

The role of demand and vRES flexibility in carbon-neutral power systems: Insights from Portugal and Spain in prospective 2050 scenarios

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Abstract— The goal of a carbon-neutral society by 2050 is speeding up the integration of variable renewable energy sources (vRES) in European power systems. For the expected levels of vRES, the adaptation of the demand will be crucial to manage the stochastic behaviour of these technologies. This work evaluates the impact of four prospective 2050 energy mix scenarios in the Iberian electricity market. All scenarios consider near 100% vRES shares. Scenarios that incentivize demand flexibility (S2 and S4) result in the lowest wholesale prices and costs for society. Peak load reduction using demand response occurred in the two scenarios (S1 and S3) with low demand flexibility and high share of renewable generation. S3 is the most unstable leading to the higher wholesale prices. The results highlight that an equilibrium between demand flexibility and investments in the generation side is essential for reducing costs and ensuring stability.

Keywords— Active demand, Carbon-neutrality, Electrification, Flexibility, Variable renewable energy sources, Wholesale prices.

I. INTRODUCTION

The participation of vRES in power systems has been increasing to accomplish the target of a carbon-neutral society by 2050. Indeed, some European countries already plan to be carbon-neutral by 2035. Portugal and Spain's National Energy and Climate Plans for 2030 (NECPs) already expect vRES, mainly onshore wind and solar photovoltaic (PV), as the main energy providers by 2030 [1-3]. So, their power sector will be mostly satisfied by renewable energy sources (RES). However, the power sector is only a small component of the used energy. Electrification of industry and transport sectors is important to achieve carbon neutrality, as reported in 2030 NECPs. Furthermore, sector coupling with the heat sector and replacing gas by hydrogen (H₂) can be another important aspect to achieve carbon neutrality, reduce external energy dependency, and adjust to vRES production [4-6]. For large-scale integration of vRES, their stochastic behaviour and reduced dispatchability will need the adaptation of the demand to avoid vRES curtailments and load shedding events. Against this

background, demand and vRES flexibility is the key to future carbon-neutral, stable, and affordable energy systems by 2050. So, decarbonisation and sector coupling shall be supported by measures that incentivize demand and vRES flexibility, such as new market designs [7-10].

Traditional electricity markets, primarily developed during an era dominated by fully dispatchable conventional power technologies, operate on a marginal-cost pricing model to efficiently allocate resources, incentivize technological investments and minimize costs [11]. However, this market mechanism becomes ineffective in power systems with high shares of vRES with low marginal costs. Despite the environmental advantages of large-scale vRES integration, their inherent variability can lead to periods with excess energy in the market, driving electricity prices to zero or even negative values, based on the "merit order effect" [9-12]. While this price reduction benefits consumers, at certain vRES penetration levels, it also diminishes the market-based remuneration of (all) power producers, a challenge commonly referred to as the "self-cannibalization effect" [12]. This, in turn, reduces incentives for investment in new capacity, potentially hindering the ambitious RES targets for the coming decades in Europe. Conversely, when demand is high and vRES generation is low, energy prices highly increase. Unexpected events, such as the European energy crisis, have further amplified price volatility, raising significant concerns regarding the existing market design, investment risks/de-risking, and consumer protection [13, 14]. Against this background, this work uses an integrated daily trading framework combining different tools to simulate four different prospective 2050 scenarios in the Iberian electricity market (MIBEL). Each scenario assumes different assumptions on the demand flexibility and power generation. The Iberian electricity market (MIBEL). Some changes to actual market designs and rules to better integrate vRES and demand flexibility are proposed in the simulation framework.

$$Bid_{(sce,tec,unit,p,d,m)}^{volume} = \begin{cases} \frac{Bid_{(tec,unit,p,d,m)}^{volume}}{\sum_{unit=1}^{Nunit} (Bid_{(tec,unit,p,d,m)}^{volume})} \times Volume_{(tec,p,d,m)}^{sce} & \text{if } \in \text{unit} \\ \frac{Capacity_{(tec,unit)}^{sce}}{\sum_{unit=1}^{Nunit} (Capacity_{(tec,unit)}^{sce})} \times Volume_{(tec,p,d,m)}^{sce} & \text{if } \notin \text{unit} \end{cases} \quad (1)$$

$$\forall sce \in N_{sce}, \forall unit \in N_{unit}, \forall p \in N_p, \forall d \in N_d, \forall m \in N_m$$

carbon-neutral power systems by 2050. The installed capacities in the four scenarios are obtained using the open-access optimization tool Backbone [15] based on 2030 NECPs and vRES potentials for Portugal and Spain. The OptiRES.Lines tool is used to obtain hourly dynamic line rating (DLR) values of the cross-border tie-lines connecting Portugal and Spain [16]. The Multi-Agent Simulators of Competitive Electricity Markets (MASCEM) [17] is used to simulate the day-ahead and continuous intraday markets. The open-access version of the Multi-agent Trading of Renewable Production (RES.Trade) [18] simulator is used to compute the outputs of balancing markets and the imbalance settlement.

