICEV'}_{h,a,f,z} = CON_{a,'ICEV'} \cdot E_{f,z} \cdot KM_{h,f,z,'ICEV'}$ is the hourly ICEVs CO_2 emission. Finally, the interzone network constraints are defined as in [11].

D. *Remaining constraints*

<u>*Electricity sector*</u>: power systems constraints, BEV operation, can be found in equations (3)-(37) of [6] and further explained in [8].

<u>*Hydrogen sector*</u>: equation (7) ensures that the H_2 produced ($h_{h,a,z}$) matches the demand and storage:

$$h_{h,a,z} = h^{H2}_{h,a,z} + h^{STO}_{h,a,z} \leq H^{M}_{a,z} \tag{7}$$

where $H^{M}_{a,z}$ is the electrolyser capacity [tonH$_2$]. Equation (8) keeps track of the H_2 stored $sh_{h,a,z}$ [tonH$_2$] considering the stored H_2 $sh^{H2}_{h,a,z}$ [tonH$_2$] that satisfy the H_2 demand and the stored H_2 $sh^{ELE}_{h,a,z}$ [tonH$_2$] used by the electrolyser to produce electricity (when running in reverse mode):

$$sh_{h,a,z} = sh_{h-1,a,z} + h^{STO}_{h,a,z} \cdot \alpha H^{STO}_{a,z} - \frac{sh^{H2}_{h,a,z}}{\alpha H^{STO}_{a,z}} - \frac{sh^{ELE}_{h,a,z}}{\alpha H^{STO}_{a,z}} \leq SH^{M}_{a,z} \tag{8}$$

where $SH^{M}_{a,z}$ is the H_2 storage capacity [tonH$_2$].

<u>*Transport sector*</u>: Similarly to equation (4) of [9], equation (9) counts the number of vehicles, considering current ($c_{a,f,z,t}$) and new ($nc_{a,f,z,t}$) vehicles and those decommissioned:

$$c_{a,f,z,t} = c_{a-1,f,z,t} + nc_{a,f,z,t} - I_{a \leq LS_{f,t}} \cdot \frac{C^{I}_{f,z,t}}{LS_{f,t}} - I_{a > LS_{f,t}} \cdot nc_{a-LS_{f,t},f,z,t} \tag{9}$$

where I_A is the indicator mathematical function, $LS_{f,t}$ the vehicles lifespan [years] and $C^{I}_{f,z,t}$ the initial number of vehicles [Kunits]. Equation (10) imposes the number of vehicles growth:

$$\sum_{t} car_{a,f,z,t} \geq (1 + GR_a) \cdot \sum_{t} car_{a-1,f,z,t} \tag{10}$$

where GR_a is the inter-year growth rate of vehicles [%].

<u>*FCEV transport:*</u> FCEV Boolean refuelling decision $r_{h,a,f,z}$ is computed as:

$$r_{h,a,f,z} = \begin{cases} 0, & if \;\; t_{h-1,a,f,z} > T_a^m \\ 1, & if \;\; t_{h-1,a,f,z} \leq T_a^m \end{cases} \tag{11}$$

where $t_{h,a,f,z}$ [kgH$_2$] is the H$_2$ stored in the FCEV tank and parameter T_a^m [kgH$_2$] the FCEV H$_2$ reserve tank. Logical implications in (11) are transformed into the next linear constraints:

$$\begin{gathered} t_{h-1,a,f,z} - T_a^m \leq \left(1 - r_{h,a,f,z}\right) \cdot T_a^M \\ t_{h-1,a,f,z} + \varepsilon - T_a^m \geq r_{h,a,f,z} \cdot (-T_a^m) \end{gathered} \tag{12}$$

Where ε is a very small positive parameter and T_a^M [kg H$_2$] the FCEV H$_2$ tank capacity [kg H$_2$]. Equation (13) keeps track of the tank level:

$$t_{h,a,f,z} = \begin{cases} t_{h-1,a,f,z} - CON_{h,f,z,a}^{'FCEV'}, if \;\; r_{h,a,f,z} = 0 \\ t_{h-1,a,f,z} - CON_{h,f,z,a}^{'FCEV'} + (T_a^M - T_a^m), if \;\; r_{h,a,f,z} = 1 \end{cases} \tag{13}$$

