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Review

TSO/DSO Coordination for RES Integration: A Systematic Literature Review

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Abstract: The increasing penetration of large-scale Renewable Energy Sources (RESs) has raised several challenges for power grid operation. Power management solutions supporting the integration of RESs, such as those based on energy storage technologies, are generally costly. Alternatively, promoting a more proactive role of the Distribution System Operator (DSO) to successfully manage RESs' uncertainty, and take advantage of their flexible resources for the provision of ancillary services, can avoid installing expensive devices in the network and reduce costs. In this line, improved coordination between Transmission System Operators (TSOs) and DSOs is highly desirable. In this paper, the feasibility of solving different aspects of the integration of RESs through an improved TSO/DSO coordination is evaluated. In particular, a Systematic Literature Review (SLR) is conducted to study the most relevant TSO/DSO coordination approaches, exclusively focused on integrating distributed RESs, currently available in the literature. Their main operational, managerial, economic, and computational challenges, advantages, and disadvantages are discussed in detail to identify the most promising research trends and the most concerning research gaps to pave the way for future research toward developing a solid TSO/DSO coordination mechanism for integrating RESs efficiently. The main results of the SLR show a clear trend in implementing decentralized TSO/DSO coordination models since they provide efficient facilitation of RESs' services, while reducing computational burden and communication complexity and, consequently, reducing operative costs. In addition, while different aspects of the TSO/DSO coordination implementation, such as reactive power and voltage regulation, operational cost minimization, operational planning, and congestion management, have been thoroughly addressed in the literature, further research is needed regarding data exchange mechanisms and RESs' uncertainty modeling and prediction. In this line, the development of standardized communication solutions, based on the Common Grid Model Exchange Standard (CGMES) of the International Electrotechnical Commission (IEC), has shown promising interoperability results, whereas the use of learning-based approaches to predict RESs' uncertain behavior and distribution networks' responses, using only historical data, which relieves the need for access to commercially sensitive and proprietary network data, has also shown itself to be a promising research direction.

Keywords: Renewable Energy Sources (RESs); Coordination of Transmission System Operators (TSOs) and Distribution System Operators (DSOs); RESs integration

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1. Introduction

In recent years, the energy market has shifted toward more sustainable electricity production, favoring the penetration of Renewable Energy Sources (RESs) in the distribution grid. In general, installing control devices, such as energy storage systems, to manage the nonsynchronous power generation from RESs at the distribution level is expensive. Alternatively, planning strategies based on the coordination between Transmission Systems Operators (TSOs) and Distribution System Operators (DSOs) can be used to solve

RESs power management, avoiding the need for expensive devices and reducing operative costs [1–5]. Within a coordination framework, TSOs should support voltage in the transmission network and maintain the overall system security via frequency control, as well as congestion management across borders and on the TSO level. DSOs, for their part, should manage voltage stability and congestion on the distribution grid and be responsible for providing data about consumers and distributed generation behavior to the TSOs. In order to do so in a cost- and resource-efficient way, both TSOs and DSOs should rely upon scheduled and coordinated access to a common set of supply and demand side resources enabling them to fulfill their missions while keeping a power system sustainable and secure in its supply of power.

In general, the main barriers to designing and implementing market concepts for TSO/DSO coordination are regulatory [5]. Nevertheless, numerous technical challenges remain unsolved [3–10], In [6], the EU regulation has introduced different network codes where the bases for developing different TSO/DSO coordination concepts are set. According to [6], further research is needed regarding market design, operational procedures, and data exchange toward allowing TSOs and DSOs to support each other within a reliable, efficient, and cost-effective grid operation in the presence of RESs. In [3], different market designs for coordinating TSOs and DSOs are studied. In particular, DSO-leader, DSO-follower, and TSO/DSO hybrid-managed models are considered. Results in [3] show that the TSO/DSO hybrid-managed model enables higher social welfare at the expense of more technical, computational, and administrative complexity. In [8], five options to organize the collaboration between TSOs and DSOs are studied. In particular, local Ancillary Service (AS) markets, centralized AS markets, common TSO/DSO AS markets, integrated flexibility markets, and shared balancing responsibility models are considered. Authors in [8] conclude that, independently of the chosen coordination model, business processes and communication infrastructure need to be updated toward properly integrating RESs. In a recent review in [7], these conceptual models' technical feasibility and barriers are evaluated. Authors in [7] have found that, although different solutions, such as the single-phase Alternating Current (AC) Optimal Power Flow (OPF) are available to solve medium-scale Distributed Energy Resources (DERs) connected to Medium Voltage (MV) levels, there is a need for three-phase approaches capable of handling multiple voltage levels, including MV and Low Voltage (LV). In [4], the economic aspects of the different conceptual market options are evaluated through a cost-benefit analysis. Results in [4] show that the TSO/DSO hybrid managed model, relying on a common AS market, achieved the best economic performance. Nevertheless, authors in [4] highlight that this performance is highly dependent on forecasting errors, making it necessary to develop more accurate forecasting techniques.

In [9], the regulatory framework for data exchange between TSOs, DSOs, and other aggregators is studied. Since most of the RESs are connected to its grid, the DSO plays a vital role in the data exchange mechanism. In particular, it is crucial for the DSO to accurately estimate network data for balancing and visibility purposes, so as to avoid installing new and expensive devices. In this line, an extensive survey studying the current real scenario of data exchange between TSOs and DSOs is presented in [5]. Results in [5] show a need to develop dedicated platforms for energy data exchanges and cross-sector interoperability between such platforms. In addition, the importance of implementing standardized approaches to use case descriptions for TSO/DSO coordination is highlighted. The results of the recent review conducted in [10], where the current European scenario regarding TSO/DSO coordination is evaluated, agree with the ones discussed in [9] and [5]. In particular, they show that, although researchers agree that a fully integrated and regulated market is the solution to the integration issue of RESs, stakeholders are still concerned about the lack of a standardized exchange data mechanism.

Despite the great efforts in the literature, there are different aspects of the real-life implementation of a TSO/DSO coordinated environment to integrate RESs that require further investigation. In particular, further research is needed regarding the economic, operational, managerial, and computational feasibility of each of the conceptual frameworks available for TSO/DSO coordination, data exchange and the uncertainty of RES forecasting issues being of particular interest. In this paper, a Systematic Literature Review (SLR) is conducted to study the most relevant approaches currently available in the literature to perform direct coordination between TSOs and DSOs as a mechanism for integrating the continuously increasing number of different types of RESs—Distributed Generators (DGs), Photovoltaic (PV) generators, and wind units—in multi-carrier energy distribution grids. Their implementation is analyzed, with a special focus on to what extent, and how, they have addressed and solved the most concerning economic, operational, managerial, and computational grid challenges within the context of a high RES penetration. In particular, TSO/DSO coordination approaches are evaluated in terms of the conceptual framework supporting the coordination, the proposed model to solve the coordination problem, its implementation, encompassing formulation, optimization, and solution, and the field or simulation tests conducted to evaluate its performance, along with the results obtained. The results of the SLR provide valuable insights into the best available practices to coordinate TSOs and DSOs for purposes of the integration of RESs, giving stakeholders useful tools to design, and implement, a suitable TSO/DSO coordination approach that can adequately adapt to their needs. In addition, solid research directions toward developing and implementing novel and more efficient TSO/DSO coordination strategies to integrate distributed RESs are discussed.

