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Electricity balancing challenges for markets with high variable renewable generation

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ABSTRACT

This research studies how the process of equalizing the supply and demand of electrical energy can be improved in a foreseeable scenario characterized by a high share of renewable energy and distributed energy plants. The increase in the number of distributed energy resources can intensify the difficulties in balancing supply and demand but, at the same time, can help to enable an efficient settlement of active power imbalances. In the European market the distributed energy resources, either independently or in aggregate, have a modest contribution to the equalization process. This research focuses on an analysis of prevailing configurations for balancing the supply and demand of electrical energy in Europe and on checking its suitability for a prospective scenario with a much higher share of renewable energy than the present one. The results show that the ongoing configuration in Europe is an inheritance that constraints present choices. Furthermore, the study compares the current configurations in the European Union and the United States and highlights the challenges that the European Union is facing, mainly due to infrastructure bottlenecks between member states.

1. Introduction

Electricity balancing encompasses procedures and operators' actions, mainly from the transmission system operators (TSOs) to guarantee, unceasingly, that the demand equals supply [1] and that the supply is provided with the required quality (both qualitative and quantitative aspects). Distributed energy resources (DERs) are small to medium-sized plants that include distributed generation such as biogas plants or renewable energy sources like wind and solar, small-scale battery energy storage, controllable load and systems, heat pumps, or demand response [2]. Among many other potential issues due to the natural spatiotemporal variability of solar and wind energy resources and associated energy generation, a significant penetration of renewables might create problems in maintaining the grid balance [3,4]. Therefore, in the near future, DERs are expected to have, among other advantages, the possibility of being able to provide cost-effective balancing services [5]. The integration of these new DERs is needed to ensure that the energy objectives to decarbonize the power systems are reached and, subsequently, directly impact in other related challenges such as climate change or the achievement of UN Sustainable Development Goals.

Individual DERs do not generally meet the minimum size requirements to participate in the transmission system under current participation models [6,7] but they do participate to a limited extent in the provision of electricity services. In general, the balance of electricity is the main service offered by DERs although their participation is so far circumscribed to some specific groups and capacities. DERs are not yet allowed to operate in some markets for electricity balancing purposes and when they are, they are often connected at high voltage levels [8]. Considering this system configuration, the arrival of fluctuating renewable energy sources in addition to DERs, alongside the current shutdown of conventional power plants in some countries [9], requires the development of new proposals about the operation of the power system and its ancillary services [10]. The term "ancillary services" refers to a number of functions developed by TSOs to ensure the security of the energy system [11]. These functions include, in addition to electricity balancing, the capability to (i) restore a network subsequently a power outage; (ii) maintain system frequency with automatic and fast responses; (iii) provide additional power when needed; (iv) provide reactive power and other miscellaneous services [11].

TSOs may trade balancing electricity reserves between countries and operators. This task requires market harmonization and an extensive development of new solutions both from a technical and regulatory

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Abbreviations

BA	Balancing authority
BRPs	Balance responsible parties
DCM	Distribution congestion management
DERs	Distributed energy resources
DSOs	Distribution system operators
EESs	European electricity systems
ENTSO-E	European Network of Transmission System Operators
IGCC	International Grid Control Cooperation
HV	High voltage
MARI	Manually Activated Reserves Initiative
MOL	Merit order list
PICASSO	Platform for International Coordination of Automatic Frequency Restoration and Stable System Operation
RCC	Regional coordination centers
RTM	Real-time market
SoSs	System of systems
TCM	Transmission congestion management
TERRE	Trans European Replacement Reserves Exchange
TSOs	Transmission system operators

point of view [12]. In Europe, there is a high share of renewable energy plants. Therefore, one of the main tasks of the European TSOs in the last years has been the integration of European electricity systems (EESs) [13], a process that is evolving rapidly [14]. With the fast development of new renewable energy plants and the ambitious plans to achieve by 2050, particular attention has been focused on the harmonization of technical, operational, and market rules governing the balancing of electricity markets. One of the most important items was the creation of the Balancing Electricity Directive, developed by the European Commission in 2017 to regulate the exchange of balancing electricity across internal European Union (EU) borders. The aim was to create a harmonized, barrier-free pan-European electricity market [15]. From the evidence, it is possible to conclude that institutional changes are extensive, that significant market harmonization and integration effort has taken place and the process is in development [16].

In the previous introductory subsection, the most important aspects involving DER integration have been analyzed. There is a large number of recent research papers exploring the impact of DERs on electricity balancing. Among the most notable may be those carried out by Díaz et al. [17] who focused on the coordination role of specialized energy aggregators to provide balancing services. Also important is the study developed by Poplavskaya & de Vires [18] who assessed the impact of different market design options on the DERs' participation in the balancing market and the investigation conducted by La Bella et al. [19] who proposed a hierarchical approach, based on an optimization model, to efficiently provide balancing services by microgrids' aggregators. Despite these previous efforts it is important to remark that the problem analyzed in this new study, the evaluation of the present configurations of the electricity balancing systems, has not received the same attention. From a deep survey of grey literature and updated literature related to this topic [20–28] it is possible to conclude that most contributions are focused on separate or individual aspects of the required integration or on the impact of DER but there is no previous global approach.

Considering the state of the art based on the DER capabilities previously studied, synthetized in Table 1, are limited for large systems such as European or American markets, [29].

This study analyzes to what degree the process of equalizing the supply and demand of electrical energy in Europe might be adapted to better accommodate the current increase of renewable energy share. The objective is to analyze, from a novel point of view that comprises all the involved aspects, how the process of equalizing the supply and demand of electrical energy can be improved in a foreseeable scenario for the whole European region. In Europe, the most important regulation, the Directive (EU) 2018/2001, aims to develop a power system with a high share of renewable energy and a large presence of DER systems. This represents a technical and market challenge as the increase in the DER systems can directly impact the required equalizing of the supply and demand of electrical energy. On the positive side, it is important to analyze if this new scenario could make it possible to avoid or minimize active power imbalances for the European networks.

