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RES.Trade: An Open-Access Simulator to Assess the Impact of Different Designs on Balancing Electricity Markets

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Abstract: The 2050 global ambition for a carbon-neutral society is increasing the penetration of the most competitive variable renewable technologies, onshore wind and solar PV. These technologies are known for their near-zero marginal costs but highly variable time-dependent generation. Power systems with major penetrations of variable generation need high balancing flexibility to guarantee their stability by maintaining the equilibrium between demand and supply. This work presents the open-access Multi-agent Trading of Renewable Energy Sources (RES.Trade) system, which includes different market designs of the imbalance settlement and the secondary and tertiary reserves. A new imbalance settlement is also proposed in this work. The main features of RES.Trade are demonstrated using two case studies and projected 2030 scenarios: the first analysed four imbalance settlement mechanisms in Portugal, achieving a 43% reduction in penalties using the new method; the second case study assesses the impact of five procurement mechanisms of secondary power reserves in the Spanish power system, resulting in a cost reduction by 34% in the case of dynamic reserves.

Keywords: balancing markets; imbalance settlement; secondary reserves; market design; RES.Trade; tertiary reserves; variable renewable energy sources

Citation: Algarvio, H.; Couto, A.; Estanqueiro, A. RES.Trade: An Open-Access Simulator to Assess the Impact of Different Designs on Balancing Electricity Markets. *Energies* **2024**, *17*, 6212. https://doi.org/10.3390/en17246212

Academic Editor: Jesús Manuel Riquelme-Santos

Received: 9 October 2024
Revised: 5 December 2024
Accepted: 6 December 2024
Published: 10 December 2024

1. Introduction

Global warming and the gas energy crisis speed up the European Union's investment in carbon-free technologies towards a carbon-neutral society [1–3]. Investments in increasing capacities of variable renewable energy sources (vRES) with near-zero marginal costs may lead to changes in electricity market (EM) designs that are currently dominated by dispatchable technologies [2–4]. Actual designs of EMs consider the day-ahead market (DAM) as the main market for wholesale physical transactions of electricity. In the European day-ahead coupled regions, the DAM closes at noon (CET-Central European Time), between 11 (CET + 1 h, e.g., Finland) and 37 (CET − 1 h, e.g., Portugal) hours before operating according to the time zone of each country [4–6]. The liberalisation of the power sector adopted this DAM design to adjust for dispatchable technologies with low ramp rates and, thus, a rather "long-term" planning of operational periods since the beginning of the competitive wholesale trading of electricity in the 80s [6,7]. Naturally, due to their variability, the day-ahead programming dispatches of vRES have high uncertainty, even when advanced forecasting models are involved [8]. To adjust their programming dispatches, vRES can use marginal real-time and intraday markets (IDMs) and continuous IDMs closing between 5 h and 15 min ahead of real-time operation to cover their expected deviations, respectively. However, these markets have low liquidity, which means that vRES may not trade all the energy required to balance themselves [4,5,9,10].

Power systems with large penetrations of vRES generation need high balancing flexibility to guarantee their stability by maintaining the equilibrium between demand and supply. In Europe, primary and secondary power reserves are used for real-time balancing for a maximum of 15 min. Normally, while the participation of all technically capable technologies is mandatory in primary reserves, secondary reserves are procured based on a deterministic approach and, in most areas of control, without considering the behaviour of variable generation [5,11,12]. Therefore, a more dynamic and holistic approach may be needed [13–15]. Further, tertiary and replacement energy reserves are also used to balance deviations of more than 15 min. The most flexible agents participate in balancing markets (BMs), making them costlier than spot markets [5,9,12,14]. Unbalanced Balance Responsible Parties (BRPs) may pay the costs of these mechanisms [9–12,16]. vRES are the agents that most contribute to the imbalance of the system, thus paying high penalties. However, some countries like Spain and Denmark already allow vRES to also support these balancing mechanisms, therefore increasing their remuneration and reducing the balancing needs and costs [9–12].

According to the National Energy and Climate Plans (NECPs) across the European Union, by 2030, it is expected that vRES will be the power technologies with the highest penetrations of most power systems [17–19]. Against this background, future EMs shall have their market designs adapted to the behaviour of vRES. The European legislation for the internal market of electricity has already proposed several changes to current market designs, mainly in the DAM and IDMs [5,20,21]. It considers that: (i) the trading time unit shall be reduced to 15 min (from the previous 1 h-period), enabling a better capture of the variability of vRES while providing the flexibility signals to better integrate these technologies, (ii) aggregated bids helping to minimise forecast errors [4,5,20], (iii) implicit bids and the implicit allocation of the cross-border capacity, and iv) balance responsibility to vRES. Furthermore, the market shall open to smaller players by considering a minimum bid size of 0.1 MW, increasing competition. Competitive options like auction-based and continuous markets IDMs and bilateral over-the-counter (OTC) contracts shall be reduced to only one option to avoid the lack of liquidity of actual markets [5,21].

Regarding BMs, the major challenges are related to the lack of harmonisation of pricing mechanisms, techniques for procuring balancing energy, and methods for defining imbalance prices. The urgency should be given to improve the elements of the design of BMs that inhibit (in some way) a free fluctuation of prices for balancing energy, such as an ineffective trade of balancing power, regulated prices, and pricing mechanisms not based on marginal pricing, which decrease the motivation of producers and the demand-side to answer to instantaneous balancing needs [4,5,11,12,18,19]. Against this background, stakeholders shall focus on the market designs of BMs that potentially can be more efficient to accommodate high penetrations of vRES. The literature contains a significant set of power system simulators, mainly focusing on the DAM, bilateral agreements, and support schemes as risk mitigation after the gas energy crisis in Europe [1–3]. However, being BMs the most profitable, the adaptation of these markets to vRES can be very important to guarantee the return to market players without continuing to incentivise externalities like feed-in-tariffs and regulated contracts for differences that cause market distortions and lead to price cannibalisation [20–24].

The Multi-agent Trading of Renewable Energy Sources (RES.Trade) system has the designs for the secondary power and energy markets, the tertiary energy market, and imbalance settlement (IS), being modelled based on the actual balancing markets of Portugal and Spain. Furthermore, it also considers new designs adapted to the behaviour of vRES, allowing them to participate in balancing markets and reducing their penalties in the IS. These designs incorporate adjustments to (1) gate closures, (2) rolling time horizons, (3) time granularities, and (4) bidding formats, such as block or flexible bids presented in previous works (e.g., [12,15,16,22]). Additionally, RES.Trade incorporates a new IS mechanism, presented in this work, inspired by the Spanish system, where all balancing responsible parties (BRPs) directly cover the reserve costs needed to balance vRES.

RES.Trade allows users to perform a sensibility analysis of different market designs according to the characteristics of their power systems. This work presents the open-access RES.Trade system, highlighting its main features and demonstrating its capabilities using two case studies. The first case study uses all modules of the system to compute the IS prices of the first day of 2030 in Portugal. The second case study tests the impact of different procurements of secondary power reserves in the Spanish power system for a 2030 scenario. Testing different market design configurations is important to regulators and policymakers to define the most adequate market designs for the characteristics of future vRES-based power systems.