2. Review Methodology

2.1. Review Scope

The SLR conducted in this paper is mainly focused on studying to what extent, and how, the most concerning economic, operational, managerial, and computational grid challenges within the context of a high RES penetration have been addressed and solved by the TSO/DSO coordination approaches available in the literature. In particular, how the TSO/DSO coordination problem is formulated, optimized, solved, and evaluated is analyzed. Here, it is important to highlight that the penetration of RESs refers to the percentage of electricity generated by RESs, which is usually compared to the amount of electricity consumed, since RESs are generally close to the load. In this paper, multi-carrier grids are considered, studying the penetration of different types of RESs, including, but not limited to, DGs, PV generators, and wind units.

2.2. Research Questions

In the SLR conducted in this paper, the following Research Questions (RQs) are defined:

- RQ1: What are the current trends in the TSO/DSO coordination to efficiently integrate distributed RESs?
- RQ2: How are the main TSO/DSO coordination frameworks implemented?
- RQ3: Which are the main operational, economic, managerial, and computational grid challenges addressed and solved by these TSO/DSO coordination approaches?

2.3. Literature Search

The literature search conducted in this paper is based on the database search methodology [11,12]. According to [12], a well-conducted literature search should include multidisciplinary sources, which provide broad coverage, and specialized ones, which offer a high coverage of a particular topic. Different famous publishers, such as Wiley, Institution of Engineering and Technology, Institute of Electrical and Electronics Engineers (IEEE), Springer, and Elsevier, provide good coverage of electrical and energy engineering articles. Some of their libraries are indexed in Google Scholar (GS). In this paper, GS has been used to retrieve free-access articles from these publishers, as well as to search for grey literature, including Ph.D. theses and reports from the leading associations in the field of power systems, such as *Conseil International des Grands Réseaux Électriques* (CIGRE) and the European Network of Transmission System Operators for Electricity (ENTSO-E) [13]. In addition, Wiley, ScienceDirect, IEEE Xplore, and Springer database engines have also been used to search the literature.

The databases were searched for relevant contributions to the SLR topic based on the following search strings:

- Practical implementation of TSO/DSO coordination schemes for integrating distributed RESs.
- Economic, operational, managerial, and computational grid challenges solved by TSO/DSO coordination-based RESs' integration.

2.4. Inclusion/Exclusion Criteria

In this paper, books, international journals, proceedings of international conferences, and grey literature, such as Ph.D. theses and CIGRE and ENTSO-E reports, were considered for inclusion in the SLR. Articles that lacked a peer-reviewed process, such as online presentations, were not. In particular, it is essential to highlight that the SLR is exclusively focused on studying the TSO/DSO direct coordination as a mechanism for integrating distributed RESs. In this line, articles addressing the technical interaction or the organizational cooperation between TSOs and DSOs, as well as articles that were not focused on integrating distributed RESs, were out of the scope of the SLR. Finally, as the main objective of the SLR was to study the most recent developments and the current trends in the TSO/DSO coordination schemes, only articles published from 2011 were considered.

2.5. Literature Search Results

Figure 1 shows the literature search conducted in this paper. In the first step, 733 articles were retrieved. A preliminary relevance study was then performed by evaluating the title of each one of them. Whenever the article's title suggested it discussed the TSO/DSO direct coordination as a mechanism for integrating distributed RESs, the complete reference, which included the abstract, was retrieved for further evaluation. After that, 58 duplicated articles were removed. Then, to evaluate to what extent the articles were relevant to the SLR subject, abstract screening was performed, resulting in 126 articles. The full-text articles were acquired for each of these, and their quality and eligibility were evaluated. After a careful reading, 61 articles that did not meet the inclusion criteria introduced in Section 2.3 were excluded. The main reason for excluding these articles was that they did not address the TSO/DSO coordination problem from a RES integration perspective. In addition, articles that were poorly written, or the results of which were not statistically significant were also excluded.

As a result of the literature search described above, 65 articles were included in the SLR. Of these, 60% (39 out of 65) were journal articles, 21.54% (14 out of 65) were conferences papers, 12.3% (8 out of 65) were technical reports, 4.61% (3 out of 65) were Ph.D. theses, and 1.54% (1 out of 65) were books. In addition, it is important to highlight that 78.46% (51 out of 65) of the selected articles have been published in the last three years (2019, 2020, and 2021), 25.5% (13 out of 65) of which were published in the last year (2021). This confirmed that TSO/DSO coordination, focused on integrating distributed RESs, is a hot research topic. The list of the selected articles is as follows: [3–10,14–70]. Their full reference can be found in Table A1 in Appendix A.

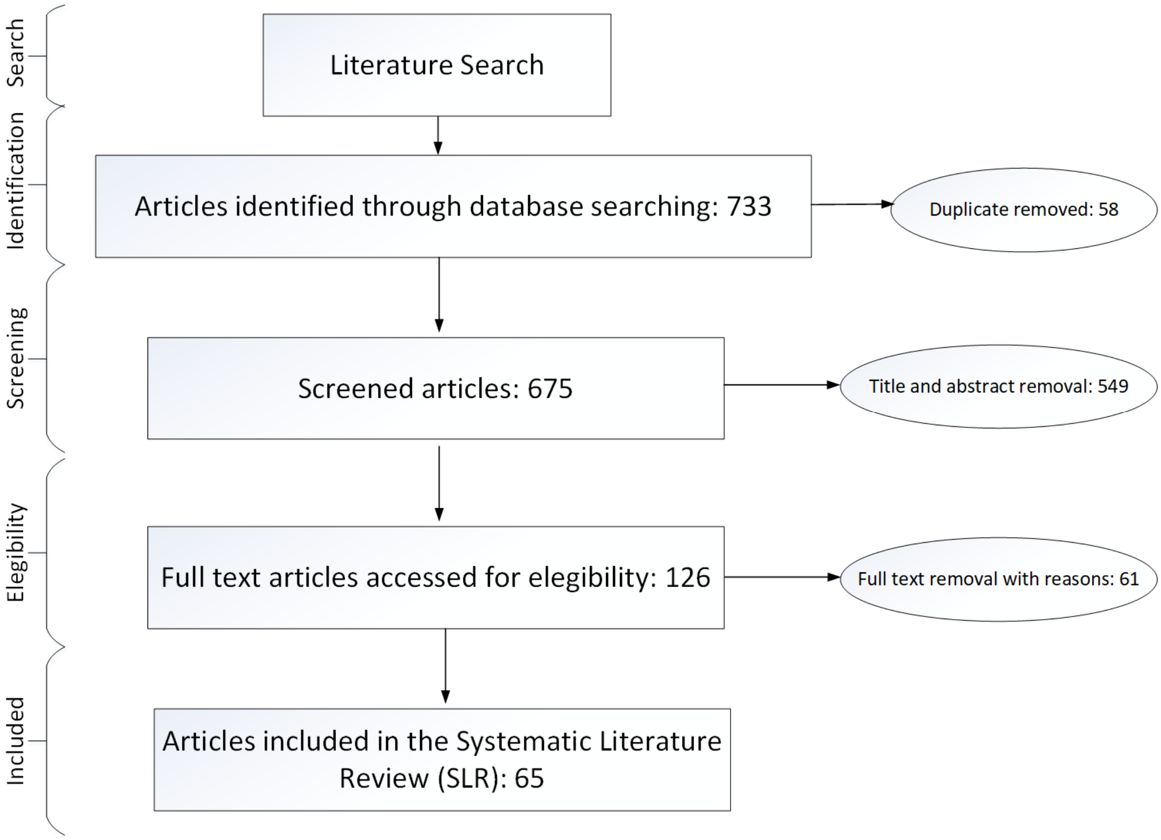

Figure 1. Literature search flow diagram.