II. METHODOLOGY

The simulators Backbone, MASCEM, RES.Trade, and OptiRES.Lines are used to simulate future energy scenarios [15-18]. The last three models integrate a *daily trading framework*, Fig. 1.

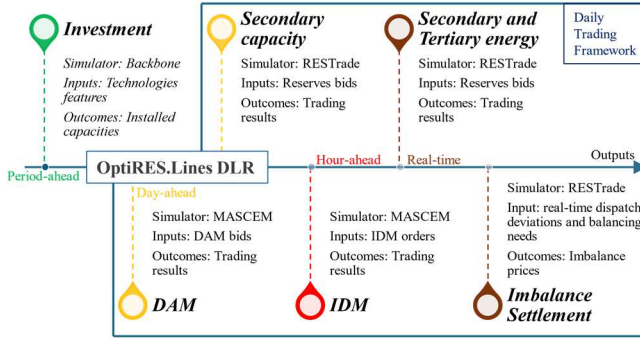


Figure 1: Workflow of the steps and models to simulate the future carbon-neutral scenarios analysed in this work.

The OptiRES.Lines models and tool identifies market splitting events caused by overhead power line congestion, applying the CIGRÉ 601 DLR methodology [16,19].

Backbone optimizes the generation capacity for each country or market zone by considering technology capacity limits and expected variable and fixed costs, consumption estimates, and the DLR of tie-lines. Its primary objective is to minimize the total power system costs over a given period, including investment, operational, and maintenance expenses [16]. Based on the capacities defined by Backbone, hourly bids are calculated to support the near real-time market mechanisms illustrated in the boxed workflow of Fig.1

MASCEM simulates the main market entities and their interactions, representing them as software agents including buyer and seller agents (e.g., consumers, producers, and prosumers), aggregator agents, and market and system operators. It supports the simulation of three key European electricity markets (EM): MIBEL's day-ahead market, the auction-based intraday market, and the continuous intraday

market, as well as both double-sided (symmetrical pool) and single-sided (asymmetrical pool) auction models [17].

RES.Trade models traditional power and energy reserve markets, enabling the participation of conventional dispatchable power plants, vRES, and demand-side players to maintain system balance. Additionally, it incorporates newly designed models for balancing markets and imbalance settlement in alignment with new European legislation [7, 20]. These improvements focus on i) separate procurement, ii) marginal pricing, iii) non-discriminatory access, and iv) equitable cost distribution to enhance market efficiency [18].

A. Bids generation for the DAM and the continuous IDM

Significant effort was dedicated to generating DAM bids with highly realistic input data, considering existing market participants, their units, and associated technologies. The mathematical formulation for the bid generator, specifically regarding the energy volume distribution, is presented in (1). Where, *sce* identifies the scenario, *Nsce* is the total number of scenarios, *tec* identifies the technology, *unit* identifies the player's unit, *Nunit* is the total number of units, *p* identifies the trading period, *Np* is the total number of periods, *d* identifies the day, *Nd* is the total number of days, *m* identifies the month, *Nm* is the number of months, $Bid_{(sce,tec,unit,p,d,m)}^{volume}$ represents the bid's energy volume per scenario, technology, unit, period, day, and month, $Bid_{(tec,unit,p,d,m)}^{volume}$ represents the bid's energy volume executed in a previous period per scenario, technology, unit, period, day, and month, $Volume_{(tec,p,d,m)}^{sce}$ represents the scenario's total energy volume available per technology, period, day, and month, and $Capacity_{(tec,unit)}^{sce}$ represents the scenario's capacity per technology and unit.