The remainder of the paper is organised as follows. Section 2 presents a literature review of electricity market simulators available. Sections 3 and 4 present an overview of the RES.Trade simulator and its main features, respectively. Section 5 presents the case studies. Finally, Section 6 addresses the conclusions.

2. Literature Review on Relevant Electricity Market Simulators

Nowadays, several simulators using agent technology to model the actual market designs are available in the literature. Notable examples include AMES (Agent-based Modelling of Electricity Systems) [25], AMIRIS (Agent-based Market model for the Investigation of Renewable and Integrated energy Systems) [26], ASAM (Ancillary Services Acquisition Model) [27], EMCAS (Electricity Market Complex Adaptive System) [28], EMLabpy (Energy Modelling Laboratory) [29], GAPEX (Genoa Artificial Power Exchange) [30], MASCEM (Multi-Agent Simulator of Competitive Electricity Markets) [31], SEPIA (Simulator for Electric Power Industry Agents) [32], and MATREM (Multi-Agent Trading in Electricity Markets) [33]. Additionally, non-agent-based simulation tools such as Backbone [34], Power Web [35] and SREMS (Short Medium run Electricity Market Simulator) [36] also handle electricity markets with some simplifications (e.g., Backbone considers a simplified real-time economic dispatch based on marginal pricing).

AMES is an open-source multi-agent system developed in JAVA for the Repast platform. It features four main components: traders, transmission grids, day-ahead and real-time markets, and an independent system operator (ISO) responsible for system reliability assessment, day-ahead unit commitment, dispatch, and settlement. Repast is a free, open-source toolkit for agent-based modelling and simulation used in various applications [25].

AMIRIS is an open-access tool designed to simulate future energy markets, study their design, and assess related policy instruments, considering the strategic bidding behaviour of agents in the day-ahead market [26].

ASAM is an open-source, agent-based model with different design options for ancillary services and electricity markets. It offers a range of design parameters for each market and agent-specific strategies, along with clearing algorithms for the day-ahead market, continuous intra-day trading, redispatch processes, and imbalance management [27].

EMCAS incorporates both bilateral contracts and spot markets, utilising autonomous agents to represent producers, intermediaries, consumers, and ISOs. These agents make decisions based on forecasted prices for pool and bilateral contracts derived from historical data and future projections [28].

EMLabpy is an agent-based tool designed to explore the long-term impacts of energy policies for capacity investment, also considering capacity mechanisms and subscriptions. In this model, agents represent power companies whose investment decisions are driven by the anticipated profitability of various technologies with limited foresight into the future power system [29].

GAPEX, implemented in MATLAB, models and simulates artificial power exchanges, replicating the market-clearing techniques of major European markets [30].

MASCEM simulates market participants, including facilitators, generators, consumers, market operators, traders, and system operators. It includes bilateral contracts and spot and continuous markets, where agreements are verified by the market operator [31].

SEPIA is designed to develop electricity market models to understand participant behaviour and market impact. It supports only bilateral contracts involving agents such as grid zones, generators and their companies, the generator of last resort, consumers, retailers, the transmission grid, and the system operator [32].

Backbone is a multi-sector optimisation simulator that computes optimal capacities with the goal of minimising the power system costs. It computes the optimal long-term investment considering investment costs and the short-run dispatch based on marginal costs [33]. Power Web allows for testing and analysing different energy markets but supports only fixed demand for spot markets [33]. SREMS, based on game theory, supports short-to-medium-term scenario analysis and evaluates transacted power, though it is specifically designed for the Italian electricity market [34].

MATREM assists market participants in making crucial decisions about future power systems with high levels of renewables and alliances. It features adaptable agents and supports various market contexts and models. It includes several agents such as consumers, producers, retailers, and power systems and market operators. It simulates day-ahead and intraday markets with zonal and nodal marginal pricing and supports trading in derivatives markets, such as forwards, futures, and contracts for differences. It also facilitates bilateral contract negotiations in secondary and tertiary balancing markets and includes an IS algorithm to calculate imbalance prices. Indeed, the traditional balancing markets of RES.Trade are integrated into MATREM. It is a daily decision-support tool, i.e., it was not designed for long-term simulation nor to test new market designs [33].

RES.Trade incorporates existing IS mechanisms to compute the penalties paid by BRPs, especially retailers, energy communities and vRES power producers. Additionally, this work introduces a new mechanism based on the Spanish system, but all BRPs directly pay the reserve costs used to balance them [37,38]. Other applications of RES.Trade considered the impact of changing the market designs and rules of spot markets in the balancing prices using the IS mechanisms [37,38]. Algarvio et al. considered the Portuguese IS mechanism of RES.Trade as part of MATREM to simulate the advantages of postponing the gate closure of the day-ahead market by reducing the imbalances and, thus, the penalties paid by wind power producers [37]. Algarvio et al. considered the use of dynamic line rating in the computation of the cross-border capacities in the Iberian market of electricity (MIBEL) using RES.Trade to compute the penalties that BRPs need to pay. It has been concluded that an increase in cross-border capacities may decrease penalties by reducing vRES curtailments and not pushing out of the market the most competitive power plants [38]. Some applications use RES.Trade to test new balancing market designs. Algarvio et al. presented the newly designed double pricing and penalties "Separated" IS mechanism. This mechanism considers that BRPs directly pay the costs of the balancing markets used to balance them with a net zero profit to TSOs. It incentivises self-balancing according to balancing prices, remunerating BRPs when their deviations benefit the system. This mechanism was compared with the existing Portuguese and Spanish mechanisms in 2019, presenting lower penalties than the ones observed with the Spanish mechanism. The Portuguese mechanism only computes lower penalties if most BRPs do not balance themselves, penalising the other BRPs [16]. Algarvio et al. tested the participation of wind power producers in the balancing markets. They increased their market value and decreased their imbalances as desired. However, a new market design considering 15-min trades in the tertiary energy market was the option with the highest increase in their market value of 6% [9]. Furthermore, balancing market designs adapted to wind power producers may increase their market value by 22% [22]. Using RES.Trade, a new dynamic procurement of secondary power was studied in Spain using 2022 data. This approach was compared to the Spanish TSO procurement, resulting in a reduction of 11% of the procured power, freeing up the committed players to participate in other markets [15]. According to the authors, the work performed also highlighted the benefit of using dynamic reserves in power systems with high vRES shares. Furthermore, RES.Trade allows coupling balancing markets from different market zones using different: (1) gate closures, (2) rolling time horizons, (3) time granularities, and (4) bidding sizes and types (block or flexible). Table 1 presents the main features of RES.Trade tested in the literature.

Table 1. References that used the presented features of RES.Trade.

References	New Market Designs	Secondary Power	Secondary Energy	Tertiary Energy	Imbalance Settlement
[4,12]	√	√	√	√	√
[15]	√	√			
[16,22,37,38]	√				√

3. Balancing Markets and RES.Trade Market Model Capabilities

In 2019, the European Commission (EC) introduced a proposal to regulate the European Internal Market for Electricity, recognising current electricity markets (EMs) were not originally designed to handle high penetrations of vRES [21]. That new EC regulation reinforces the necessity to analyse existing marginal markets and adjust their design and structure to manage the variability of these "new" stochastic sources and aid them in participating in competitive trading while avoiding incurring high costs for balancing services, due to their physical nature [5,21,39]. The ongoing harmonisation of European EMs should be further encouraged to reduce costs and ensure equitable conditions for all market participants [4,5,21,40–43]. Deviations from the DAMs and IDMs schedules are addressed in BMs, which involves paying imbalance prices or penalties when an operation plan is not fulfilled. The approach to determining imbalance prices varies by market, ranging from straightforward methods in Nordic countries to more complex approaches in Portugal and Germany [11,12,44,45]. For a pan-European BM with consistent (and fair) rules for all participants, including vRES and demand-side players, a standardised and transparent method should be implemented [16,40–43].