3. Results of the SLR

To guarantee the full integration of distributed RESs, an accurate state estimation of the distribution system in terms of power flow predictability, proper voltage regulation, and active power modulation should be ensured [9]. On the one hand, the distribution grid state estimation and the voltage regulation increase the hosting capacity and the optimization of network development. On the other hand, the active power modulation avoids uncontrolled island operation, ensuring that the distribution system works safely. The energy and power management strategies to integrate RESs are usually classified into planning methodologies, focused on strategic and tactical issues, and control techniques, focused on operational purposes. In this paper, the planning methodologies based on TSO/DSO coordination approaches for RESs integration were of particular interest.

According to [71], a successful TSO/DSO coordination environment should ensure coordinated access to resources, regulatory stability, grid visibility, and data management. In this section, the results of the SLR are analyzed and discussed to evaluate to what extent, and how, the different TSO/DSO coordination approaches proposed in the literature achieved these objectives. Table 1 shows the research proposal of the selected articles in the SLR. According to Table 1, 6 (9.23%) articles reviewed the literature, 16 (24.62%) provided a conceptual study, 4 (6.15%) conducted a pilot study, and 39 (60%) proposed a novel TSO/DSO coordination approach.

Table 1. Research proposal of the selected articles.

Research Proposal	Articles
Review	[3,7,9,10,25,47]
Conceptual study	[4–6,8,36,49,50,54,55,58–60,63–65,67]

Table 1. *Cont.*

Research Proposal	Articles
Pilot study	[18,24,31,37]
Novel TSO/DSO coordination approach	[14–17,19–23,26–30,32–35,38–46,48,51–53,56,57,61,62,66,68–70]

3.1. TSO/DSO Coordination: Conceptual Framework

The different frameworks proposed in the literature to coordinate TSOs and DSOs can be broadly classified into centralized and decentralized schemes [14,15]. In the centralized approach, the TSO uses generators at the transmission and distribution levels to satisfy both systems. In this case, different systems, such as balancing markets, should be in place to help the TSO to balance the grid. Although TSOs can, to some extent, manage to operate the system even in the presence of RESs in the distribution grids, the increasing share of RESs has taken this approach to its boundaries. On the one hand, the TSO requires visibility for all the parameters of the transmission and distribution networks, including generators and loads, making the process computationally expensive and requiring a complex communication infrastructure. On the other hand, the distributed, large number, and small scale parameters at the distribution level are difficult to control centrally at the transmission level [15].

To overcome the technical issues of the centralized approach, the decentralized approach proposes a more common market where the TSO and the DSO are responsible for their own operation cost minimization, taking into account the RESs connected to each system. In this way, decentralized approaches are expected to facilitate RESs' services more efficiently, while having fewer computational, modeling, and communication requirements. These advantages have made decentralized approaches very popular among researchers in the field. The SLR results shown in Table 2, where the articles implementing centralized and decentralized strategies are listed, confirm this popularity. In particular, only 2 (5.12%) out of the 39 articles that actually implement a TSO/DSO coordination approach implement a centralized one.

Table 2. TSO/DSO coordination model.

Approach		Articles
Decentralized	Distributed	[21–23,26–28,33,38,39,44,45,48,52,53,56,57,65,68]
	Hierarchical	[14–17,20,29,30,32,34,40,41,43,51,56,61]
Centralized		[14,56]

Centralized versus Decentralized TSO/DSO Coordination

In [14,56], the performance of centralized and decentralized TSO/DSO coordination approaches implemented on the same power system were compared. In the centralized approach analyzed in [14], the TSO is responsible for the entire system operation, having access to the distribution system data. In such a case, the objective is to minimize the deviation of the distribution system voltage from reference, the distributed resources cost, and the transmission system operating cost. In the decentralized approach, the TSO and the DSO collaborate to allocate all resources in the system optimally. Results in [14] show that both coordination schemes reduce operational costs for both TSOs and DSOs, relieve congestion, and favor the use of distributed generation. In addition, it is highlighted that the use of distributed RESs, rather than traditional generators connected at the transmission level, promoted by the decentralized approach, significantly reduces the transmission operation cost. In [56], a centralized and two decentralized TSO/DSO coordination approaches are compared. The centralized approach is formulated as a standard constrained optimization problem, whereas the decentralized ones are developed based on a game-theoretic strategy. Results in [56] show that the centralized approach outperforms the decentralized approaches in terms of resource allocation. This is usually the case, since decentralized approaches tend to increase system imbalance. Nevertheless, the decentralized approaches have shown themselves to be more profitable for the TSO, due to their lower computational costs.

3.2. TSO/DSO Coordination: Problem Formulation

3.2.1. TSO/DSO Coordination: Optimization Problem

Optimization methods have been widely used in power system operation, analysis, and planning [72]. According to the SLR results, it is common practice to formulate the TSO/DSO coordination problem as an optimization problem. Optimization problems aim to minimize (or maximize) a mathematical objective function. The optimization result is the selection of the best elements (i.e., the best-suited model parameters) from a given set of available alternatives. In the case of TSO/DSO coordination, the optimization problem minimizes or maximizes an objective function while satisfying a set of operational and physical constraints [72,73]. Depending on the main aim of the TSO/DSO coordination problem, the objective functions can be related to operational costs or voltage stability, among others [72]. To capture the different aspects involved in the TSO/DSO optimization problems, different mathematical formulations can be used, OPF and Unit Commitment (UC) problems being among the most frequent ones. In Table 3, how the TSO/DSO coordination optimization problem has been formulated in the different articles in the SLR is shown.

Table 3. TSO/DSO coordination optimization problem formulation.

Optimization Problem Formulation	Articles
Optimal power flow	[14,16,26–30,32,34,39,43–46,48,49,51,53,56,64,68]
Unit commitment	[20,34,57]
Volt-Var optimization	[27,41]
Economic dispatch	[17,26,30,34,51]
Others	[15,22,35,40,56,61,69]

3.2.2. TSO/DSO Coordination: Optimization Problem Solution

Finding the optimal solution for the TSO/DSO coordination optimization problem is a crucial step toward ensuring the success of the whole TSO/DSO coordination approach, since their convergence capability directly impacts the feasibility, as well as the time and resource consumption, of the implementation. Different methods are available in the literature to solve the optimization problems, referred to in Table 3. These methods range from heuristic techniques to complex mathematical algorithms, such as Diagonal Quadratic Approximation (DQA), and benchmark commercial solvers, such as CPLEX, Gurobi, KNITRO, and FICO Xpress solver. Table 4 lists the different optimization problem solvers used in the selected articles, while Table 5 shows the mathematical modeling tools used to implement them.

Table 4. Optimization-solving techniques.

Optimization Problem Solver	Articles
Interior point solver	[16,39,46,51,55,61]
Heuristic techniques	[21,27,44]
Multi-parametric programming	[17]
Diagonal quadratic approximation	[32]
Pareto front optimization	[14]
Fuzzy min-max approach	[35]

Table 4. *Cont.*

Optimization Problem Solver	Articles
CPLEX	[28,40]
Pattern search optimization	[41]
Gurobi solver	[15,49,52,53]
Nabetani, Tseng and Fukushima	[55]
KNITRO	[39,45]
FICO Xpress solver	[20]
Sequential least squares programming	[22]
MOSEK	[51,55]
Discrete and continuous optimizer	[43]
Gauss-Newton method	[44]
Interior point optimizer	[29,46,55,61]
Newton-Raphson method	[30]
Dynamic programming	[69]

Table 5. Mathematical modeling tools.