where $CON_{h,f,z,a}^{'FCEV'} = CON_{a,'FCEV'} \cdot KM_{h,f,z,'FCEV'}$ is the hourly FCEV H$_2$ consumption. Implications in (13) are equivalent to the next linear constraints:

$$\begin{aligned} -r_{h,a,f,z} \cdot T_a^M \leq t_{h,a,f,z} - t_{h-1,a,f,z} + CON_{h,f,z,a}^{'FCEV'} \\ \leq r_{h,a,f,z} \cdot T_a^M \\ -\left(1 - r_{h,a,f,z}\right) \cdot T_a^M \\ \leq t_{h,a,f,z} - t_{h-1,a,f,z} - (T_a^M - T_a^m) \\ + CON_{h,f,z,a}^{'FCEV'} \leq \left(1 - r_{h,a,f,z}\right) \cdot T_a^M \end{aligned} \tag{14}$$

Equation (15) defines the H$_2$ consumed by all FCEV fleets (included as H$_2$ demand in the balance equation in (5)):

$$dt_{h,a,z} = \sum_f dt_{h,a,f,z} \tag{15}$$

The H$_2$ demand per fleet is computed in (16) as a function of $r_{h,a,f,z}$:

$$dt_{h,a,f,z} = \begin{cases} 0 & if \;\; r_{h,a,f,z} = 0 \\ c_{a,f,z,'FCEV'} \cdot (T_a^M - T_a^m) & if \;\; r_{h,a,f,z} = 1 \end{cases} \tag{16}$$

The above implications are equivalent to the next linear constraints:

$$\begin{gathered} dt_{h,a,f,z} \leq r_{h,a,f,z} \cdot T_a^M \\ -\left(1 - r_{h,a,f,z}\right) \cdot T_a^M \leq dt_{h,a,f,z} - c_{a,f,z,'FCEV'} \cdot (T_a^M - T_a^m) \\ \leq \left(1 - r_{h,a,f,z}\right) \cdot T_a^M \end{gathered} \tag{17}$$

<u>*BEV transport*</u>: As mentioned, equations (3)-(37) of [6] includes the BEV operation constraints.

III. CASES STUDY

A. Inputs and assumptions

The study considers a time horizon from 2022 to 2045, using a representative week per year to reduce computation time [12]. No new generation capacity is added beyond the NECP plans, though secondary reserve operations are included. Spain-Portugal interconnection capacity evolves per NECP projections. The Spanish and Portuguese power systems are calibrated with data from [11] and [13]. Electrolyzer efficiency improves linearly from 61.6% in 2022 to 72.5% in 2045. ICEV, BEV, and FCEV usage patterns follow [8], with additional data from [8] and [9] refined in this study. FCEV capital costs are assumed to drop 70% from 2019 levels [13], while BEVs are cheaper due to simpler manufacturing, reaching ICEV cost parity post-2030 ([14] suggests 2027). Maintenance costs follow [9] and [15], with FCEVs 12% higher than BEVs due to greater manufacturing complexity. ICEV operating costs, fuel prices, and consumption rely on historical data ([8], [11], [17]). FCEV maturity improves post-2035, stabilizing consumption at 0.73 kg/100 km by 2045. Tank capacities, including 100 km reserves, are estimated from commercial FCEVs [16]. The total number of vehicles is an exogenous variable updated with [18], and vehicle replacement, with a lifespan of 12 years, follows [9] and [17].

B. Scenarios

Three scenarios are analysed, departing from a base case, to assess the model behaviour and compute the expansion paths of the mobility alternatives.

<u>EMP scenario</u>: a raw material shortage that significantly increases batteries and vehicle prices. Based on [18] and [19], Figure 1 shows the vehicle price *CT*^{INV} evolutions assumed.

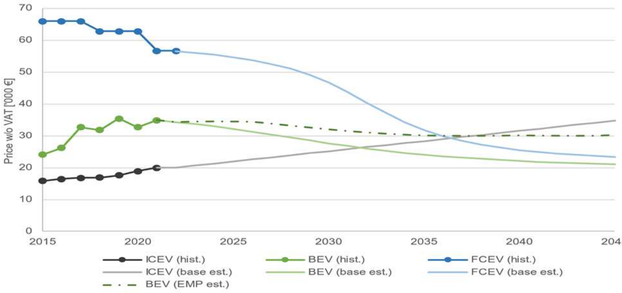

Figure 1: Vehicle price evolution for EMP scenario

<u>DTH scenario</u>: late development of H$_2$ refuelling stations, modelled by delaying two years the FCEV price reduction compared to the base scenario, see Figure 2.