In most European power systems, frequency reserves consider the Frequency Controlled Reserve (FCR), also known as the primary control resaerve, the automatic-activated frequency restoration reserve (aFRR), known as the secondary reserve, and the manually-activated frequency restoration reserve (mFRR), or the tertiary reserve [11,12]. These balancing control reserves are mandatory and mandated by the European Network of Transmission System Operators (ENTSO-E). Operationally, each TSO is responsible for ensuring that the power reserve values for these services are met within their control zone in accordance with ENTSO-E requirements [46]. In some countries like Portugal and Spain, FCR is a mandatory and non-remunerated system service for all (non-vRES) conventional generators connected to the grid that have the technical capability for a fast response [11,12]. This non-remunerated reserve in Portugal and Spain was not modelled in RES.Trade that is focused on market trading [12].

For aFRR and mFRR control, TSOs usually set schedules in 15-min intervals. In the associated markets, auctions are held for each hour of the day (or for multiple-hour blocks), allowing technically eligible players to submit bids. The auction's goal is to select the bids with the lowest power and energy price in the aFRR markets and the lowest energy price in the mFRR market, utilising marginal pricing theory (MPT), pay-as-bid (PAB), or other pricing mechanisms. In some markets with reduced competition, the energy regulator may opt to define its prices, which is the case for the price of aFRR energy in Portugal, to avoid monopoly or oligopoly [11,12]. RES.Trade uses MPT, PAB or the regulator's pre-defined price, according to users' selections [11,12,47]. The system also allows users to select if they assume block or divisible flexible bids [48]. In RES.Trade, vRES and demand-side players can participate in these markets [12,43].

In RES.Trade, the aFRR power requirements are calculated based on the balancing guidelines of ENTSO-E, with the option to compute them according to the Portuguese system [12,15,42]. Additionally, dynamic or user-input aFRR power needs can be used using the MPT and PAB pricing mechanisms. Different sets of combinations can be tested considering the provided methodologies, the possibility of bid block and flexible bids and the new design by separating the upward and downward procurement of secondary power. This work focuses on four methodologies, including the "ENTSO-E flex", which is the same as the benchmark considering flexible bids where the TSO contracts exactly the power it procures. In the "ENTSO-E separated", there is a symmetrical separate procurement of upward and downward power, i.e., the TSO procures the same value for upward and downward aFRR power, but agents only strategically submit bids in the direction that maximises their profit. Then, the "Dynamic block" and "Dynamic flex" consider a dynamic separated procurement of aFRR power considering block and flexible bids, respectively. The secondary energy price is computed considering the previous mechanisms or the regulator's price. The mFRR energy market is cleared considering the MPT or PAB mechanisms. The system also calculates ISs either using the (different) Portuguese or Spanish formulations. Under the Portuguese formulation, all BRPs, A, have the same penalty, p_t^{pen}, and dual pricing for each, a, deviation, $q_{t,a}^{dev}$, being computed considering the energy, $q_{o,t}$, used to balance the system in each balancing option, $o \in O$ (all balancing options) and the difference between the spot price, $p_{s,t}$, and the price of each balancing option, $p_{o,t}$, as follows:

$$p_t^{pen} = \sum_{o=1}^{O} (p_{o,t} - p_{s,t}) q_{o,t} / \sum_{a=1}^{A} \left| q_{a,t}^{dev} \right| \tag{1}$$

In contrast, the Spanish formulation, similar to the used in Nordpool countries, determines the balance direction and requires only the BRPs responsible for creating the balancing needs to directly pay or receive the system's energy balance price as follows [11,12,16,47]:

$$\begin{cases} p_t^{up,pen} = 0 & if \sum_{o=1}^{O} q_{o,t}^{up} < \sum_{o=1}^{O} q_{o,t}^{down} \\ p_t^{up,pen} = min\left[\sum_{o=1}^{O} \left(p_{o,t}^{down} - p_{s,t}\right) q_{o,t}^{down} / \sum_{o=1}^{O} q_{o,t}^{down,}, 0\right] & if \sum_{o=1}^{O} q_{o,t}^{up} \leq \sum_{o=1}^{O} q_{o,t}^{down} \\ p_t^{down,pen} = 0 & if \sum_{o=1}^{O} q_{o,t}^{up} > \sum_{o=1}^{O} q_{o,t}^{down} \\ p_t^{down,pen} = min\left[\sum_{o=1}^{O} \left(p_{s,t} - p_{o,t}^{up}\right) q_{o,t}^{up} / \sum_{o=1}^{O} q_{o,t}^{up}, 0\right] & if \sum_{o=1}^{O} q_{o,t}^{up} \geq \sum_{o=1}^{O} q_{o,t}^{down} \end{cases} \tag{2}$$

where:

1. $p_t^{up,pen}$ and $p_t^{down,pen}$ are the up and down penalties in period, t, respectively;
2. $p_{o,t}^{up}$ and $p_{o,t}^{down}$ are the up and down prices of each balancing option, o, respectively;
3. $q_{o,t}^{up}$ and $q_{o,t}^{down}$ are the up and down quantities of each balancing option, respectively.

The "Spanish All BRPs" is a similar alternative to the Spanish mechanism, considering that all BRPs in the dominant unbalanced direction pay the energy balance price, considering the total up, $q_t^{up,dev}$, and down, $q_t^{down,dev}$, deviations as follows:

$$\begin{cases} p_t^{up,pen} = 0 & if \sum_{o=1}^{O} q_{o,t}^{up} < \sum_{o=1}^{O} q_{o,t}^{down} \\ p_t^{up,pen} = min\left[\sum_{o=1}^{O} \left(p_{o,t}^{down} - p_{s,t}\right) q_{o,t}^{down} / \sum_{a=1}^{A} q_{a,t}^{down,dev}, 0\right] & if \sum_{o=1}^{O} q_{o,t}^{up} \leq \sum_{o=1}^{O} q_{o,t}^{down} \\ p_t^{down,pen} = 0 & if \sum_{o=1}^{O} q_{o,t}^{up} > \sum_{o=1}^{O} q_{o,t}^{down} \\ p_t^{down,pen} = min\left[\sum_{o=1}^{O} \left(p_{s,t} - p_{o,t}^{up}\right) q_{o,t}^{up} / \sum_{a=1}^{A} q_{a,t}^{up,dev}, 0\right] & if \sum_{o=1}^{O} q_{o,t}^{up} \geq \sum_{o=1}^{O} q_{o,t}^{down} \end{cases} \tag{3}$$