Mathematical Modeling Tools	Articles
DIgSILENT programming language	[46]
A mathematical programming language	[44]
Matlab	[16,26,29,30,41,43,44,48,49,51–55,57,61]
Advanced interactive multidimensional modeling system	[39]
Python	[22]
General algebraic modeling language	[26,35,43,45,51]
MOSEL programming language	[20]

Distributed versus Hierarchical Approach

According to the chosen TSO/DSO coordination framework, the optimization problem—formulated as in Table 3—can be addressed in a centralized or decentralized way. In the former, mathematical methods, such as the ones in Table 2, solve a single large-scale optimization problem. As shown in Table 2, this is rarely done in the literature because of its complexity. In the latter, the large-scale problem is decoupled into smaller optimization subproblems, and each is solved by a solver, like the ones in Table 4. To simplify the optimization problem solution, the large-scale problem decomposition of decentralized methods can be organized according to a distributed or hierarchical scheme. In distributed approaches, all local RESs connected to the market communication graph can potentially be selected to meet the load. In hierarchical methods, the interaction between the distributed resources in the distribution and transmission levels is based on a leader–follower scheme, where the leader has fixed decision variables and leads the followers in making decisions [74]. As shown in Table 2, 18 (46.15%) articles proposed distributed schemes, while 15 (38.46%) provided hierarchical solutions. In general, these approaches have different pros and cons; choosing one depends on the application.

In distributed approaches, the different system operators, such as the TSO and DSO, solve their own optimization subproblems, based on the decomposition of boundary bus variables, and iteratively return results to another system until an equilibrium is achieved. In this way, the data privacy of the independent system operators is preserved, and a simple communication infrastructure is required. In addition, the distributed structure is robust against nodal attacks or failures, allowing the whole architecture to remain in place and information to find other paths to circulate, thus avoiding malicious nodes and corrupted paths. In [23], a multiple-input multiple-output distributed control concept for TSO/DSO coordination is proposed. The proposed approach provides operational flexibility to the TSO and neighboring DSOs by tracking reference functions for the power flow interconnection, while respecting internal voltage limits for its buses. Results in [23] show the advantages of the proposed distributed approach, where the TSO and DSO controllers are independent and have the authority to maintain local voltage limits, which avoids the need for any central control. In this way, different DGs can be connected or disconnected with no integration into each other and no redesign of the control architecture. In [26], a robust and fast distributed TSO/DSO coordination scheme for multi-period Economic Dispatch (ED) of transmission and distribution systems, based on TSO and DSO subproblems, solved by the accelerated augmented Lagrangian method, is proposed. Each subproblem is formulated based on linearized and Second-Order Cone Programming-based relationships to address the uncertainties of distributed RESs. Simulation results in [26] confirm that the proposed approach achieves economic benefits and improves power and congestion management. In addition, compared to a centralized, and other decentralized methods, the proposed approach provides computational advantages in terms of accuracy and time. In [27], a novel distributed approach called competitive decentralized transmission and distribution is introduced to solve the Volt-VAr optimization problem. Results in [27] confirm the efficiency of the proposed framework in terms of power loss, voltage profile, and reactive power generation, compared with other decentralized approaches based on isolated and interactive cooperative methods.

One of the main issues of distributed schemes is that their iterative nature makes them computationally expensive, and it is not always possible to reach an overall optimum solution. In addition, the cross-couplings and interactions among the individual control loops may be difficult to avoid and lead to grid instability. Hierarchical methods, for their part, can make coordination easier, more reliable, and computationally efficient by implementing a master–slave structure. They divide the large-scale optimization problem into slave subproblems solved by a system operator (for instance, the DSO) and a master problem solved by a central coordinator (for example, the TSO). Each subproblem is solved in parallel by the slaves, which optimizes computational time, and the solution is sent to the master. During each iteration, only a few boundary variables need to be shared, and each slave communicates only with the master [74]. In this way, the data exchange remains minimal, and the communication infrastructure is still simple. Unfortunately, since they require a central coordinator, hierarchical approaches are usually more vulnerable to cyberattacks than distributed ones.

Analytical Target Cascading (ATC) [15,32,61] and Alternating Direction Method of Multipliers (ADMM) [16] are decomposition methods which are highly used to implement hierarchical TSO/DSO coordination. In [32], a bi-level hierarchical optimization of TSO/DSO coordination is proposed, based on ATC. The TSO solves the upper-level OPF, while the DSO solves the lower-level OPF. Each OPF is locally and parallel solved by the DQA and the Truncated DQA (TDQA) algorithms. In this way, the computational time is kept low, especially in the case of the TDQA, which takes fewer iterations to converge to the optimal solution. Results in [32] show that the proposed ATC-based hierarchical optimization approach can coordinate the DSO and TSO while keeping their commercially sensitive information private, by exchanging a limited number of target and response variables. In addition, the proposed strategy to initialize the target/response pairs and multipliers significantly enhances the solution speed. In [61], the economic planning scheme is solved by a stochastic bi-level hierarchical TSO/DSO coordination approach. The planning problems of the distribution and transmission networks, in which active and reactive power, as well as voltage are considered, are solved in parallel to minimize the operation cost while satisfying security constraints. Results in [61] show that the proposed stochastic and hierarchical approach provides robust and computationally efficient coordination between TSOs and

DSOs with few communication burdens. In [15], a coordinated restoration of TSOs and DSOs is performed, based on the ATC approach. In particular, a modified ATC approach is proposed to overcome non-convergence issues due to the tremendous discrete variables and special constraints in the restoration application. Results in [15] show the benefits of the modified ATC approach compared to the traditional one in terms of convergence and computing time for restoration applications.

In [16], ADMM is used to implement a three-level hierarchical TSO/DSO coordination approach. In the proposed approach, the DSO acts as the coordinator (master) of the first level and aggregates the RESs in the LV and MV levels, consisting of the second and third levels, respectively. Results in [16] show the benefits of the three-level hierarchical solution, which allows different control functions, including voltage regulation, power loss reduction, and congestion management, respectively. In addition, the authors in [16] highlight the advantages of using ADMMs, which ensure a convergence that can be easily improved by adequately choosing a tuning parameter. Benders decomposition has also been widely used for hierarchical TSO/DSO coordination [51]. In [51], it is used to implement an efficient ED between the TSO and DSO. The proposed approach is based on communicating the generalized bid function from the DSO to the TSO. Results in [51] show that the proposed approach provides very competitive results compared with the centralized dispatch within only three iterations. In addition, modeling the generation reserves schedule by the convex AC-OPF model allows the proposed TSO/DSO coordination framework to efficiently coordinate energy and reserves simultaneously, balancing the power system in real time.

Finally, game theory provides valuable tools to implement decentralized approaches, either distributed or hierarchical [56]. In [56], distributed and hierarchical TSO/DSO coordination schemes are implemented resorting to a noncooperative game and a Stackelberg game, respectively. These game-theoretic-based approaches rely on reformulating the power balance equations by introducing linear mappings between the state and the decision variables and are solved by spanning a set of generalized Nash equilibria solutions. Results in [56] show that the hierarchical approach, based on the Stackelberg game, provides higher profits for the TSO than the noncooperative distributed approach; however, its resource allocation performance is poorer.

Deterministic versus Stochastic/Robust Approach

The TSO/DSO coordination optimization problem to integrate distributed RESs is especially challenging due to the injection of large amounts of randomness into the power system, which makes the power balance equation stochastic rather than deterministic [73]. In this line, the traditionally used deterministic optimization approaches, which consider no uncertainty, have been gradually replaced by stochastic and robust approaches to deal with the RESs' uncertainty.