Table 1
Current distributed energy resources flexibility capabilities at operational and experimental level. Adapted from [29].

Distributed energy resources flexibility capabilities	Current ranges
Regulation capabilities	Months ahead and pilot plans of intraday and near real time
Market operation	Auction or continuous trading
Maximum price regions	Up to 10 contract areas
Voltage level	≤20 kV Some HV pilot plans up to 132 kV
Number of flexibility providers	5 to 10
Flexibility magnitude	18.1 MW on a total of 94.8 MW demand Energy ranging from 10 to 100 MWh

The previous scientific literature mainly analyzes solutions to mitigate market entry obstacles of DERs but there is a lack of discussion on the role of DER in the equalization process. The objective of this study is to analyze the prevailing configurations for equalizing the supply and demand of electrical energy in Europe and, at the same time, evaluate the suitability of this future scenario. The study also compares current configurations in the European Union and the United States to highlight the challenges in both power systems.

This research is organized as follows: the first section briefly introduces the basic questions of electricity balancing; the second section presents a description of the main features of the balancing systems in the EU and in the United States of America (USA); the third section discusses the presence of DERs in electricity balancing and presents alternative proposals for electricity balancing and analyzes future research needs and the fourth section presents the conclusions.

2. Description of operations

2.1. Equalizing supply and demand: European Union and USA

This section studies how the process of equalizing the supply and demand of electricity is currently arranged in the EU and compares it with the USA's balancing system. Some non-EU European countries (such as Switzerland, Norway, the United Kingdom (UK), and some Balkan states) are to some extent grid-connected to the EU. However, while the UK and Norway have to a great extent adopted the EU's energy market rules, Switzerland and the Balkan states have not [30]. Given Switzerland's geographical centrality in the EU internal electricity market, some EU partners identify Switzerland, to a certain degree, as a "free rider" since, in various aspects, Switzerland has enjoyed privileged access to the EU market and sectoral governance, while not complying with the EU regulatory framework [31]. Therefore, in this study, the term "European Union" includes Norway and the UK.

A synchronous zone is an area in which interconnected electricity TSOs operate [32] with a coincident steady-state network frequency [33]. As the frequency in a steady-state synchronous zone is the same everywhere, in case of a disturbance the responsible entities will act at the same time in the entire synchronous zone [34]. The EESs, whose interdependent management is designated to the European Network of Transmission System Operators [35], are organized into five synchronous zones: Continental Europe, Nordic, Baltic, the UK, and Ireland [36], comprising 34 countries, and 41 TSOs [37]. The US electricity system has three major interconnections: the Eastern Interconnection, the Western Interconnection, and the Texas Interconnection [38]. Fig. 1 shows the synchronous zones in the EU (a) and in the USA (b).

To maintain balance inside the synchronous zones there are two types of controls: a primary control and a secondary control. The synchronous zone is obliged to meet the frequency quality requirements through the frequency containment process [41]. The frequency containment process, which is the primary control [42,43], stabilizes the frequency of the power system following an energy lack of balance by introducing or removing further power to the electric grid [44,45]. The objective will be met by joint action of the frequency containment reserve throughout the synchronous zone [46]. Proper activation of the frequency containment reserve results in compensation of the power system frequency at a stationary value following a lack of balance in the timespan of seconds [47]. The frequency containment process represents the fastest measure to counter frequency discrepancy [48].

The frequency restoration process, which is the secondary control [42], comprises the needed actions to mobilize the active power to recover the power system frequency to the nominal frequency [49]. The secondary control is activated by the disturbed control area [47,50].

In the USA, the electricity network is operated by balancing authorities, which ensure that energy supply and demand are balanced to sustain the reliability of the electricity network [51]. A balancing authority is in charge of the operation of an electricity transmission control area [52,53].

Although in the EU the Electricity Balancing Guideline was already adopted in November 2017, its implementation continues in discussion as the time horizons are deliberately broad [54]. It should also be noted that this process requires the harmonization of essential components of the energy directives, and all European electricity TSOs and their national regulatory authorities must agree on common protocols and standards [54]. Currently, European balancing markets for electricity are largely national markets [55]. This means that with few exceptions, each control area is responsible for the sizing, procurement, and activation of its electricity reserves [55]. The application of the European energy balancing platforms is the outcome of the work carried out by the TSOs to ensure that the balancing demand of each country is satisfied by activating the most efficient offers in Europe. This further considers operational security requirements along with increasing security of supply in Europe [13].

2.2. Balancing market platforms in Europe

In the EU there are several projects aiming to implement balance cooperation in electricity: the International Grid Control Cooperation (IGCC), the Trans European Replacement Reserves Exchange (TERRE), the Platform for International Coordination of Automatic Frequency Restoration and Stable System Operation (PICASSO) and the Manually Activated Reserves Initiative (MARI).

The IGCC is the project selected by the European Network of Transmission System Operators in February 2016 to turn into the European Platform for the imbalance netting process as defined in the electricity balancing guideline. There are two types of members of the IGCC: the operational members, those that are physically connected to the IGCC by means of communication lines that execute the imbalance netting process through the platform, and then on-operational members, those who actively participate in the decision-making of the IGCC but do not yet perform the imbalance netting process. There are twenty-one operational members and three non-operational members as represented in Fig. 2a [56].

The TERRE is the European implementation project for the exchange of electricity replacement reserves in accordance with the electricity balancing guideline. Currently, the TERRE project is implementing the Cooperation Agreement between TSOs. TERRE has been in service since January 2020. Since then, six TSOs have connected to the platform as shown in Fig. 2b [58].

The PICASSO is the implementation project approved by all TSOs through the European Network of Transmission System Operators (ENTSO-E) Market Committee (Fig. 2c). PICASSO aims to establish a European platform to provide frequency restoration with automatic activation [59].