If a unit already exists and participates in the market, its bidding volume for a given scenario is determined based on its bidding volume ratio. For newly added units, the bidding volume is calculated according to the unit's capacity ratio within the respective technology. Additionally, vRES-based units are incorporated, with specific energy volume forecasts for each trading period, day, and month. Considering that in the future vRES may participate in balancing markets (BMs), the implemented strategy in this work assumes that they bid 80% of their forecasted energy volume, reserving the remaining 20% for BM participation. Bid prices are based on the marginal cost of the respective technology or the social value of water. The use of water values reflects the behaviour of market participants utilizing hydroelectric with reservoir technology, allowing strategic bidding based on water abundance or scarcity in reservoirs [21]. When reservoir levels exceed 50%, the social value of water positions this technology ahead of other dispatchable renewable generation in the market merit order.

Moreover, hydroelectric plants can displace nuclear power plants from the market when reservoir levels exceed 90%. Conversely, as a last resort to avoid forced load shedding, hydroelectric plants are only dispatched after demand-side response measures when reservoir levels fall below 10%.

For the generation of IDM orders, the process considers the untraded volumes from the DAM, updated forecasts for vRES units, and the exclusion of units allocated to secondary reserves.

B. Bids generation for the balancing markets

Power bids to the secondary reserve are determined based on the programmed dispatch from the DAM and the available capacity of each fast-response power plant. According to the defined strategy, vRES submits bids for 20% of their expected deterministic power forecast for upward regulation and their programmed dispatch from the DAM for down-regulation. The upward regulation value is set considering the high likelihood of real-time dispatch for vRES. Energy bids for the secondary reserve are based on the clearing bids from the secondary power market, while price bids are determined using the outputs of the DAM and the marginal costs of the power plants. Any bids not cleared in the secondary market are transferred to the tertiary reserve market. The tertiary market includes also the bids from participants whose technical capabilities restrict them from participating in this market. Finally, bids for the tertiary energy market are finalized after clearing the IDM.

III. CASE STUDY AND RESULTS

This case study focuses on evaluating the impact of four future 2050 scenarios in the Iberian countries, each characterized by varying levels of RES and demand flexibility: S1: conservative, S2: flexible, S3 variable, and S4: radical. Scenarios S1 and S2 assume a minimum RES share of 85% in the consumption, with the remaining energy demand met by nuclear power plants. In the case of scenarios S3 and S4, the RES share increases to 95%. The level of sector coupling is determined by H2 prices, with higher prices making domestic production more economically attractive. Scenarios S1 and S3 assume a H2 price of 45 €/MWh, while S2 and S4 consider a H2 price of 117 €/MWh. It was considered 2019 as the most recent typical meteorological year to obtain the vRES and inflexible demand time series, computing the water values of Portugal and Spain. Furthermore, has been considered the bids of 2022 to calibrate the bid generation for 2050 [22].

A. Market design assumptions

By 2050, it is assumed that electricity markets design has evolved to better integrate vRES generation and demand flexibility. Leveraging the high level of harmonization across Europe, the current market design of the European single day-ahead coupling market was used. For the pan-European continuous single intraday coupling (SIDC) model, simulated with the MASCEM, was addressed the low liquidity for vRES caused by their tendency to bid closer to the end of each session to minimize large power forecast errors. Continuous bidding but not trading was implemented, with market clearing occurring at the end of each session to prioritize vRES, using the SIDC pay-as-bid scheme [23]. Cross-border power flow

validation and market splitting detection, accounting for overhead power line congestion, were conducted using a DLR approach, simulated with the OptiRES.Lines tool. The designs of the Portuguese and Spanish secondary reserves were adapted to align with future needs, incorporating the separate procurement of upward and downward power while allowing vRES participation. This reserve was modelled and implemented in the RES.Trade simulator based on the European Network of Transmission System Operators for Electricity (ENTSO-E) guidelines for power procurement [24]. The participation of vRES in tertiary reserves was also enabled. Additionally, the Portuguese imbalance settlement mechanism was applied to both countries. This mechanism distributes all balancing costs equally among the balance responsible parties (BRPs), regardless of the balance direction.

B. Optimal generation capacity in Portugal and Spain

The generation capacity of each country was optimized using the Backbone approach within the scope of the European-funded TradeRES [25]. The optimisation considers as baseline the RES capacities established in 2030 NECPs, forecasts for the expected variable and fixed costs of technologies, and projected consumption in 2050. The input data used by Backbone 2050 simulations and the features of the scenarios can be found in [25]. However, the simulation is limited by only considering H2 trades between neighbouring countries. The optimal power system for each scenario was identified at a European level, although, in this work, the focus will be on the generation capacities of Portugal and Spain, presented in Fig. 2. It also presents the results from the 2030 scenario obtained in TradeRES to help understanding changes in the energy mix.