Deterministic approaches assume the random variables in the power balance equation are known and predefined and replace them with values that best represent their estimates. This is usually done via mixed integer programming resorting to dynamic programming, priority list, and Lagrangian Relaxation techniques, among others. For instance, in [28], a deterministic TSO/DSO operational planning coordination problem is solved by decomposing it into TSO and DSO subproblems coordinated by updating Lagrangian multipliers. Results in [28] demonstrate the effectiveness of the proposed TSO/DSO coordination approach to handle nonlinear constraints that delineate convex and non-convex feasible regions to handle AC-OPF within UC problems. Non-probabilistic optimization methods, such as the one in [28], have the advantage of being simple. However, their efficiency decreases when there is a large-scale RES penetration, since the accuracy of the deterministically predicted uncertainty values significantly differ from the real ones, preventing the model from fully capturing the RESs' dynamics in terms of fluctuations, varying demands, and intermittent economic parameters.

To overcome the drawbacks of deterministic approaches, stochastic methods use probabilistic or fuzzy logic techniques to model the uncertain variables related to RESs [43,57,61,75].

In particular, Probability Density Functions (PDFs) or scenarios, which are discrete PDFs, are used. Stochastic models have been used to address different aspects of the grid operation to integrate RESs. In [75], a stochastic multi-objective daily energy management for Multi-Microgrids (MMGs) is proposed to optimize the MMGs' cost and their independent performance. The RESs' uncertainty is modeled using a scenario generation and reduction decision-making method and solved by a Compromised Program method to deal with the proposed non-homogeneous objective optimization. The results of the different case studies conducted in [75] show that the proposed approach reduces CO2 emissions and improves the MMGs' independence. In [43,57] and [61], stochastic approaches were implemented to coordinate TSOs and DSOs for the sake of RES integration. In [57], a stochastic TSO/DSO coordination algorithm is proposed to solve the security-constrained UC problem. In particular, a single TSO/DSO coordination problem, based on two different penalty functions, Augmented Lagrange and Quadratic, is solved using probabilistic characteristics, such as mean and Standard Deviation, of the shared variables. Results in [57] show that the proposed approach outperforms the traditionally used method of solving the coordination problem for different scenarios. In addition, the Augmented Lagrange penalty function provides a faster convergence in large-scale systems. In [43], the uncertainty of RESs is modeled by probabilistic spatiotemporal trajectories and handled via a stochastic AC-OPF optimization problem. Results in [43], obtained using real generation and consumption test data, show that the proposed stochastic TSO/DSO coordination approach allows the DSO to provide services to the TSO based on the RESs' leverage.

Stochastic methods rely on statistical approaches, such as the Monte-Carlo simulations, to construct PDFs, which only work well when a significant amount of data is available. If this is not the case, the method is not able to reliably compute or estimate a representative PDF, and the stochastic-based RESs' uncertainty predictions are unrealistic. According to [76], when the optimal stochastic solution cannot be achieved, it is better to focus on critical outcomes that have to be satisfied, rather than focusing on optimality. In this scenario, robust strategies, which focus on the methods' robustness to uncertainty, rather than on the solution's optimality, have been demonstrated to achieve good results [76]. In recent years, robust approaches have been implemented in different grid applications to integrate RESs [26,40,52]. In [77], a robust control of microgrids is proposed to minimize the total economic cost and satisfy different requests of final users. The proposed approach handles the data uncertainty by a robust Model Predictive Control (MPC). In addition, various robustness factors are defined, and their performance against uncertainty variations is evaluated. Results in [77] show that the proposed robust MPC-based control can efficiently schedule multi-faceted system components while protecting them against data uncertainty. In [26,40], and [52], robust approaches have been implemented to coordinate TSOs and DSOs. In [40], the uncertainties introduced by the RESs in the distribution system are modeled, resorting to the gap decision theory. Then, a local market model, based on a hierarchical bi-level optimization approach, is proposed to coordinate the transmission systems, the distribution systems, and the DER aggregators. On the one hand, the decision-making framework of active distribution systems is modeled as the upper-level problem. On the other hand, the clearing process of the market by the wholesale market operator is modeled as the lower-level problem. Results in [40] show the effectiveness of the proposed approach to alleviate overloads in the distribution system by shifting the power consumption from peak-load hours to other hours through the optimal scheduling of DERs, and decreasing the DSO operation costs and power losses. In [52], the uncertainty of distributed RESs and the boundary-bus voltage are handled via a two-stage linear robust TSO/DSO coordination model for reactive power management. Different case studies analyzed in [52] show that the proposed robust and linear approach accurately evaluates reactive power potential, even in the presence of high uncertainty.

Linear versus Nonlinear Approach

The bidirectional AC power flow constraints present in transmission and distribution systems introduce nonlinearities to the power balance equation [14]. In this context, the TSO/DSO optimization problem can be formulated and solved as Mixed-Integer Nonlinear Problem (MINLP) [39,43–46]. In [45], a multi-objective OPF problem to optimize voltage and reactive power is modeled as a MINLP using general algebraic modeling language. The MINLP is solved by the advanced solver for nonlinear optimization KNITRO. Results in [45] show that the proposed approach successfully coordinates distribution and transmission OPFs in real time, fulfilling voltage and reactive power set points. In [44], a state-of-the-art modeling environment especially designed for nonlinear optimization, called A Mathematical Programming Language (AMPL), is used to solve the OPF problems associated with the TSO/DSO coordination for reactive power and congestion management. Results in [44], obtained within the context of a German network, show that the proposed approach could meet the optimization demands of the DSOs and TSOs while ensuring a safe grid operation. In [46], a coordinated TSO/DSO reactive power management approach is proposed, where all the optimization problems are formulated as nonlinear problems and solved by the open-source Interior Point OPTimizer (IPOPT) solver. Results in [46] show that the proposed approach maintains voltage within acceptable ranges while reducing reactive power deviations from set points. In [39], the planning and operation optimization problems involved in a dual-horizon rolling scheduling model are formulated as MINLPs using the advanced interactive multidimensional modeling system and solved with KNITRO. Results in [39] show that the proposed formulation of the optimization problems provides a realistic distribution network model, which allows accurate capture and management of congestion issues.

Although the nonlinearities can be considered by solving a MINLP with different benchmark solvers, such as KNITRO, AMPL, and IPOPT, this is computationally expensive and time consuming. In this context, most of the selected articles in the SLR propose alternative approaches based on approximations of the optimization problem by representing the distribution and transmission systems with linearized power equations to reduce the problem complexity. In general, they propose solving a Mixed-Integer Linear Problem (MILP) [14–17,20,26–29,32,34,40,49,51,52,56,61]. In [34], a TSO/DSO coordination framework is proposed based on the implementation of a Distribution Locational Marginal Prices (DLMPs)-based local market. In particular, the nodal local market clearing process is solved by a security-constrained UC problem modeled using linear and mixed integer programming techniques. Results in [34] show that the proposed approach provides DLMPs all the way down to the customer level, contributing to the growth of transactive energy markets. In [49], a TSO/DSO coordination framework is proposed for power balancing purposes. The two considered optimization problems were those of optimal deployment of flexibilities for the support of re-dispatch measures and optimal application of the available flexible units as secondary reserve products in the given AS scheme. The two optimization problems were linearized and solved by the Gurobi solver. Results in [49] show that distributed flexibilities are not economically suitable for re-dispatch support; however, they can reduce the TSO's operational costs.