The MARI is the European implementation project for the establishment of a platform to provide frequency restoration with manual activation. Due to the usefulness of an adequate balancing mechanism for an integrated electricity market, twenty-eight TSOs are working on the design of such a platform as represented in Fig. 2 d [57].

2.3. Comparison between Europe and USA

The balancing market in Europe is the ultimate market opportunity to balance production and consumption [60]. The present European real-time market (RTM) is only an energy balancing market and does not trade the real-time electricity reserve [61]. Differently, in the USA the RTM is an equilibrium market in which clearing prices are determined

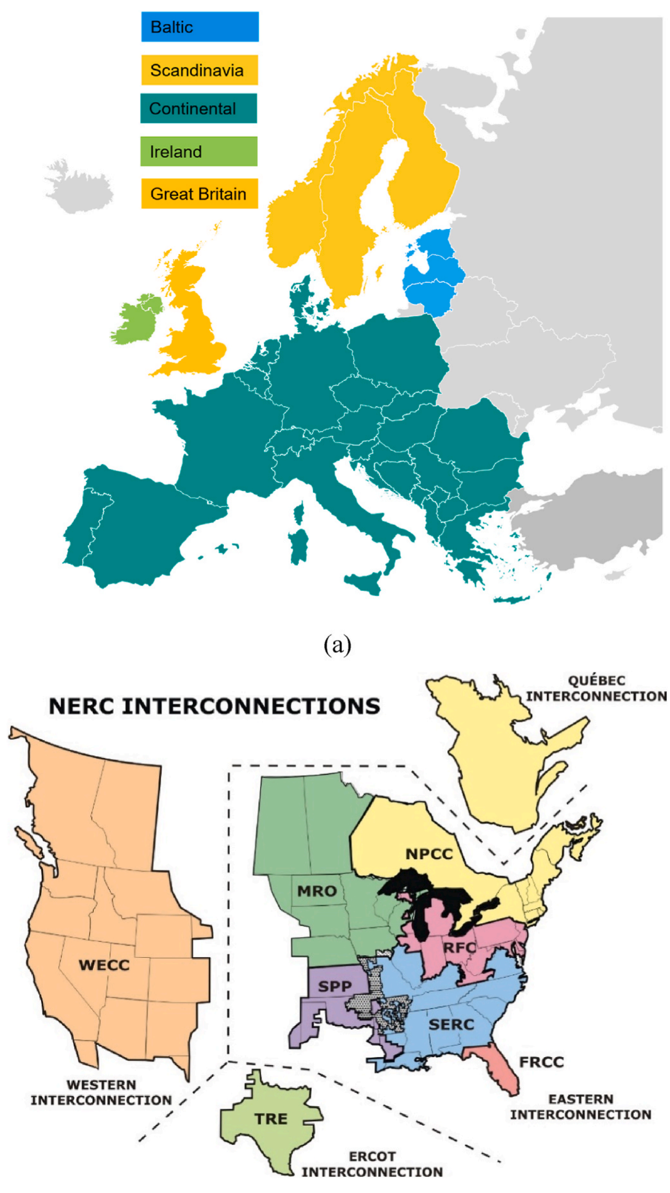

Fig. 1. Synchronous zones in EU (a) and in USA (b) [39] (a) Self-authored with data from Ref. [40] and b).