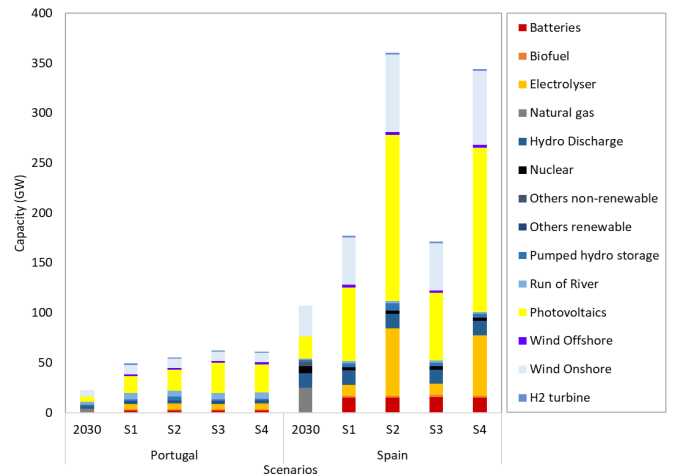


Figure 2: Installed capacity by technology in Portugal and Spain per scenario.

From Fig. 2, it can be concluded that with the electrification of the demand, there will be a need for high investments in vRES and storage technologies towards carbon-neutrality. In scenarios S2 and S4, higher H2 export prices drive significant investments in additional vRES and electrolysers, particularly, in Spain. Conversely, in Portugal, this effect in S2 and S4 scenarios is not observed due to the Backbone's limitation in what concerns the H2 trading of Portugal exclusively with

Spain. By using Backbone and considering marginal production prices, the optimal dispatch of each technology can be determined, along with estimations of wholesale electricity costs and cross-border flows. These values reflect the optimal dispatch, excluding forecast errors or the strategic behaviour of market participants, which are analysed in the next section.

C. Carbon-neutrality and security of supply

This section presents the results of the 2050 scenarios, using the *daily trading framework*. Fig. 3 presents the share of RES in the electricity consumption.

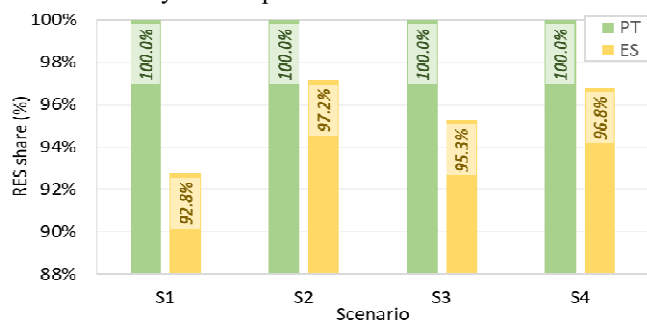


Figure 3: Integration of RES in electricity consumption.

Analysing Fig. 3, it can be observed that in Portugal, all electricity generation to meet consumption is based on RES. In Spain, however, nuclear generation is still utilized, resulting in a RES share of final consumption ranging from 92.8% (S1) to 97.2% (S2). Scenarios with greater flexibility from demand (S2 and S4) lead to a higher RES share, as demand partly adjusts to consume energy during cheaper periods associated with high shares of vRES production. Fig. 4 presents the annual forced curtailment of market-based energy from vRES.

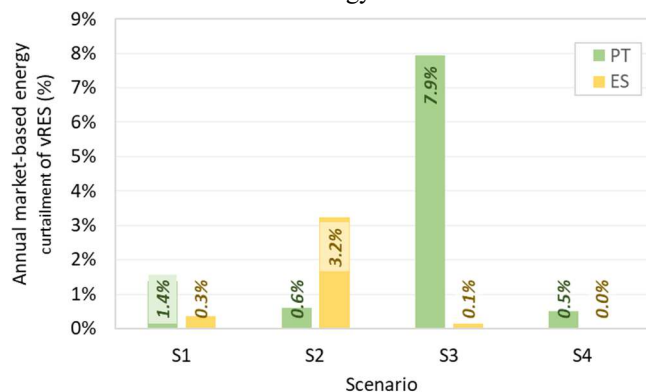


Figure 4: Percentage of annual vRES forced energy curtailments.