Therefore, if the balancing prices are cheaper than spot prices, no penalties are applied. Furthermore, the "Separate" IS mechanism considers that all unbalanced BRPs must directly pay the costs of the energy used in the opposite direction of their deviations as follows [16]:

$$p_t^{up,pen} = \sum_{o=1}^{O} \left(p_{o,t}^{down} - p_{s,t}\right) q_{o,t}^{down} / \sum_{a=1}^{A} q_{a,t}^{down,dev} \tag{4}$$

$$p_t^{down,pen} = \sum_{o=1}^{O} \left(p_{s,t} - p_{o,t}^{up}\right) q_{o,t}^{up} / \sum_{a=1}^{A} q_{a,t}^{up,dev} \tag{5}$$

The imbalance prices that BRPs must pay for their down, p_t^{down}, and up, p_t^{up}, deviated energy is computed as follows:

$$p_t^{down} = -\left(p_{s,t} - p_t^{down,\ pen}\right) \quad (6)$$

$$p_t^{up} = p_{s,t} + p_t^{up,pen} \quad (7)$$

In the Portuguese mechanism $p_t^{pen} = p_t^{down,\ pen} = p_t^{up,pen}$. In the case of a positive imbalance price, BRPs receive a remuneration, otherwise, they pay the total cost, C_t^{dev}, with deviations as follows:

$$\begin{cases} C_t^{dev} = q_t^{dev} p_t^{up}, & for\ q_t^{dev} > 0 \\ C_t^{dev} = \left|q_t^{dev}\right| p_t^{down}, & for\ q_t^{dev} < 0 \end{cases} \quad (8)$$

4. Description of RES.Trade Models and Simulation Tool

The RES.Trade system includes sub-models of the traditional and newly designed power and energy reserve markets [4,12,15,16]. It consists of a modular tool where users can run it sequentially or each module separately. It aims to test different market designs, considering data from different power systems to assess the impact of increasing vRES penetration and of different designs in the overall behaviour of the studied electricity markets. This simulator considers the participation of traditional dispatchable power plants, variable renewable energy sources, and demand-side players in maintaining system balance, specifically in the automatic (aFRR) and manual (mFRR) frequency restoration reserve markets [5,12]. Both MPT and PAB schemes to determine prices were implemented. The model was designed to simulate, in the first phase of development, the balancing markets of Portugal and Spain under MIBEL. Therefore, by default, it always considers the simulation of these countries separately as they are operated in terms of reserves. However, it can also consider market coupling and compare single balancing markets for each country with a common balanced control zone. Indeed, it can run any single or two coupled balancing markets that shall follow the indicated date structure. Figure 1 presents the structure of the system.

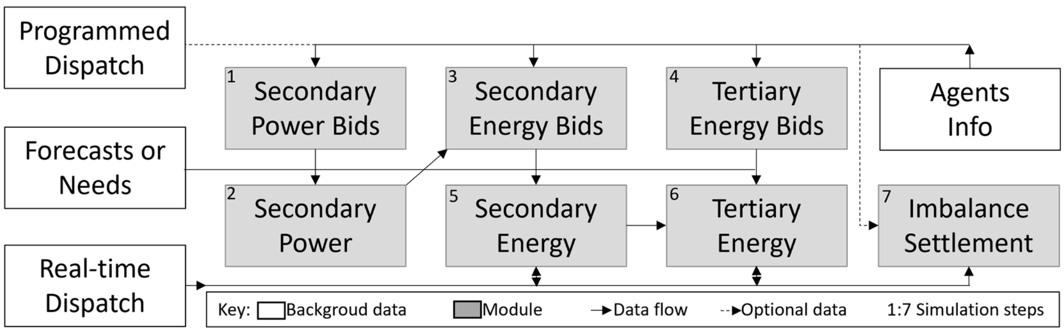

Figure 1. Flowchart of the RES.Trade System.

4.1. Configuration

The RES.Trade simulator was developed in JAVA. When running the executable ".Jar" files of a module or the system, users have to define the configuration of the desired simulation. When running RES.Trade presents a window to setup the configuration of the simulation, as presented in Figure 2.

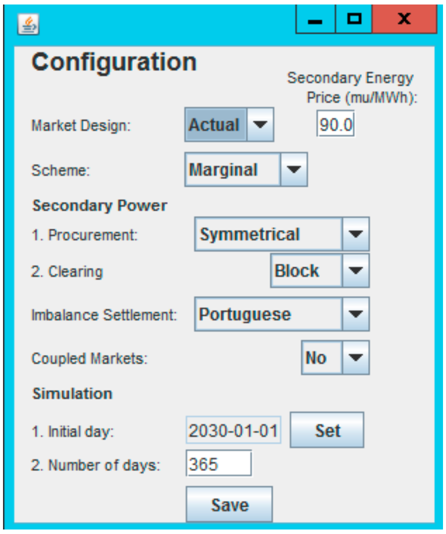

Figure 2. Configuration of the simulation.

In RES.Trade is possible to run actual and new (briefly presented in Section 3) designed balancing markets. The actual market design considers the procurement of an hourly power band for both upward and downward secondary regulation and a fixed price for the used secondary energy defined by the user, which reflects the price defined by the regulator. In this design, agents shall bid the power band according to the TSO-defined procurement. The new design considers the new European legislation for balancing markets [5,12,21]. Thus, all balancing prices are defined in competitive markets considering any time step (e.g., 15 min or 1 h) according to input data. In this case, the upward and downward secondary power procurement are computed separately. Users may select the clearing scheme according to MPT and PAB and the procurement for secondary power between the symmetrical "ENTSO-E" rule, the "Portuguese" asymmetrical, the "Dynamic" or using their own "Input" [11,12,15,46].

The clearing methodology considers that agents bid block or divisible flexible bids [43]. In the case of flexible bids, TSOs obtain exactly the secondary power they procure. In the case of block bids, it is considered the Portuguese guidelines, where the TSO shall get at least 95% of the power it procures [11,12]. The IS mechanism computes the costs that each unbalanced BRP must pay according to the selected methodology between the "Portuguese", "Spanish", "Spanish All BRPs" and "Separated" [16]. Furthermore, users may select if they will compute the balancing markets of two different countries, coupled or not.

The system was designed to do daily simulations as the minimum time horizon, so input and output data are presented in daily folders. Against this background, users must select the initial date to simulate and the total number of continuous days to simulate from this date. Naturally, all folders with simulated dates must be present for a successful run. To run a module or the system, users may collect or compute background data.

4.2. Background Data

Background data is composed of files with information about the market agents, the programmed and real-time dispatches, and the energy forecasts or reserve needs.

The "Agents Info" presents the information about agents in the "in/units_info" folder at the root of the system. This file consists of the identification of the agent ("unitID"), its "capacity", its "country", its technology ("energySource") and if it has the requirements to participate in the "reserves" markets (0 if none, 2 for the secondary and 3 for the tertiary).