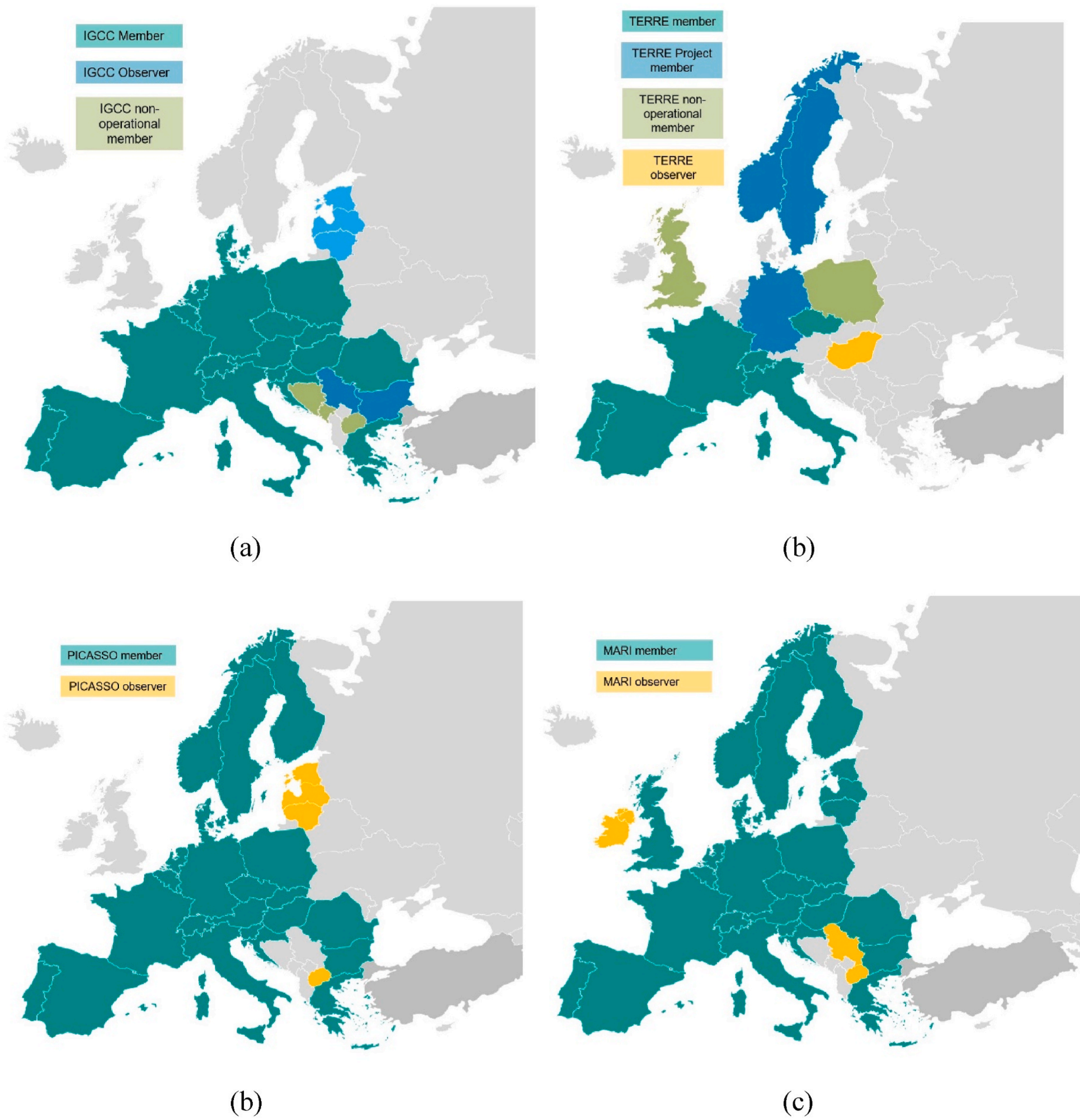

Fig. 2. IGCC membership status (a), TERRE members (b), PICASSO and MARI (d) [57] implementation project. Self-made with data from (a) [56], (b) [58], (c) [59] and (d) [57].

every 5 min based on economic dispatch with security constraints [62]. It should be mentioned that, in the USA, TSOs typically operate in two markets: the day-ahead market and the RTM. The day-ahead market, which accounts for about 95 % of power transactions, is based on the load forecast for the following day and usually takes place the morning before so that generators have time to prepare for trading. The rest of the energy market transactions (around 5 %) take place in the RTM [63]. Unlike liberalized electricity markets in the USA, which apply nodal pricing, European electricity markets are based on uniform pricing within bidding zones [64].

While European electricity grids are well developed and favor the integration of indigenous energy sources (mostly renewables), investment is needed to remove infrastructure bottlenecks between member states [65]. In Fig. 3, severe bottlenecks between the electricity systems of the EU member states are shown on the borders highlighted in red, while less severe bottlenecks are shown on the borders highlighted in amber. Bottlenecks are classified as severe is bottlenecks appear in N constraints, structural if bottleneck happens with N-1 constraints.

TSOs can make more reliable forecasts of the status of the electricity grid as the actual delivery date of electricity approaches. The available electricity transmission capacity ready for use between supply areas is decided by converting the physical electricity transmission constraints into commercial transaction constraints. These commercial transaction constraints are taken into account in the market clearing algorithm, which will determine the market prices and exchanges between bidding zones. This process is carried out one day before the delivery date, i.e., daily capacity calculation and allocation, and also continuously throughout the delivery date, for example, intraday capacity calculation and allocation. Congestions appearing subsequently in the market coupling process demand re-dispatching actions, which are coordinated between all affected electricity transmission system operators during real-time network operation [67].

Regulators, policymakers, and power system operators generally conceive electricity balancing as a “linear” process. According to this consideration, exogenous stochastic disturbances, like unforeseen atmospheric condition variations affecting wind and solar generation or

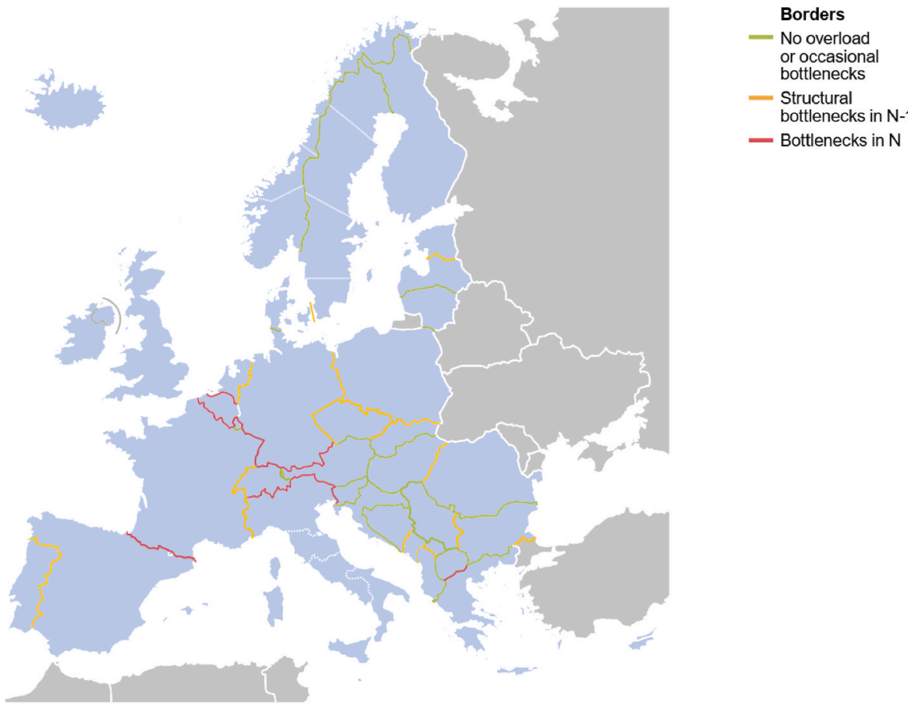

Fig. 3. Border bottlenecks between European countries [66].

technical interruptions of energy-producing stations, lead to disparities in electricity demand or supply. The aggregation of these individual deviations and the system imbalance is physically resolved by the activation of balancing reserves by the TSOs and financially settled at the imbalance price. From this point of view, the imbalance of the electricity system is the consequence of a random process that is dictated by technical parameters, such as the quality of climate predictions and power plant failure rates and there is no feedback from imbalance prices to the behavior of market parties [68].

Although this linear view is likewise aligned with the legal picture of various EU member states, it has long been suggested that there is feedback from the imbalance price of electricity to the behavior of market parties, where companies can increment revenues by purposely differing from their schedules, based on the imbalance price [68]. Fig. 4 represents the feedback effects.