3.3. TSO/DSO Coordination: Implementation

Although researchers in the field recognize the importance of demonstrating the feasibility of the different TSO/DSO coordination approaches proposed in the literature by deploying technological pilots, there is a lack of real-life experiences reported in the literature [31]. In [18,24,31], and [37], the European project SmartNet, which is a pilot study within the context of a real-life scenario, is discussed. Authors in [18,24,31], and [37] demonstrate different potential TSO/DSO coordination schemes and evaluate their main advantages, as well as their main issues. In addition, different types of RESs, and their impacts on the TSO/DSO coordination performance, are also studied to better understand their potential flexibilities and main operational challenges. The rest of the SLR articles provide simulation results from different power system models. Table 6 shows the most used power system simulation tools in the selected articles. According to Table 6, the most used simulation tool is MATPOWER (8 (12.5%) articles), a Matlab open-source tool capable of solving steady-state power system simulations and optimization problems. The DIgSILENT PowerFactory, used by 4 (6.25%) articles, ranks second. The DIgSILENT PowerFactory is a power system analysis software for analyzing generation, transmission, distribution, and industrial systems. Finally, it is important to highlight that, unlike the other simulators identified in the selected articles, in [37], the SmartNet Simulator is introduced. This simulator has been exclusively developed within the SmartNet project to accurately estimate the impact of TSO/DSO coordination schemes.

Table 6. Power system simulation tools.

Power system Simulation Tools	Articles
Opsim	[44]
PSCAD	[38]
Pandapower	[44]
NICTA NESTA [78]	[56]
DIgSILENT PowerFactory	[16,21,22,38]
MATPOWER	[29,30,43,51–53,55,57]
SimBench	[46]

4. Discussion

Table 7 shows the main grid issues addressed by the articles proposing the original TSO/DSO coordination approaches analyzed in Section 3. From Table 7, it can be seen that most of the proposed approaches in the literature are concerned with grid operational aspects when coordinating TSOs and DSOs. In particular, reactive power and voltage regulation, operational cost minimization, operational planning, and congestion management are among the most recurrent ones. Nevertheless, according to [30], a universal and efficient TSO/DSO coordination approach to solve all the central management functions, including OPF, ED, and voltage stability assessment is still lacking. To this end, a TSO/DSO coordination approach based on a General-purpose Transmission–Distribution Coordination Model, which enables the application of the Generalized Master–Slave-Splitting to different central management functions, rather than focusing on only one of them, is proposed. To solve the optimization problem, a basic and a modified version of the heterogeneous decomposition algorithm, based on the heterogeneous decomposition of the Karush-Kuhn-Tucker conditions, is used. Results in [30] are promising, since the approach facilitates the successful solving of a series of central management functions, such as OPF, contingency analysis, and ED; however, the need for a general-purpose universal solution for integrated TSO and DSO frameworks is still an open research issue.

Table 7. Main objectives of the articles that develop and implement a TSO/DSO coordination approach.

Main Objective	Articles
Voltage control	[19,23,27,29,30,38,40,41,44,45,51,53,68]
Optimization of offers and bids by distributed energy resources	[34]
Coordinated restoration	[15]
Support fast frequency response	[21]
Minimize operational cost	[14,17,26,29,41,49,56,57]
Multi-period economic dispatch	[26]

Table 7. *Cont.*

Main Objective	Articles
Reactive power management	[16,19,27,32,38,41,43–46,52]
Storage coordination	[19]
Reduce power losses	[27,40,68]
Operational planning	[20,22,28,39,61,69]
Congestion management	[14,19,22,33,35]
Energy market clearance	[33]
Calculate uncertainty margins	[48]
Storage coordination	[19]
Data exchange infrastructure	[42,62,70]

Regarding the TSO/DSO coordination frameworks proposed in the literature to address the main operational grid issues listed in Table 7, it can be concluded that decentralized models are here to stay. Decentralized approaches are gaining popularity since the currently complex and exponentially expanding power system, including many distributed RESs at different voltage levels, has taken the TSO capability to centrally control the power system to its limits. In particular, the full visibility required by centralized approaches makes the process computationally expensive, and a massive investment in communication infrastructure is needed. Decentralized approaches, for their part, propose a more common market, where the TSO and the DSO solve their own operational problems and handle the RESs connected to their grids, allowing more efficient facilitation of RESs' services while having fewer computational, modeling, and communication requirements.

Whether to use a distributed or hierarchical approach to solve the decentralized TSO/DSO coordination problem depends on several factors. In general, distributed approaches have shown themselves to be better suited to solving nodal optimization problems, while hierarchical approaches are better suited for solving area-based optimization problems. No significant preference was identified among the reviewed articles. In [56], a comparative analysis is conducted where it is stated that while the hierarchical approach provides higher profits for the TSO than the distributed approach, its resource allocation performance is poorer. To give further insights into the pros and cons of hierarchical and distributed approaches, Table 8 summarizes their main advantages and disadvantages.

Although the results of the SLR demonstrate that decentralized approaches are currently the best option to solve large-scale TSO/DSO coordination problems, their intrinsic decentralized nature tends to increase system imbalance. In addition, different practical and technical barriers still prevent their implementation from being fully successful. On the one hand, although to a lesser extent than applies to centralized ones, decentralized approaches still require access to commercially sensitive information on distribution networks, especially in hierarchical architectures. Unfortunately, DSOs are autonomous entities usually unwilling to give access to such information. In this sense, it is hard to implement a decentralized approach in a real-life distribution environment with ambiguous, unknown, or proprietary parameters. On the other hand, the success of the decentralized methods, either distributed or hierarchical, depends on reliable data exchange between TSOs and DSOs, being negatively affected by communication delays and failures.

In order to overcome the burden posed by accessibility to commercially sensitive information, alternative approaches based on the use of historical data, rather than hardly accessible information, can be used [49,69]. In [69], a novel approach relying only on offline historical data of the transmission and distribution networks to coordinate TSOs and DSOs is proposed. In particular, a series of observations of the nodal price and the power intake at the distribution grid are used to learn the grid response to the electricity price in the form of a nonincreasing bidding curve that can be easily embedded into current procedures for transmission operations. Results in [69] show that the proposed TSO/DSO coordination approach is computationally affordable and comparable with current market practices, demonstrating the feasibility of using learning-based methods to predict the response of the distribution network based only on historical data. In this sense, the need for accessing proprietary and commercially sensitive information to coordinate TSOs and DSOs is relieved, providing a promising starting point to further investigate the use of learning-based methods using historical data to predict the grid response for the sake of developing novel and innovative TSO/DSO coordination approaches capable of efficiently integrating distributed RESs.

Table 8. Main advantages and disadvantages of distributed and hierarchical approaches.

	Distributed Approach	**Hierarchical Approach**
Advantages	• Preserves data privacy. • Avoids costly communication. • Robustness against nodal attacks or failures. • Flexibility. Allows connection and disconnection of distributed RESs without redesigning the control architecture.	• Simple coordination structure. • Reliability. • Computationally efficient. • Minimal data exchange. • Simple communication infrastructure.
Disadvantages	• Privacy constraints can prevent system operators accessing the same information. • Data exchange can be insufficient. • Computationally expensive. • Overall optimum solution is not always reached. • Cross couplings and interactions among the individual control loops can lead to grid instability.	• They are vulnerable to cyberattacks.