The "Programmed Dispatch" data contains obligatory data from the day-ahead market and optional data files of other market outputs, such as intraday and bilateral markets. It is used to compute the bids in simulation steps 1, 3 and 4. Users may use their own bids and directly simulate steps 2 and 5–7. However, to use the bidding behaviour presented in the simulation steps 1, 3 and 4, users must provide each period (PP) and session (S) outputs of the day-ahead market presented in the following file format "YYYY_MM_DDPPS.json" in the "out" folder. This file shall have the clearing "marketPrice" of the different market countries, the agent ID (offerUUID), the offered "price" and "energy" if it traded ("wasTraded", true or false) if it "buy" or "sell" energy and the "tradedEnergy". Furthermore, in the case, the users want to consider different bilateral agreements of bilateral markets, continuous intraday markets and over-the-counter agreements, they shall use an Excel file with the following format "YYYY_MM_DD_S.xlsx". The file shall have information about the "Bidding Area", "Agent", and "Unit" name, the "Country", the "Transaction Type" (buy or sell), the offered "Price" and "Energy", the "Clearing Price" and the "Traded Energy".

The "Forecasts or Needs" data consists of the expected dispatch of each agent, enabling RES.Trade to compute the procurement of secondary reserve power and the real-time needs for secondary and tertiary energy. The type of forecast depends on the selected procurement methodology (check [15] for more details). Users may also input these reserve needs directly in the files without any further computation using RES.Trade only for the market clearing. The required data is presented in the three "Needs.xlsx" files of each country presented in the "in\date\" folder. Users may fill these files to use RES.Trade.

The "Real-time Dispatch" data can be obtained from a dispatch simulator or can be added by users to compute the unbalances of BRPs and the secondary and tertiary energy real-time needs. This data is also important to compute the IS.

4.3. Modules

RES.Trade includes six different executable "Jar" files: "RESTradeOA", "SecondaryBids", "SecondaryCapacity", "BidsTertiary"," SecondaryEnergy" and "Tertiary". Those files contain the following modules: "Secondary Power Bids", "Secondary Power", "Secondary Energy Bids", "Tertiary Energy Bids", and "Secondary Energy", "Tertiary Energy" and "Imbalance settlement". Some of the executable files include more than one module, which can be dependent on previous modules, according to Figure 1. Below is a summary of these executable files and the required input data.

"RESTradeOA" is the main executable used to configure the simulation and run the other executables.

"SecondaryBids" processes the output of the day-ahead market along with data from each aFRR participant, calculating bids for the aFRR capacity market. Bids per agent and negotiation periods are either calculated or added as input by users in the "Secondary.xls" file, with each period recorded on different sheets of the file. In RES.Trade, it is also considered that agents not cleared to support the secondary reserve can participate in the tertiary reserve and cover extraordinary secondary reserve needs. So, in this process, the bids to provide energy reserve are also computed in the "Tertiary.xls" files.

"SecondaryCapacity" handles both the procurement of aFRR power and the aFRR power market. To calculate aFRR procurement, users must input the maximum expected consumption (second column in "SecondaryNeeds.xls" file) or the dynamic aFRR Up and Down capacities (second and fourth columns, respectively) for each simulation period (first column). The TSO submits the aFRR power up and down requirements and collects the agents' bids, determining the market-clearing price(s) and power. This module also collects agents' bids and calculates power prices using the "Secondary.xls" file. After collecting the data of the day-ahead market and the aFRR power markets are cleared, the module receives each agent's programmed dispatch and prices, adapting bids for the aFRR energy market in the "SecondaryE.xls" file and automatically removing their bids from the "Tertiary.xls", because these agents were assigned to support aFRR. Users input or calculate aFRR and mFRR energy bids per agent and negotiation period in "SecondaryE.xls" and "Tertiary.xls" files, respectively. The format of these files is similar. Results from this executable are present in the "out/date/SecondaryOutput.xls" file.

“BidsTertiary” executable adapts the bids of the secondary agents not cleared to support it and computes the bids of the agents that can support mFRR considering their programmed dispatches not only from the DAM but optionally also from the IDM and OTC bilateral agreements. Instead of using this process, users may provide their own bids to the “Tertiary.xls” file.

”SecondaryEnergy” simulates the aFRR energy market. Using the functions of the TSO agent, RES.Trade reads the secondary dispatch needs from the “SecondaryENeeds.xls” file, which requires data on Period, Up Needs (MW), and Down Needs (MW). This executable collects agents’ bids and calculates up and down energy prices using the “SecondaryE.xls” file. Results from this executable are present in the “out/date/SecondaryEOutput.xls” file.

“Tertiary” includes algorithms for the mFRR energy market and IS. RES.Trade reads the mFRR dispatch needs from “TertiaryNeeds.xls” and gathers agents’ bids from “Tertiary.xls”, calculating up and down energy prices. Tertiary energy needs and total imbalances can be modified in “TertiaryNeeds.xls”. Additionally, this process calculates energy costs for the reserve markets and penalties for imbalanced agents. Results such as penalties and imbalance prices are available in “TertiaryOutput.xls”. “TertiaryOutput.xls” files contain all outputs of balancing markets from the RES.Trade system.

4.4. Main Limitations

RES.Trade focused on the Portuguese and Spanish electricity BMs and future designs adapted to vRES. Several BM designs have not been considered but can be tested in other systems (e.g., [27]) and compared with the presented designs. Furthermore, it only clears the coupling of a maximum of two system/market/control areas. Its agents’ bidding behaviour is simplistic and based on the DAM bids, considering the maximisation of the agents’ return from BMs also based on DAM prices. However, users may input their bids. It does not have a dispatch model, meaning users must input deviations and balancing needs. It can detect and solve some input mistakes, but the name and structure of the folders and files are limited to the ones mentioned in this section.

5. Application of the New Simulator: Case Studies with RES.Trade

This section presents two case studies considering the Portuguese and Spanish power systems deployment scenarios for 2030. The capacities in these scenarios were obtained using the Backbone optimisation system as well as information from the 2030 NEPC [17,34,38]. It was considered the units participating in these countries in 2022 upgraded by the new capacities in the “agents.json” file. Bidding to the day-ahead market considers marginal prices except for hydroelectric power plants considering water values according to the percentage of storage availability in aggregated reservoirs for Portugal and Spain. Inflexible demand bids the price-cap of MIBEL, 4000 €/MWh [12]. The bid quantity of the inflexible demand is computed using a hybrid forecast model. The wind power and solar PV forecasts are obtained using dimensionality reduction and feature selection algorithms to obtain the optimal combination of many meteorological parameters and then regression algorithms adjusted for diverse weather regimes [49]. Data from 2018 was used to calibrate the forecasting approach applied to 2019 data. The forecasts are then upscaled to reflect the 2030 capacity identified with Backbone. The day-ahead and intraday market outcomes are simulated using MASCEM [31]. All these values were previously obtained and computed and serve as input to RES.Trade.

The first case study consists of simulations covering the first day of January in Portugal using four different IS mechanisms. It uses all modules presented in Figure 1, considering the traditional market design and the four modelled IS mechanisms. It is used only to demonstrate how to use all RES.Trade modules, starting with the simulation of the secondary capacity market and finishing with the computation of the IS. The second case study consists of hourly annual simulations for 2030 using five different mechanisms implemented in RES.Trade to procure secondary power in the Spanish control zone using only the first two modules presented in Figure 1.

To run RES.Trade and replicate these case studies, check the "Supplementary Materials" and the "Data Availability Statement". The next section presents the first case study.