Unlike electricity balancing, re-dispatching does not take the structure of a harmonized market and is applied variously by each TSOs [69]. Article 13 of the EU Electricity Market Regulation requires all member states to give access to redispatch to all suppliers containing renewable energy systems and storage systems. Furthermore, it establishes that a market-based approach to redispatch should be designed by default [70].

The main objective of the electricity imbalance price is to correctly reflect the real-time value of energy [71]. In the EU, the balancing period varies from country to country, ranging from 15 min to 1 h of settlement [72]. To encourage market participants to be in balance or to help the system restore its balance, an imbalance price is needed that corresponds to the real-time value of energy. This price should be determined by the balance between the residual supply and demand for electricity in the system [73]. In the EU, TSOs actively provide the current imbalance price almost instantaneously, so that electricity balancers can trade in real-time to adjust their production/consumption according to the price signal provided [74]. Title V of Commission Regulation (EU) 2017/2195 states that imbalance prices should indicate the real-time value of energy [75] in order to ensure that balance markets and energy systems are suitable for the integration of the growing number of DERs. In contrast to the existing integration of organized markets in the USA, the organizations in charge of managing the integrated day-ahead and intraday electricity markets are in the EU the Nominated Electricity Market Operators, not the TSOs [76].

3. The role of DERs in electricity balancing and alternative setups for electricity balancing

3.1. The role of DERs in electricity balancing

The current approach to the coordination strategy between TSOs and DSOs is shown in Fig. 5. The red color in the generator indicates a reduction of energy production in electricity dispatch, green an increase of energy production in electricity dispatch, while white indicates a lack of capacity to coordinate specific sources.

TSOs are responsible for (i) the procurement of the necessary

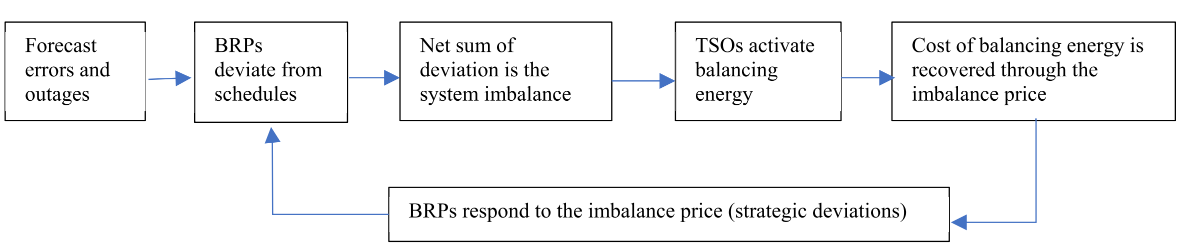

Fig. 4. Feedback perspective on the balancing system: Balance Responsible Parties respond to the imbalance price [68].

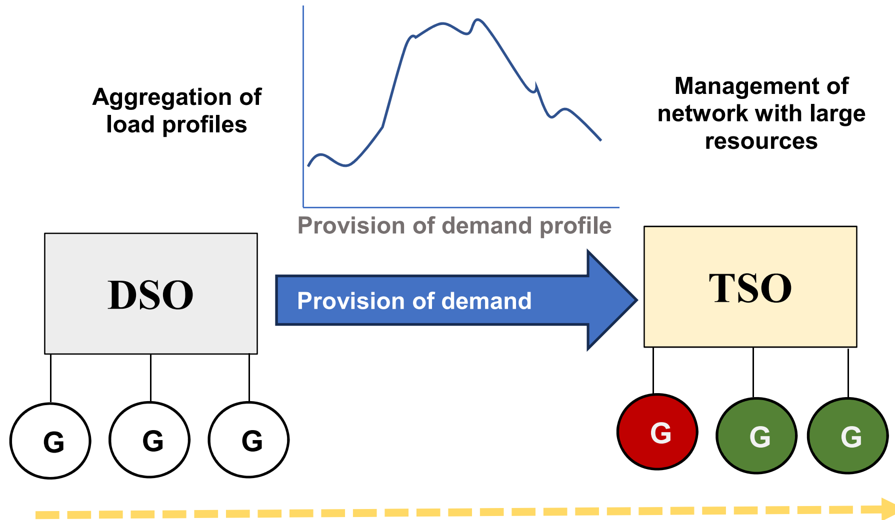

Fig. 5. Current approach to the coordination strategy between the TSO and the DSO (G stands for generator). Source: Adapted from [77].

electricity balancing capacity at the national level [78]; (ii) the implementation of globally coordinated and optimized electricity re dispatching [79]; and (iii) the control of voltage in the system as part of secure supply [80]. It is important to recall that balancing and dispatching of electricity are crucial services for the security and stability of the electricity grid which, in the EU, have not yet been fully integrated into the provision of ancillary services [81]. In this respect, the current state of reactive power compensation excludes distributed generation [82,83]. Taking Germany as an example, until very recently (October 2021) [84], electricity dispatch was only carried out with large conventional power plants from 10 MW upwards [85]. However, with the introduction of Redispatch 2.0, the DSOs are also being involved in the process. In addition to management tasks, the DSOs assume responsibility for data exchange as well as financial clearing with the Balance Responsibility Parties [86]. Virtually all of Germany's DSOs (more than 800) are involved in some way in the redistribution process [84]. Redispatch 2.0 requires increased participation of the DSOs at various voltage levels, as well as the inclusion of renewable energy system units above 100 kW [87].