In order to bridge the gap of the lack of standardized communication infrastructures to exchange data between TSOs, DSOs, and other stakeholders, different communication infrastructures have been proposed in [42,70], and [62]. In [42], the adoption of European Commission Regulation rules to provide a legal framework for the operation of interconnected transmission and distribution networks is discussed. In particular, the representation of distributed RESs is studied, and the necessary data to be exchanged within the context of different grid applications, including system development, operation planning, and real-time management, are evaluated. Results in [42] show that the proposed TSO/DSO coordination framework allows modeling aggregated DERs and loads in the distribution grid, as well as modeling the transmission system in a computationally efficient way. In [70], different standard-based solutions, using the concept of International Electrotechnical Commission (IEC) Common Information Model for data exchange between TSOs and DSOs, are studied. Results in [70] highlight the need for TSOs and DSOs to rely on standard-based solutions when exchanging vital data for the efficient operation of power grids. In particular, they show that the IEC Common Grid Model Exchange Standard (CGMES) can provide promising interoperability solutions. In [62], a business use case based on the categorization of IEC 62913-1 is used to define data that should be exchanged between the TSO and the DSO to exploit distributed RESs for system balancing purposes. Results in [62] show the feasibility of implementing the proposed real-time data exchange mechanism using a cloud computing platform. The results in [42,70], and [62] are promising and highlight the need for further research in this direction.

5. Main Research Findings and Gaps

The results of the SLR conducted in this paper provide an in-depth insight into critical aspects of TSO/DSO coordination. On the one hand, they allow identification of the grid issues that have been thoroughly addressed in the literature, such as reactive power and voltage regulation, operational cost minimization, operational planning, and congestion management, and those that need further research, such as RESs' uncertainties modeling and prediction, and standardized data exchange infrastructures. On the other hand, the most relevant TSO/DSO coordination approaches available in the literature have been analyzed from the coordination framework design to the mathematical problem formulation, optimization, solution, evaluation, and results. In particular, the operational, managerial, economic, and computational benefits and issues of the different TSO/DSO coordination implementations have been discussed. As a result, the research findings listed in Section 5.1 and the research gaps listed in Section 5.2 can be highlighted.

5.1. Research Findings

5.1.1. TSO/DSO Coordination Framework

The main research findings regarding the different conceptual frameworks proposed in the literature to coordinate TSOs and DSOs are summarized as follows:

- Although traditionally used, centralized TSO/DSO coordination schemes are unsuitable for efficiently integrating RESs [15]. The main reasons for this are:
    - The TSO requires visibility for all the parameters of the network. This leads to high computational costs and modeling complexity [15].
    - The large number of distributed RESs is difficult for the TSO to centrally control [15].
- Although its feasibility in practice is highly questionable, centralized TSO/DSO coordination approaches are the most efficient in terms of the overall system operation, since decentralization tends to increase system imbalance. In this sense, they are currently used as benchmark models [7,26,56,69].
- There is an increasing trend in using decentralized TSO/DSO coordination approaches, since they allow the use of distributed RESs to a greater extent than centralized ones and, thus, provide more efficient facilitation of RESs' services. In addition, they have fewer computational, modeling, and communication requirements, usually only restricted to the DSO modeling complexity [7,14,26,51,56].
- Although to a lesser extent than the centralized approaches, decentralized TSO/DSO coordination approaches also require access to commercially sensitive and proprietary information and are highly vulnerable to communication delays and failures [69].

5.1.2. TSO/DSO Coordination Implementation

The main research findings regarding the implementation of the most relevant TSO/DSO coordination approaches proposed in the literature are summarized as follows:

- Most existing TSO/DSO coordination problems are formulated as optimization problems.
- Although non-probabilistic approaches, that do not account for RESs' uncertainties, can still be found in the literature, stochastic and robust methods provide superior RESs' uncertainty modeling and, thus, better TSO/DSO coordination performance [26,43,48,52,57,61].
- Although the TSO/DSO coordination optimization problem is nonlinear and nonconvex, it is common practice to reduce its complexity by linearizing the associated power equations and solving a convex optimization problem.
- The Distributed TSO/DSO coordination approach has the following key points:
    - It is well suited for solving nodal optimization problems.
    - It is flexible and allows the connection and disconnection of distributed RESs without redesigning the control architecture.
    - It is robust against nodal attacks or failures.
    - It avoids costly communication.
    - It preserves data privacy; however, the exchanged data may be insufficient.
    - It is computationally expensive, and the overall optimum solution is not always reached.
    - Cross couplings and interactions among the individual control loops can lead to grid instability.
- The Hierarchical coordination approach has the following key points:
    - It is well suited for solving area-based optimization problems.

  - It is a simple, reliable, and computationally efficient coordination structure.
  - It requires a simple communication infrastructure with minimal data exchange.
  - It is vulnerable to cyberattacks.
- Almost all of the TSO/DSO coordination approaches proposed in the literature are numerically simulated using power system simulators, MATPOWER and DIgSILENT PowerFactory being the most popular ones. Moreover, the SmartNet Simulator, introduced in [37], has been developed to exclusively estimate the impact of TSO/DSO coordination schemes within the context of the SmartNet project.

5.1.3. TSO/DSO Coordination Future Perspectives

- Learning-based techniques can be used to predict different functions of the distribution network within the context of a high RES penetration to relieve the need for accessing commercially sensitive and proprietary information, which constitutes an implementation burden of traditional centralized and decentralized TSO/DSO coordination approaches [69].
- Although different stochastic and robust approaches have been proposed in the literature to account for RESs' uncertainty, its modeling and prediction are still open research issues [26,43,48,52,57,61]. Learning-based techniques can be used to predict RESs' uncertain behavior to improve TSO/DSO coordination.
- The development of standardized communication solutions based on IEC CGMES is a promising research area to bridge the gap regarding the need for more standardized and efficient data exchange mechanisms between TSOs, DSOs, and stakeholders [5,9,10,70].

5.2. Research Gaps

The main research gaps identified in the literature are summarized as follows:

- There is a lack of a universal and efficient TSO/DSO coordination approach capable of solving all the central energy management functions, including reactive power management, ED, and voltage stability assessment [30].
- There is a lack of real-life experiences for testing and demonstrating the technical feasibility of the TSO/DSO coordination approaches available in the literature. In fact, only four of the selected articles in the SLR ([18,24,31,37]) conduct experiments in the real-life scenario. Moreover, all of them are related to the SmartNet project.
- While different aspects of the TSO/DSO coordination implementation—reactive power and voltage regulation, operational cost minimization, operational planning, and congestion management—have been thoroughly addressed in the literature, further research is needed regarding data exchange mechanisms [5,9,10,70], and RESs' uncertainty modeling and prediction [26,43,48,52,57,61].
- Further research needs to be conducted regarding the use of learning-based methods to predict relevant functions of the distribution network within the context of a high RES penetration to relieve the need for accessing commercially sensitive and proprietary information, which constitutes an implementation burden of conventional centralized and decentralized TSO/DSO coordination approaches [69].
- Further research needs to be conducted toward developing and implementing standardized communication solutions [5,9,10,70]. The promising results obtained based on the IEC CGMES standards can be used as a solid starting point [70].

6. Conclusions

In recent years, the increasing share of RESs in the distribution grid has raised new operational, economic, managerial, and computational challenges for power system operators. Promoting a more proactive role of the DSO toward successfully managing RESs' uncertainty, and taking advantage of their flexible resources to provide Ass, can avoid considerable investments in new network devices to support RESs' integration. In this line, it is crucial to enhance the coordination between TSOs and DSOs. In this paper, a SLR was conducted to evaluate to what extent, and how, the TSO/DSO coordination approaches currently available in the literature address and solve the most concerning economic, operational, managerial, and computational grid challenges within the context of high RES penetration. In particular, TSO/DSO coordination approaches were evaluated in terms of the conceptual framework supporting the coordination, the proposed model to solve the coordination problem, its implementation, encompassing formulation, optimization, and solution, and the field or simulation tests conducted to evaluate its performance, and the obtained results.