Analysing Fig. 4, it can be concluded that forced curtailments are almost non-existent, except in Portugal in the S3 scenario, where there is high vRES investment but low demand-side flexibility. This highlights that the demand flexibility is insufficient to accommodate all vRES generation. Programmed curtailments of vRES are also noted due to their participation in balancing markets. Regarding security of supply, no load shedding events were identified. However, Fig. 5 illustrates the use of demand response measures to prevent such events from occurring.

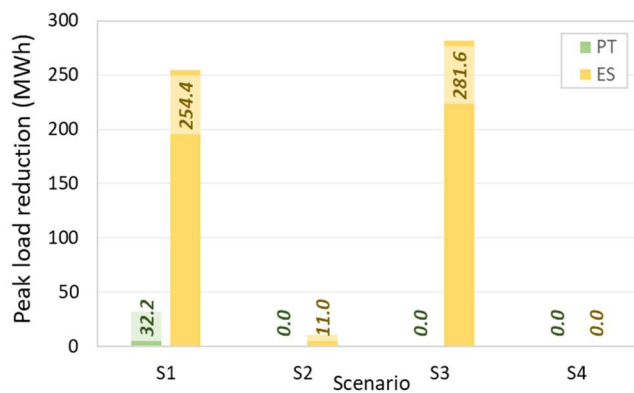


Figure 5: Peak load reduction for scenarios S1-S4.

Analysing Fig. 5 it is possible to conclude that peak load reduction by using demand response was observed in the two scenarios with lower demand flexibility: S1 and S3. From Fig. 4 and Fig. 5 it is possible to conclude that scenario S3 brings more challenges regarding to the energy balance and security of supply. While Portugal faces periods with excess of energy (see Fig. 4) Spain has periods with lack of energy (see Fig. 5). This occurs because Portugal and Spain have similar generation mixes and meteorological conditions. However, due to only exporting to Spain and low investment in storage, Portugal experiences excess/curtailed renewable energy in several periods. Contrariwise, Spain can also trade with France and has more storage assets, using its demand response contracts in the case of missing energy (see Fig. 5). Therefore, a centralized European H2 marketplace could be key to promoting more efficient investments in renewable generation and chemical storage across Europe.

D. System costs and market results

This section presents the total (fixed and variable) costs for society, the average market costs and the MIBEL price convergence. Fig. 6 presents the costs for society.

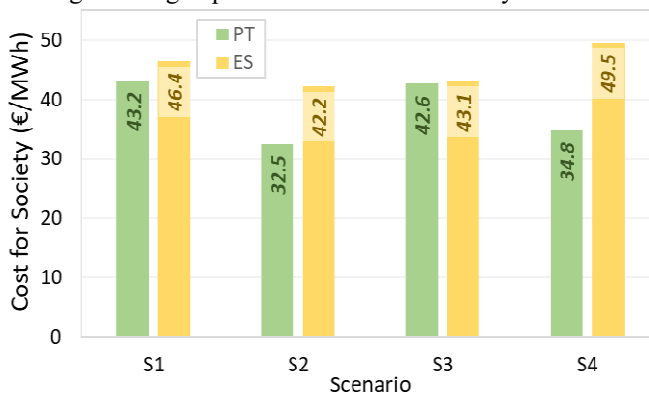


Figure 6: Costs for society of the power system

Analysing Fig. 6 it can be concluded that in Portugal, society's costs are significantly lower in the more flexible scenarios (S2 and S4). In these scenarios, despite the increased consumption observed in the electrolyzers and batteries, Portugal benefits from the significant vRES investments in

Spain, which allows to decrease wholesale prices (see Fig. 7). The investment costs in Portugal remain similar across all scenarios (see Fig. 2). In Spain, costs increase in scenario S4, but the rise is significantly lower than the H2 price. Therefore, the results from this scenario and scenario S2, the ones with the highest demand flexibility, suggest that exporting H2 could benefit society. In the optimal scenarios under analysis, Spain is one of the main H2 exporters, while Portugal only invested in H2 for internal energy balance. Fig. 7 presents the volume-weighted average day-ahead market prices (VWDAMP).

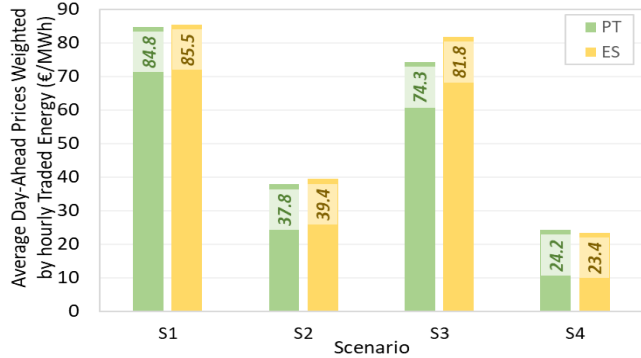


Figure 7: Volume-weighted average day-ahead market prices.