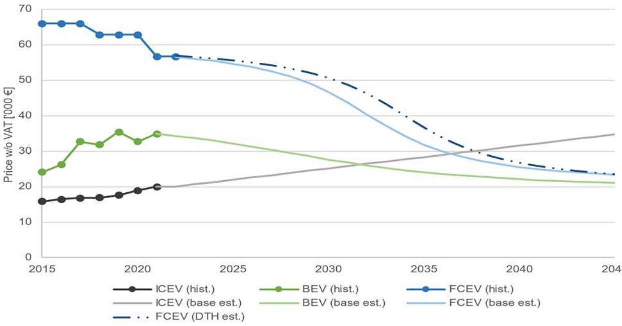

Figure 2: Vehicle price evolution for the DTH scenario

<u>EMP+DTH scenario</u>: combines both previous scenarios, increasing BEV cost and delaying FCEV price decrement.

C. Simulation, results and discussion

Figure 3 show the evolution of the number of vehicles per type for Spain (similar behaviour is obtained for Portugal) for each scenario. Each type of vehicle is represented with identical chart symbols, the symbols identifying the scenarios, and the base scenario being the shaded regions.

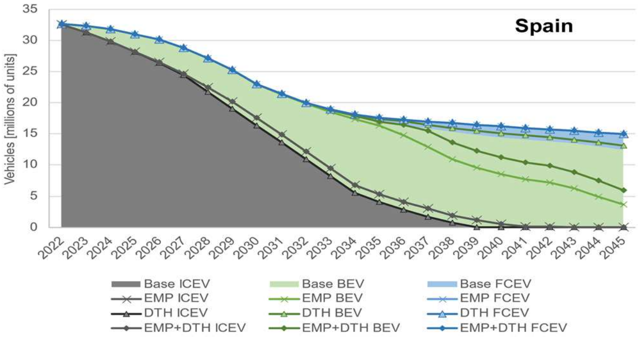

Figure 3: Evolution of the vehicle fleet in Spain

As can be seen, in the base scenario, BEV increase at a fast rate (reaching a share of 90% by 2040), while FCEV only start to be significant after 2037 (reaching a market share of 15% by 2045), partially displacing BEV. Indeed, the number of ICEV decreases rapidly between 2022 and 2039 in all scenarios due to: (i) the EU vehicle emissions norms assumed in this study [1]; (ii) the ICEV fuel cost from [20]; (iii) the increasing cost of CO_2 emissions from [21]; (iv) and the higher ICEV maintenance costs from [15]. However, the share between BEV and FCEV depends on the scenario. For example, after 2036, EMP is the worst scenario for BEV, which takes two additional years to fully replace ICEV (with a maximum penetration of 66% while in the base scenario its share was 90% by 2039). Indeed, higher BEV prices make FCEV a convenient alternative sooner, by 2036, reaching a large share (of 75%) by 2045. These signals show that acquisition prices are a dominant variable regarding vehicle adoption. The DTH scenario, as anticipated, results in a significantly lower growth in the share of FCEVs culminating in a reduced share of FCEVs by the end of the period. Finally, the EMP+DTH scenario reflects combined effects, leading to lower shares of both BEVs and FCEVs compared to the base case. However, despite this, the competitive pricing of BEVs enables FCEVs to emerge as the most cost-effective option starting in 2038 (reaching a market share of approximately 60% by 2045).

Figure 4 shows the CO_2 emissions evolution in the Spanish transport sector (similar behavior observed in Portugal).

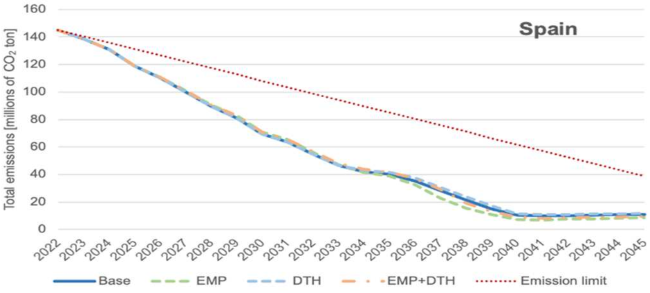

Figure 4: Spanish transport sector CO_2 emissions evolution

CO2 emissions decrease by about 50% by 2030 and 90% by 2040 across all scenarios, driven by the near-complete replacement of ICEVs (close to 100% in 2022) with FCEVs and BEVs by the end of the period. However, the remaining 10% of emissions indicate that the few ICEVs still in use are highly polluting, likely retained due to their unmatched range compared to alternative technologies.