DSOs can implement the voltage control requirements of TSOs by properly managing the reactive power flow in the distribution networks, as well as reactive power injection for distributed energy resources [88]. Local flexibility markets, which enable customers to shift when and how much electricity they use or generate for money, are still at an early stage across Europe due to the slow implementation of Article 32 of the Electricity Directive. However, some good practices can be found in the UK, Netherlands, and Norway, where initiatives by national regulators, electricity system operators, and joint projects with market participants have created a positive environment for developing innovative markets [89]. In a future scenario with increased flexibility needs, both TSOs and DSOs will have to coordinate to ensure that the acquisition and activation of the flexibility provided by distributed energy resources are done in the most efficient way and without compromising the security of the power system [90]. Article 17 of the Internal Electricity Market Directive requires member states to guarantee that national regulatory authorities encourage final customers, inclusive of those providing demand response through aggregators, to participate alongside generators on a non-discriminatory basis in all organized markets [91]. Fig. 6 shows an example of a single flexibility market for balancing electricity.

Considering the example of the UK, direct tariffs for the electricity

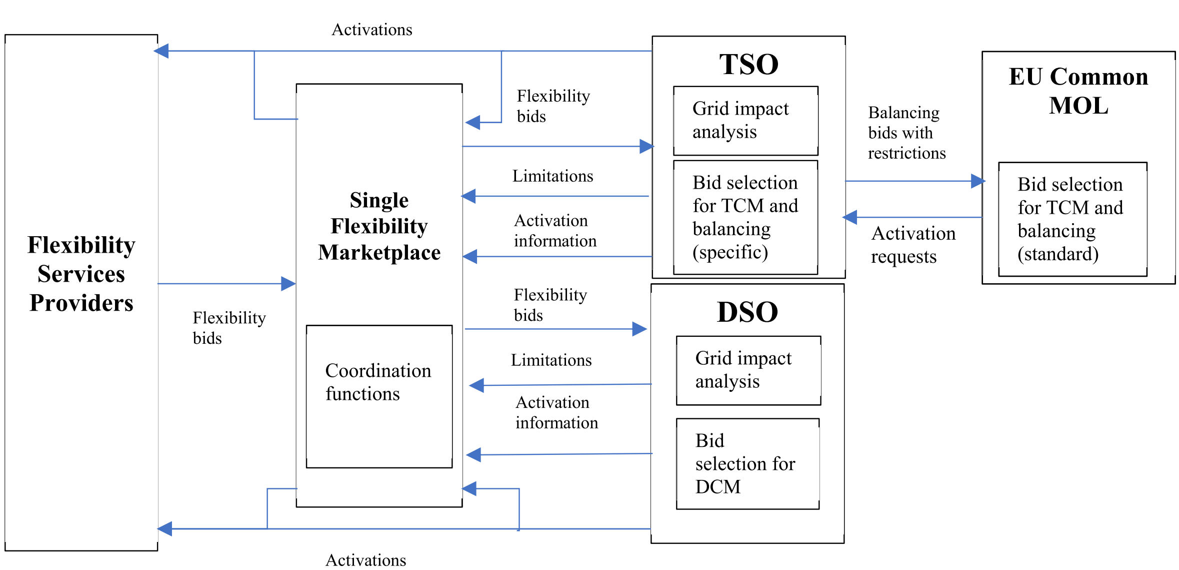

Fig. 6. Example of a single flexibility market for balancing electricity [92].

transmission network account for only five 5 % of the average annual electricity bill, while distribution networks account for approximately 25 % [93]. Distribution grids are the backbone of the digital and energy transition, guaranteeing a continuous and reliable flow of electricity, integrating most renewable energy sources, and enabling the creation of new consumer services [94]. Consequently, investments in electricity distribution networks are crucial to accelerate energy transition [95]. Visibility of power flows within distribution networks, especially in 11 kV and low voltage networks, has historically been poor, in some ways because of the absence of necessity. Nevertheless, peak demand growth, grid complexity, and decentralization [96] demand an increase in distribution system visibility and a move to greater availability of real-time data [97]. Recently, the degree of penetration of DERs in low voltage grids has been rapidly growing, which has led to the problem of voltage rise even at the furthest point of the customer in the distribution networks [98]. As a result, the traditional or natural flexibility of the distribution system is becoming insufficient due to the increasing penetration of DERs [99]. Therefore, it is widely accepted that coordination between electricity transmission and distribution markets is necessary to make the most efficient use of DERs and to avoid conflicts between the objectives of TSOs and DSOs [100].

It is necessary to remark that the total balancing capacities are quite variable and depend on some factors, the most important ones being [29]: the capability to evaluate the expected system imbalances using a near real-time or a real-time system and the share of the non-contracted real-time flexibility. This is a crucial issue because if the TSO enables the capability of proactive balancing it would be required a higher volume of ready-to-use energy and associated reserved capacity.

In the case of the EU, there are different balancing capacity markets for each of the reserve products and in each country, there is a large variety of market design parameters. An additional challenge results from the frequent modifications of the regulatory frameworks making a homogeneous operational scenario more difficult to achieve.

The particular characteristics of the balancing electricity markets in the EU, initially conceived in a centralized production framework, may restrict the presence of DERs and energy storage. Among others, these characteristics comprise long delivery periods, large minimum required capacities, and long validity periods of balancing energy offers [101]. The current European balancing markets do not sufficiently facilitate the entry of DERs [5], with some member states lacking a legal framework to allow the access and participation of new and smaller players in the different market segments [101]. In the EU, all market participants must be financially responsible for the imbalances they cause in the electricity system [70]. With regard to the abolition of priority dispatch for new renewable generators, exemptions currently only apply for renewable energy generation facilities with an installed electricity capacity of less than 400 kW (200 kW from 2026) [102,103].

3.2. Alternative setups for electricity balancing

Past decisions in the European electricity sector tend to limit the success of decarbonization efforts and strengthen the position of incumbent utilities [104]. Faced with this reality, the European Commission has recently accepted that the current European electricity market system must be adapted to the new features of mainstream renewables [105,106]. DERs pose new and unprecedented challenges to traditional planning and operations in electricity markets [107,108].

This scenario requires the creation of a new energy balancing system for all the involved countries. This demands new solutions both from technical and operational perspectives. The interconnection and widespread use of DERs will require changes in some key aspects such as infrastructure design, operation and management, real-time operational systems, generation plants, and loads interconnection or system stability.