From Fig. 7, it can be concluded that the highest VWDAMP occurs in scenario S1, while the lowest is seen in scenario S4. As expected, scenarios S2 and S4 exhibit lower VWDAMPs due to the high level of sector coupling and demand-side flexibility. These lower prices are particularly relevant for future investments in electrolyzers to produce green H2.

Scenario S4 is the only one where Spain achieves a lower VWDAMP than Portugal, because of the significant investment in vRES. However, in S4 and S2, vRES cannot recover all their costs because the prices they receive are lower than the costs they impose on society (see Fig. 6). On the other hand, S1 and S3, which involve moderate levels of sector coupling and demand-side flexibility, lead to higher VWDAMPs. The results for scenarios S1 and S3 reflect the limited demand flexibility to adapt to vRES production, which increases the market-based cost recovery for technologies, but only some can recover their costs. Fig. 8 presents the price difference and the number of market splitting events between Portugal and Spain.

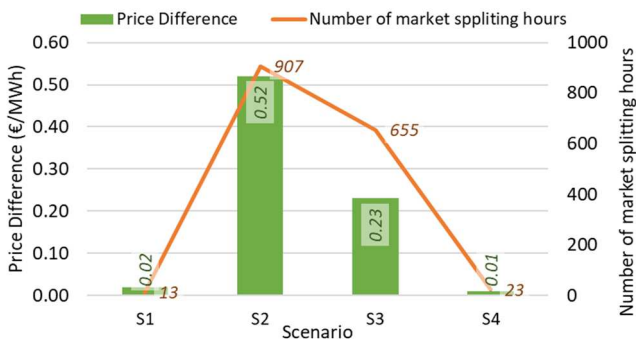


Figure 8: Price difference and market splitting events in MIBEL.

Observing Fig. 8, it is evident that the price difference is low across all scenarios throughout the year. The trend of price

convergence in these scenarios is influenced by the number of hours during the simulation's year in which market splitting occurred between Portugal and Spain. However, although Scenario S1 shows a slightly higher price difference than S4, the latter experiences ten additional hours of market splitting. This is attributed to the enhanced demand-side flexibility in Scenario S4, which allows for more effective integration of vRES. In contrast, Scenario S2 exhibits the highest frequency of events, primarily due to the substantial deployment of vRES without a proportional increase in storage capacity, thereby exacerbating system imbalances. The conservative S1 scenario is most comparable to the actual situation, exhibiting significantly fewer market splitting events.

IV. FINAL REMARKS

This work presented a simulation framework to assess the impact of demand flexibility in future power systems with high penetrations of variable renewable generation (vRES). The framework was applied to simulate the optimal technology capacities for Portugal and Spain by 2050 using the Backbone model. OptiRES.Lines was used to compute the day-ahead dynamic line ratings (DLR) for the cross-border lines connecting these countries. MASCEM was used to clear the Iberian day-ahead market and the continuous intraday market, considering the DLR. Subsequently, RES.Trade was employed to analyze the impact of the day-ahead and intraday dispatch programs on real-time balancing prices. Portugal and Spain both feature RES penetration in their power systems, exceeding 93% of total annual consumption by 2050, being the remaining consumption satisfied by nuclear power plants. The optimal capacities indicate that, for a hydrogen (H2) export price of 117 €/MWh, investments in vRES in both and storage in Spain nearly doubled compared to a H2 price of 45 €/MWh in scenarios with lower demand flexibility (S1 and S3). However, in Portugal, investments in chemical storage are similar in all scenarios, since the country is limited to trade only with Spain. Market results suggest that both countries need to align vRES investments with demand flexibility to mitigate market price volatility, and insufficient cost recovery through market mechanisms. As expected, higher demand flexibility results in greater consumer control over market prices, as observed in the low prices of the scenarios with high demand flexibility (S2 and S4). In contrast, scenarios S1 and S3, with lower demand flexibility, show higher market prices. In conclusion, despite some simplifications like the use of a non-optimized bidding strategy across different markets, this study emphasizes the crucial role of demand flexibility in future power systems and highlights the potential for Iberian countries to produce green H2 at competitive prices without overburdening society, which can also benefit from the decarbonisation of energy systems.

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