5.1. Case-Study 1: Assessment of the IS Mechanisms in the Portuguese Power System

This study aims to test the RES.Trade system in the allocation of secondary power to clearing secondary and tertiary energy, and the IS considering the actual Portuguese BM design, that is used as a benchmarking. Then, the potential impact of different IS mechanisms available in the system ("Spanish", "Spanish (SP) All BRPs", and "Separated"; more details are presented in Section 3) is assessed. Results are presented on the first day of January 2030, and they can be replicated by using the four configuration files provided with the system.

All outputs are the same in the four simulations, except for the IS prices. Figure 3 presents the first output, which consists of the symmetrical power band contracted by the TSO for a price per hour.

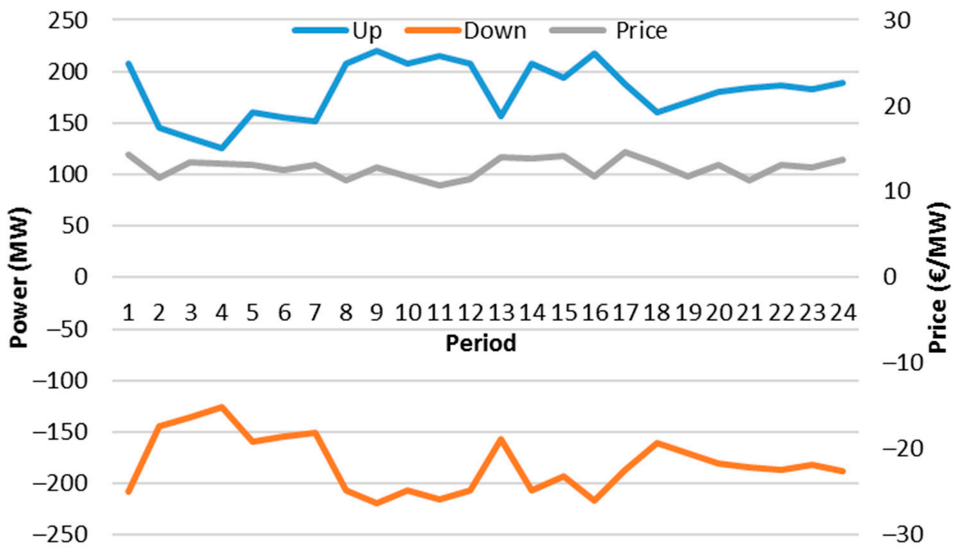

Figure 3. Contracted power band and price.

Using a simple hourly dispatch model, it is possible to compute the total hourly imbalances, such as the secondary and tertiary energy needs presented in Figure 4. In Figure 4, it is possible to verify up deviations during most of the day, which means that down reserves shall be activated. From the figure, it is also possible to observe that in some hours, the required aFRR energy is much higher than the contracted power, like in hour 11 when is required more than 1000 MWh of down aFRR but only a slightly more than 200 MW has been contacted, resulting in extra needs to be solved in the tertiary reserve. Portugal does not use a market for the activation of secondary energy being the up-regulation price defined by the regulator (90 €/MWh, as shown in Figure 2), while the down-regulation price is defined by the day-ahead price (no profit for aFRR agents and loss for BRPs). Therefore, Figure 5 presents the simulated dispatch of the secondary reserve.

Analysing Figure 5 it is possible to verify that secondary regulation is mostly activated for down-regulation, and the relevant extra needs to be activated because of the significant excess deviations. Indeed, it is possible to verify the low day-ahead price (Down Price, black line), which means that we had a high variable renewable generation in all hours except for hour 21. Some extra needs can be activated through bilateral agreements, but for simplification, all aFRR agents not participating in aFRR can participate in mFRR, being this extra aFRR needs to be activated in mFRR.

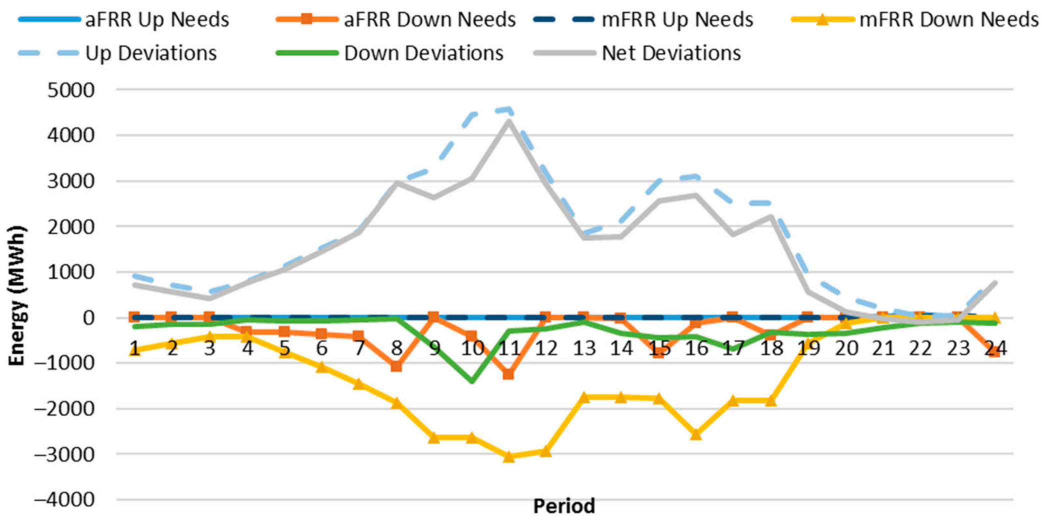

Figure 4. Hourly balancing needs and deviations.

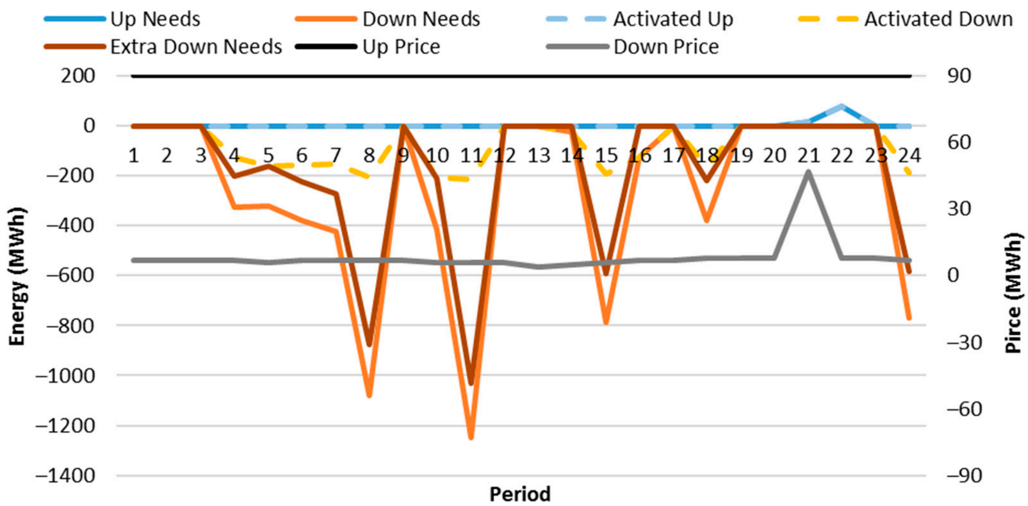

Figure 5. Secondary activated dispatch and prices. Extra needs to be activated.