Several previous approaches mainly focused on USA power systems, where the solutions were based on two important research works, one conducted in 2015 [109] and the other one in 2019 [110,111]. In 2015 [109] two alternatives for future grid operation were proposed: the Total TSO model and the Independent DSO model. The Total TSO model considers that increasing functions, both technical and economic, will increasingly be required in low-voltage systems due to the expansion of DERs in low-voltage grids. The DSO will contribute to this model as the owner of the distribution system and provide planning and operational support. The Independent DSO model considers three phases until its final implementation. Nowadays most common DSO operational strategy represents phase one. In phase two the DSO analyzes the potential value of DERs supports the distribution system operation and, if required, updates the existing infrastructure. Some EU countries are in this second phase. In the third phase of this implementation, an independent DSO organizes each of the local markets and operates the physical coordination of DERs. Consequently, the DSO acts as a distribution-transmission aggregator.

In [111] two options for the future grid operation strategy, the Enhanced Bulk BA Model and the Enhanced DSO model. The authors consider that the ongoing operational strategy is a hybrid model, a situation that can be applied to EU markets. Under the Enhanced Bulk BA model, the TSO and DSO functions are complementary, and the final operation will require their coordination. The DSO has to ensure that power flows, power balance, voltage levels, and system stability can guarantee the requirements of the distribution level, managed by the TSO. Under the Enhanced DSO Model, the only responsibility of the DSO will be to ensure the balance at the distribution level. This model is similar to the Independent DSO model presented in Ref. [109], where a DSO will be responsible for providing local scale aggregation services in the interface between transmission and distribution systems. Therefore, the DSO collects the information of all the DERs providing generation and their associated bids and will provide the TSO an aggregated planning of the demand and the supply bid of energy and their associated ancillary services after having checked that the desired power flows are feasible under different scenarios of power flows and prices. The most important aspect of this operational strategy is that the TSO does not require information on the distribution grid and their DERs plants because the DSO also controls the dispatched energy in real-time. These two proposals represent the extreme scenarios that have been analyzed.

The future European power system will be characterized by the predominance of carbon-neutral energy plants, the increase in flexible resources, and the interconnected power grid. Under this scenario, to ensure the technical and market operation, it is necessary to develop a System of Systems (SoSs) that will integrate both TSO and DSOs among all the involved countries [56–59]. This European power system proposal is also a model to be highlighted and that can be similarly applied at a global scale level because all power systems require similar actions to ensure the achievement of decarbonization and related objectives such as contributing to achieving the UN Sustainable Development Goals. The most important challenges to be addressed are analyzed as follows.

(i) Whole market design: an electrical market focused on the increase of DERs and, more specifically, carbon neutral systems, requires integration of consumers, generators, and energy storage to ensure the flexibility required by long-term investments based on price signals. The dispatch and consumption, conversely, must be based on short-term prices. Finally, the system operation and resilience must ensure the ancillary services and avoid system congestion. This may be achieved by plant flexibility, interconnected grids, infrastructure investments, and efficient market rules.

(ii) Investment and infrastructure: to ensure energy flows, capacity interconnection of both onshore and offshore grids aiming to connect all the involved actors is required. The cross-border interconnections must be associated with energy storage systems. Not only technical decisions are required, but also environmental procedure modifications, countries' consent, and stakeholders' dialogue must be addressed.

(iii) Flexibility: as it is foreseeable that the system will be subject to an increase in uncertainty of generation, of grid available capacity, and of energy production, it requires a combination of high power and high energy resources. The high-power systems will ensure handling short-duration flexibilities while high-energy resources will ensure the required energy flow during larger periods that, for example, can be produced due to the lack of renewable energy production in some periods (low radiation levels, lack of hydro resources, etc.). To deal with short-duration events, the coordination and integration between TSOs and DSOs is a key parameter because the most important strategies will depend on vehicle-to-grid, demand-side management, or small-scale batteries, among others. Conversely, for long-duration phenomena, it is required an interconnected European system is required to ensure the required power flows considering the different characteristics of each country. As an example, the hydropower availability or nuclear energy share strongly varies among different countries and, subsequently, SoSs will ensure the required flexibility. Hydrogen can act as a key technology for energy storage and large-capacity availability. Also, hydrogen has different requirements regarding electrical power flows among countries that, moreover, can be transported at a different time scale than the required power generation strategies.

(iv) Future grid operation: this last aspect is closely connected with the previous ones. The development of DERs directly implies an increase in the whole grid complexity and some technical aspects are crucial for system stability. For example, the connected inertia level and the short-circuit currents will change and therefore management adjustments are necessary. Handling these situations will be as important as congestion management or power flow optimization.

Considering the four previous aspects it is possible to remark that the most important aspect is that a control zone-based strategy is key to ensuring energy balancing and grid operation efficiency and this specific need requires further research. The proposed SoSs will integrate TSOs and DSOs coordinated by several Regional Coordination Centers (RCC). Under this proposed scheme the DSO will oversee the distribution control zone and all of them will be coordinated by the TSO. This is one of the most important challenges to tackle with because to ensure global system coordination the TSO will take control of other technologies involving alternative energy systems that can act as multi-energy systems ensuring the conversion of different energy sources.

The green hydrogen systems and the power-to-heat technologies have a vital role as they represent the interconnection of green gas and power grid and heat network and power to the grid, respectively. The Regional Coordination Centers will coordinate several TSOs and receive the alternative energy systems operators' signals (green energy or heat networks, for example). There are special risks and limitations to the proposal to be highlighted in the integration of novel DERs. The development of new DERs can suffer from different barriers depending on the associated control zone and, subsequently, some regions could present quite different investment and operational requirements in comparison with others. Hence, to avoid an imbalance, the TSO must harmonize the requirements and conditions for its associated distribution control zones. A graphical representation is shown in Fig. 7.