Figure 5 shows power system's CO_2 emissions evolution.

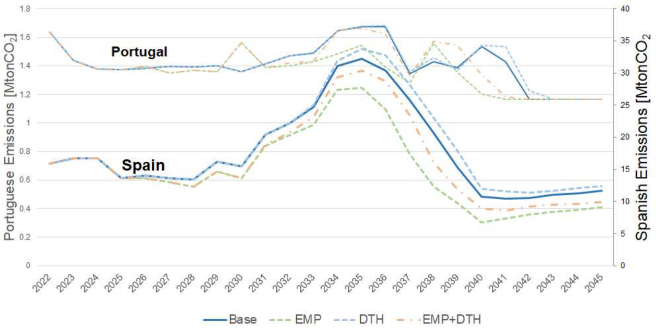

Figure 5: Power system CO_2 emissions evolution

Significant differences between Portugal and Spain arise from their distinct energy mixes, projected evolution [21], and varying vehicle ownership rates (0.527 cars/person in Portugal vs. 0.689 in Spain, [22] [23]). Portugal, with a higher share of renewable generation (RG), maintains more stable CO_2 emissions, which, by the end of the period, are primarily from combined cycle (CC) plants running to provide secondary reserve. In contrast, Spain experiences a sharp rise in emissions around 2030 due to extensive electrification, not fully offset by RG until 2036, when additional RG capacity reduces CC plant utilization. By 2040, virtually all ICEVs have been replaced, eliminating their contribution to emissions. Any slight increase in emissions beyond 2040 is attributed to the electrification of other energy uses, as outlined in the NECP. Notably, the EMP scenario achieves lower emissions due to an earlier replacement of ICEVs and a higher share of FCEVs. The greater production and H_2 storage in this scenario provide increased system flexibility, helping to balance electricity demand and further reduce emissions compared to BEVs.

Figure 6 shows electricity prices' evolution for Portugal (until 2041 prices in Spain and Portugal remain similar).

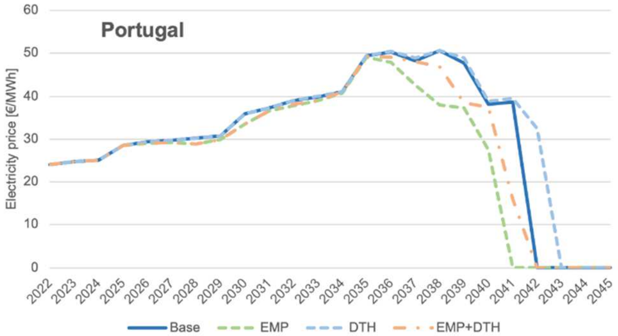

Figure 6: Electricity price evolution in Portugal

From 2042 onwards, the more widespread penetration of RG in Portugal reduces electricity prices provoking market splitting (Spain's prices remain comparatively higher). While wholesale electricity prices in Portugal reach zero by the end of the period, CO2 emissions persist due to CC plants operating to meet secondary reserve requirements. It is important to note that these price trends are based on the initial NECP assumptions from [21], which predate the Ukrainian war and gas crises.

CONCLUSIONS

This paper introduces two enhancements to the CEVESA market model. The first improves the H_2 economy model by incorporating H_2 storage, its impact on power generation capacity and electricity prices, and its flexibility. The second refines the mobility model to analyse the joint evolution of fuel cell (FCEVs), battery (BEVs), and combustion (ICEVs) vehicles, including their effects on electricity demand. Despite uncertainties inherent in such analyses, the simulations yielded results consistent with existing literature, validating the modelling improvements and scenario assumptions. The findings suggest that if FCEVs technology matures, it could rival BEVs, offering greater system flexibility via electrolyzers and extended driving ranges for users. However, the hydrogen economy remains contentious due to inefficiencies and the challenges of hydrogen handling, which were not addressed here. The work shows that achieving zero emissions is not feasible, as combined cycle power plants are still needed to provide secondary reserves. Therefore, it would be necessary for electric vehicles, for example, to provide these secondary services.

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