Figure 6 presents the energy dispatch and prices of the tertiary reserve and vRES curtailments. Analysing Figure 6, it is possible to conclude that the tertiary reserve solves all balancing needs with the exception of the period between hours 9 and 16. During this period, only vRES agents have programmed dispatches in Portugal, contributing to the lack of down-regulation capacity for balancing markets. Therefore, these agents were forced to curtail some of their excess deviations. Naturally, this is reflected in their remuneration by decreasing the amount of paid energy and increasing their penalties. One solution to solve this issue consists of allowing vRES to support balancing reserves, as in Spain, being remunerated.

The IS mechanism computes the costs each unbalanced BRP must pay according to the selected methodology. The following mechanisms were tested in this case study: "Portuguese", "Spanish", "Spanish (SP) All BRPs", and the "Separated". Figure 7 presents the penalties paid by unbalanced BRPs for the different pricing mechanisms of the IS. For readability, since the "Spanish (SP) All BRPs" and "Separated" ISs have the same results, in this figure, only the latter mechanism is presented.

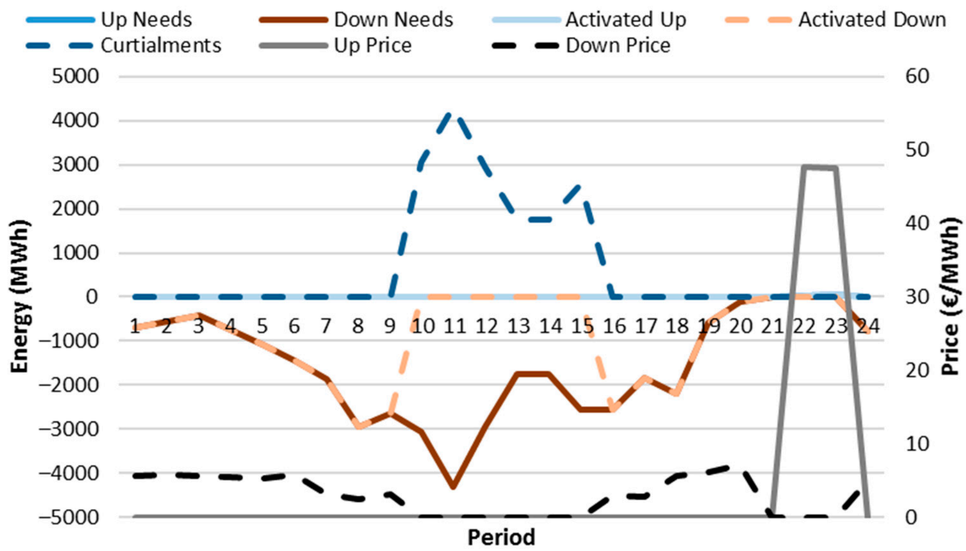

Figure 6. Activated mFRR energy and prices. vRES curtailments.

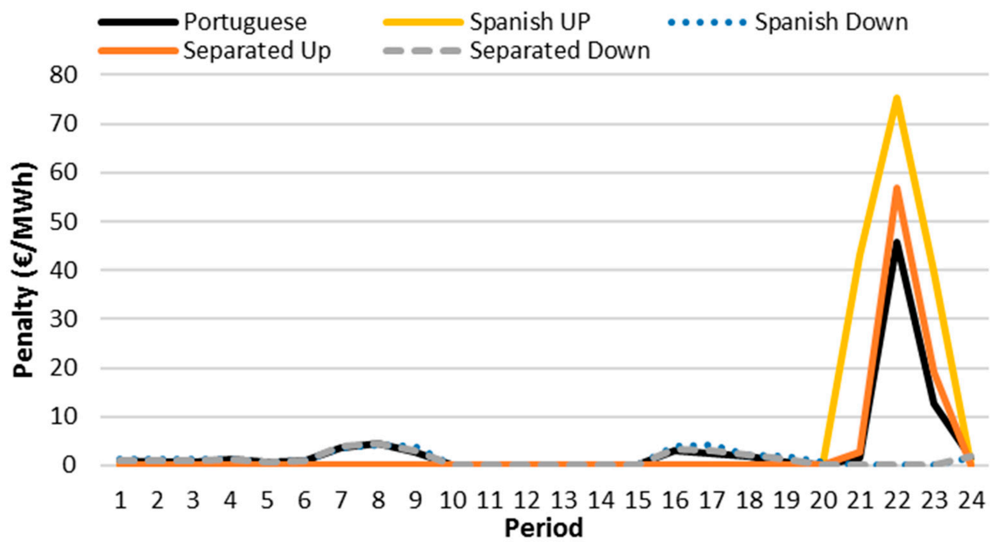

Figure 7. Penalties paid according to the selected IS mechanism.

Analysing Figure 7, one concludes the Portuguese mechanism is the one with lowest penalties. However, in this simulation, this mechanism charges penalties equally to all BRPs, with an average value of 3.58 €/MWh. This can be viewed as an unfair mechanism since BRPs that are contributing to reducing balancing needs (and prices) also pay the same penalties as BRPs contributing to increasing them [16]. The Spanish mechanism seems the most expensive for BRPs, with an average value of 3.98 €/MWh, because penalties are only paid by BRPs in the dominant direction that needs to be balanced. In this simulation, due to the hourly dispatches and imbalance clearing, only balancing needs in one direction are identified. In the case of simulating real-time dispatches with a smaller time granularity, e.g., 15 min, the system may have to balance needs in both up and down directions during the market time horizon of one hour, computing the dominant direction for the Spanish mechanism. Indeed, due to the hourly dispatch simulation and the balancing prices that are always more costly than spot prices, the "Spanish (SP) All BRPs" and the "Separated" ISs have the same results, with an average penalty of 2.25 €/MWh. These mechanisms are cheaper and incentivise self-balancing, which tends to reduce balancing needs and prices. They reduce the average penalties by 37% and 43% in comparison to the Portuguese and Spanish mechanisms, respectively.

Results with the highest statistical significance, based on simulations for the entire year of 2019, which are aligned with the findings from this work, can be found in [16]. Further simulations of future power systems with high shares of vRES shall be used to test the performance of the different IS mechanisms. To conclude, these simulations highlighted the capabilities of RES.Trade and users can use and test the IS mechanism more adequately for their actual and expected power systems.

5.2. Case-Study 2: Yearly Procurement of Secondary Reserve

This case study has the goal of verifying the relevance of considering the dynamic procurement of secondary power reserves in power systems with high penetrations of vRES. It uses the simulation of the Spanish power system in 2030, considering the capacities computed by the open-access system Backbone [34] in a previous study [38]. It considers that only pumped hydro storage (PHS) power plants can support the secondary regulation. To compute the secondary dynamic procurement, forecast methodologies employed in previous studies were used [49]. This study also considers a new feature in RES.Trade, the consideration of block and divisible flexible bids, to test the difference between them. The actual market design in Spain, simulating the yearly "ENTSO-E" symmetrical block procurement of a secondary power band, is used as a benchmark [11,15,46]. This methodology implies that agents must submit a symmetrical up-and-down block power band, limiting competition and reducing efficiency/usage. Table 2 presents the main outputs of the benchmark simulation in 2030.