To enable the required energy balance the use of direct current systems will play a key role as this technology ensures maximum flexibility to integrate power electronics-based control systems and advanced power flow management systems. Consequently, information technologies, automation, and artificial intelligence will be crucial in system integration and operation and some key aspects, such as system stability or cybersecurity must be addressed. Under this scenario, which represents an intermediate case between the proposals analyzed in the previous section (Total TSO model and Independent DSO model), the supervision by a superior organism (a regional coordination center) can ensure the achievement of the aforenoted requirements in an increasingly low carbon power system and the roadmap to a final carbon-neutral one.

Finally, it is important to remark on the need for research efforts for the development of integration strategies at technical, management, and economic levels to ensure the deployment of power to x systems and active demand side management. Power to x systems (and reverse x to power systems) require the integration of different energy sources in the power system considering that some of them can also act as energy storage systems. Traditional power systems are based only on electrical energy and all the DSOs/TSOs operation was designed under this paradigm. The integration of power to x systems involves the management of conversion systems that can absorb electrical energy to produce heat, synthetic natural gas, or fuels, among others, and that also can operate in reverse mode to produce electrical energy. It is required to develop a whole coordinated system with other energy actors such as natural gas operators or hydrogen producers, among others, and also integrate its use as large- or small-scale energy storage systems. The

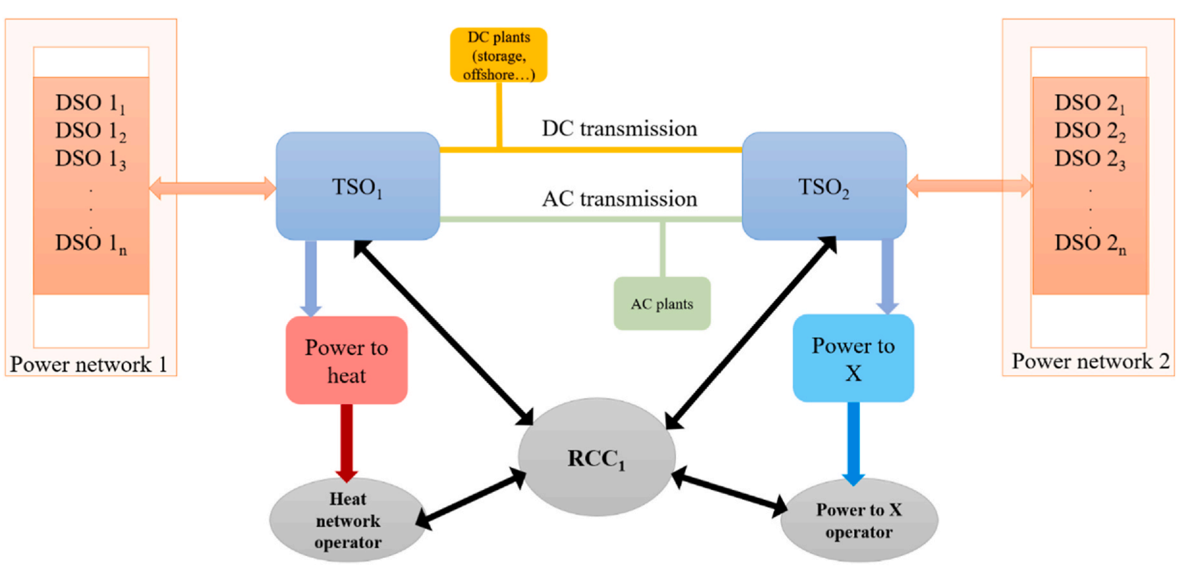

Fig. 7. Example of SoSs power structure.

effective integration of both low-level (DSO) and large-scale (TSO) active demand-side management strategies plays a vital role in ensuring power system balance. A massive deployment must be technically and economically feasible while ensuring that power grid stability is maintained. Special efforts are required to make it possible but also to enhance the integration of small-scale consumers, for example at the home level or electrical vehicles.

4. Conclusions

This study analyzes how the European power system is undergoing a fast and complex transformation towards a carbon-neutral interconnected grid. In this new scenario, DERs will increase significantly their share and other minoritarian technologies, such as energy storage or hydrogen to power, power to hydrogen, and power to x (heat, synthetic fuels, synthetic natural gas, etc.), will be vital to ensure system stability, reliability, and resilience. The market and grid conversion process must accomplish a transformation of, at least, four aspects: a new whole market design, an intensive investment and infrastructure modernization (including a large increase in interconnection grids), a flexible mechanism, and a completely new grid operational strategy. In this pan-European grid, the market opportunities will require newly provided services due to the change of current key operational aspects such as the inertia level and the short-circuit capacity of the grid. These services must be provided by the new market actors, also, new mechanisms to ensure short- and long-term flexibility are required. This new power system paradigm and model can be applied to any worldwide location as a required strategy to allow power system decarbonization.

From previous research, the operational models can be classified into two extreme scenarios: the Total TSO model, which relies on a centralized TSO, and the Independent DSO model, where each DSO would organize the local market and operate the physical coordination of DERs. Considering the complex scenario of a global European market only a mix of both proposals can ensure the required reliability and can be feasible.

This study proposes a new market organization that relies on a Systems of Systems scheme where the TSOs and DSOs will be coordinated by a Regional Coordination Centre. The Regional Coordination Centre functions will not be only electrical supervision. Also, under this system, many different energy flows (such as power to X and power to heat) must process the related power demands of other forms of energy supervisors and operators. Each TSO should coordinate several DSOs, and each of these will control and supervise one specific zone. In this complex market scheme, new technologies will be key to ensure almost real-time communication and operation, but risks of cyberattacks and cybersecurity may arise. A deep coordination between all the involved countries and regulators is required in the transformation process. Additionally, administrative changes are required to ensure a fast implementation, which requires the simplification of the procedure. As shown in this research there are several particular configurations theoretically desirable, but their feasibility depends on a vast number of circumstances. During the transformation process, when the configuration is adopted strong difficulties in economically equalizing the electrical energy supply in European are predictable.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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