Table 2. Average outputs of the "ENTSO-E" symmetrical block procurement of secondary reserve.

Power (MW)	Usage (%)	Extra Needs (MW)	Price (€/MW)
820	26.26	1706	12.87

In the benchmark simulation, it is possible to see that the usage of the actual methodology is low. Indeed, the maximum usage of this methodology is 50% since, in every instant, agents can only support frequency regulation in one of their band directions, i.e., TSOs are contracting double the power they can use during real-time frequency regulation. The most interesting result relies on the extra needs, which doubles the contracted power. These extra needs derive from the high vRES unbalances in a system with high vRES penetrations. In conclusion, using the benchmark design in a simulated 2030 in Spain, the TSO will only use 26% of the contracted power reserve but, at the same time, needs double the contracted power to maintain the frequency stability.

Further, has been simulated the four methodologies described in Section 3: (i) "ENTSO-E flex", (ii) "ENTSO-E separated", (iii) "Dynamic block", and (iv) "Dynamic flex". Table 3 presents the sensibility of the four methodologies compared to the benchmark outputs presented in Table 2. From Table 3, it is possible to conclude that using flexible bidding improved results. So, by having exactly the power they procure, TSOs may increase the efficiency of the secondary reserve. Indeed, using the "ENTSO-E flex" methodology, the TSO increases procurement and reduces the extra need for a small increase in the total cost.

Table 3. Sensibility analysis concerning the benchmark.

	Power (MW)	Usage (%)	Extra Needs (MW)	Price (€/MW)	Total Cost (%)
ENTSO-E flex	+45	−1.57	−10	−0.63	+0.49
ENTSO-E separated	−173	−9.49	+81	−0.21	−22.25
Dynamic block	−265	+21.25	+7	+1.11	−27.22
Dynamic flex	−322	+21.98	+21	+1.22	−34.24

The separate procurement of balancing power, suggested in the European legislation, can be very important in the case of high competition [5,21]. In the presented case, as only PHS power plants are participating and providing regulation in the direction they expect will maximise their profit, it may neglect the direction that needs to be activated. In this case, the TSO did not get all the power needed, resulting in a reduction in the contracted power but also in the usage of that power, which means that it was not contracting the power in the direction it needed, increasing the extra needs.

The dynamic methodologies strongly reduced the contracted power but slightly increased the extra needs, as the TSO is contracting power in the right direction. This can be verified by the increase above 21% in power usage. Indeed, by contracting more power in one of the directions, the TSO is increasing its marginal price. However, the total costs were highly reduced between 27% and 34%, which demonstrated the relevance of using a dynamic procurement of aFRR power in power systems with major penetrations of vRES.

6. Conclusions

The global ambitions for a carbon-neutral society by 2050 increase the need to adapt actual electricity market designs to high penetrations of vRES, as already foreseen in the European NECPs for 2030. While the legislation for the European internal market of electricity provides solid solutions to day-ahead and intraday markets, it only addresses the purpose of balancing market harmonisation.

This work presents the open-access RES.Trade system. The system has the actual models of the Portuguese and Spanish secondary power and energy markets, the tertiary energy market and the imbalance settlement (IS). Furthermore, it considers the new designs proposed for balancing markets by European legislation. In addition, this work presents new features of RES.Trade, enabling to simulate the:

1. separate payment of imbalances with a new mechanism that may incentivise the participation of vRES and demand-side players in balancing markets, their self-balancing and a reduction in the penalties they pay;
2. dynamic procurement of secondary power;
3. the use of flexible and block bids in the secondary power market.

To test the system two case studies were analysed. The first simulates the application of four different IS mechanisms on the first day of 2030 in Portugal. The outcomes of this study highlight that the new "Spanish All BRPs" IS mechanism allows Portuguese BRPs to reduce their penalties between:

1. 37% compared with the Portuguese mechanism;
2. 43% concerning the Spanish mechanism.

The second case study assesses the impact of five different mechanisms to procure secondary power during 2030 in Spain. The dynamic procurement methodology proposed in this work allows for reducing the costs with the Spanish secondary power by:

1. 27% in the case of block bids;
2. 34% in the case of flexible bids.

The RES.Trade capabilities, along with the two case studies, allowed an assessment of the existing balancing markets mechanisms in Portugal and Spain and the comparison with alternative mechanisms from other power systems or the literature. Therefore, a simulator like RES.Trade is important to test the impact of actual and new designs on future power systems, helping regulators and policymakers to determine the most effective mechanisms for balancing markets. Despite the case studies analysed in this work, RES.Trade is publicly available and can be easily adapted to other regions, enabling the simulation of balancing markets for either one or two coupled countries.

Future work has the goal of a continuous improvement of RES.Trade to incorporate and test new balancing market designs towards a carbon-neutral society. Currently, a machine learning technique is under development to periodically adjust the dynamic procurement of power reserves, such as the use of different time granularities, e.g., 15 min.

Supplementary Materials: RES.Trade system can be downloaded at: https://github.com/hugoalgarvio/RES.TRADE.OA (accessed on 5 December 2024).

Author Contributions: Conceptualization, H.A.; methodology, H.A.; software, H.A.; validation, H.A., A.C. and A.E.; formal analysis, H.A., A.C. and A.E.; investigation, H.A.; resources, A.E.; data curation, H.A. and A.C; writing—original draft preparation, H.A.; writing—review and editing, H.A., A.C. and A.E.; visualisation, H.A.; supervision, A.E.; project administration, A.E.; funding acquisition, A.E. All authors have read and agreed to the published version of the manuscript.

Funding: This work has received funding from the EU Horizon 2020 research and innovation program under project TradeRES (grant agreement No 864276).

Data Availability Statement: All data required to replicate the studies is available at: https://github.com/hugoalgarvio/RES.TRADE.OA (accessed on 5 December 2024).

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

aFRR	automatic-activated frequency restoration reserve
AMES	Agent-based Modelling of Electricity Systems
AMIRIS	Agent-based Market model for the Investigation of Renewable and Integrated energy Systems
ASAM	Ancillary Services Acquisition Model
BM	Balancing market
BRP	Balance Responsible Party
CET	Central European Time
DAM	Day-ahead market
FCR	Frequency controlled reserve
EM	Electricity market
EMLabpy	Energy Modelling Laboratory
EMCAS	Electricity Market Complex Adaptive System
ENTSO-E	European Network of Transmission System Operator
EU	European Union
GAPEX	Genoa Artificial Power Exchange
IDM	Intraday market
IS	Imbalance settlement
ISO	Independent System Operator
MASCEM	Multi-Agent Simulator of Competitive Electricity Markets
MATREM	for Multi-Agent Trading in Electricity Markets
mFRR	manually-activated frequency restoration reserve
MIBEL	Iberian market of electricity
MPT	marginal pricing theory
NECP	National Energy and Climate Plan
OTC	Over-the-counter
PAB	pay-as-bid
PHS	Pumped Hydro Storage
PV	Photovoltaic
RES.Trade	Multi-agent Trading of Renewable Energy Sources
SEPIA	Simulator for Electric Power Industry Agents
SREMS	Short Medium run Electricity Market Simulator
TSO	Transmission System Operator
vRES	Variable renewable energy sources
WPP	Wind power producer

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