The results of the SLR provide valuable insights into the best available practices to coordinate TSOs and DSOs for RESs' integration and the most concerning gaps that are still waiting for further research. A remarkable trend in using decentralized TSO/DSO coordination frameworks to integrate distributed RESs has been identified, since they provide more efficient facilitation of RESs' services while having fewer computational, modeling, and communication requirements. Among them, distributed structures have been demonstrated to preserve data privacy, provide flexibility, and to be robust against node attacks and failures, whereas hierarchical structures have proved to be reliable, simple, and computationally efficient. Nevertheless, although to a lesser extent than centralized ones, decentralized models still require access to commercially sensitive and proprietary data, being difficult to implement in a real-life distribution environment with ambiguous, unknown, or proprietary parameters. In addition, they are also vulnerable to communication delays or failures. In this line, the use of learning-based approaches to predict distribution network responses using only historical data, which relieves the need for accessing commercially sensitive and proprietary data, has been shown to be successful, and the development of standardized communication solutions based on IEC CGMES has shown promising interoperability results. Both are solid starting points toward conducting relevant future research.

Finally, it is important to highlight that, while different aspects of the TSO/DSO coordination implementation—reactive power and voltage regulation, operational cost minimization, operational planning, and congestion management—have been thoroughly addressed in the literature, further research is needed regarding data exchange mechanisms and RESs' uncertainty modeling and prediction. Future work will consist in developing a TSO/DSO coordination approach to integrate RESs using learning-based techniques to predict their uncertain behavior and using only historical data.

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Appendix A

Table A1. Articles included in the SLR.

Art. ID	Year	Publication	Reference
[3]	2018	15th Int. Conf. on the European Energy Market (EEM)	Y. Tohidi, M. Farrokhseresht, and M. Gibescu, "A Review on Coordination Schemes Between Local and Central Electricity Markets," in 2018 15th Int. Conf. on the European Energy Market (EEM), 2018, pp. 1–5.

Table A1. *Cont.*

Art. ID	Year	Publication	Reference
[4]	2019	16th Int. Conf. on the European Energy Market (EEM)	C. Madina, P. Kuusela, M. Rossi, and H. Aghaie, "Optimised TSO-DSO Coordination to Integrate Renewables in Flexibility Markets," in 2019 16th Int. Conf. on the European Energy Market (EEM), 2019, pp. 1–6, doi: 10.1109/EEM.2019.8916308.
[5]	2019	BRIDGE Regulation WG and Data Management WG	H. Gerard et al., "TSO-DSO Coordination," BRIDGE Regulation WG and Data Management WG, 2019.
[6]	2015	ENTSO-E	ENTSO-E, "Towards smarter grids: Developing tso and dso roles and interactions for the benefit of consumers," ENTSO-E Position Paper, pp. 1–8, 2015.
[7]	2020	Electr. Power Syst. Res.	A. G. Givisiez, K. Petrou, and L. F. Ochoa, "A Review on TSO-DSO Coordination Models and Solution Techniques," *Electr. Power Syst. Res.*, vol. 189, p. 106659, 2020, doi: https://doi.org/10.1016/j.epsr.2020.106659.
[8]	2018	Util. Policy	H. Gerard, E. I. Rivero Puente, and D. Six, "Coordination between transmission and distribution system operators in the electricity sector: A conceptual framework," Util. Policy, vol. 50, pp. 40–48, 2018, doi: https://doi.org/10.1016/j.jup.2017.09.011.
[9]	2019	CIRED 2019	C. D'Adamo, "Coordination and data exchange between DSO and TSO as key factors for optimizing DER management in the future energy system.," 2019.
[10]	2019	2019 International Symposium on Systems Engineering (ISSE)	M. Al-Saadi *et al.*, "Survey Analysis on Existing Tools and Services for Grid and Market Stakeholders and Requirements to Improve TSO/DSO Coordination," in *2019 International Symposium on Systems Engineering (ISSE)*, 2019, pp. 1–7, doi: 10.1109/ISSE46696.2019.8984489.
[14]	2021		F. Najibi, D. Apostolopoulou, and E. Alonso, "TSO-DSO Coordination Schemes to Facilitate Distributed Resources Integration," 2021.
[15]	2019	IEEE Trans. Power Syst.	J. Zhao, H. Wang, Y. Liu, Q. Wu, Z. Wang, and Y. Liu, "Coordinated restoration of transmission and distribution system using decentralized scheme," IEEE Trans. Power Syst., vol. 34, no. 5, pp. 3428–3442, 2019.
[16]	2019	Aalborg University	N. Karthikeyan, "Hierarchical Distributed Control of Active Electric Power Distribution Grids," Aalborg Universitet, 2019.
[17]	2021	Electr. Power Syst. Res	M. A. El-Meligy, M. Sharaf, and A. T. Soliman, "A coordinated scheme for transmission and distribution expansion planning: A Tri-level approach," *Electr. Power Syst. Res.*, vol. 196, p. 107274, 2021.
[18]	2019	2019 IEEE Milan PowerTech	F. P. Andrén *et al.*, "Validating coordination schemes between transmission and distribution system operators using a laboratory-based approach," in *2019 IEEE Milan PowerTech*, 2019, pp. 1–6.
[19]	2021	Sustain. Energy, Grids Networks	M. Coppo, F. Bignucolo, and R. Turri, "Sliding time windows assessment of storage systems capability for providing ancillary services to transmission and distribution grids," *Sustain. Energy, Grids Networks*, vol. 26, p. 100467, 2021.
[20]	2020	Energies	R. Dzikowski, "DSO–TSO Coordination of Day-Ahead Operation Planning with the Use of Distributed Energy Resources," *Energies*, vol. 13, no. 14, p. 3559, 2020.

Table A1. *Cont.*

Art. ID	Year	Publication	Reference
[21]	2020	IET Gener. Transm. Distrib	F. S. Gorostiza and F. Gonzalez-Longatt, "Optimised TSO–DSO interaction in unbalanced networks through frequency-responsive EV clusters in virtual power plants," *IET Gener. Transm. Distrib.*, vol. 14, no. 21, pp. 4908–4917, 2020.
[22]	2019	2019 International Conference on Clean Electrical Power (ICCEP)	G. Graditi, R. Ciavarella, M. D. Somma, and M. Valenti, "A control strategy for participation of DSO flexible resources in TSO ancillary services provision," in *2019 International Conference on Clean Electrical Power (ICCEP)*, 2019, pp. 586–592, doi: 10.1109/ICCEP.2019.8890130.
[23]	2019	Autom.	H. Hinners, D. Mayorga Gonzalez, J. Myrzik, and C. Rehtanz, "Multivariable control of active distribution networks for TSO-DSO-coordinated operation in wide-area power systems," - *Autom.*, vol. 67, no. 11, pp. 904–911, 2019, doi: doi:10.1515/auto-2019-0066.
[24]	2020	CIRED 2017	S. Horsmanheimo, C. Madina, I. Kockar, and J. M. Morales, "SmartNet: H2020 project analysing TSO–DSO interaction to enable ancillary services provision from distribution networks."
[25]	2019	Energies	H. Khajeh, H. Laaksonen, S. Gazafroudi, and M. Shafie-khah, "Towards flexibility trading at TSO-DSO-customer levels: a review," 2019.
[26]	2021	IEEE Syst. J.	M. K. Arpanahi, M. E. H. Golshan, and P. Siano, "A Comprehensive and Efficient Decentralized Framework for Coordinated Multiperiod Economic Dispatch of Transmission and Distribution Systems," *IEEE Syst. J.*, vol. 15, no. 2, pp. 2583–2594, 2021, doi: 10.1109/JSYST.2020.3009750.
[27]	2020	Electr. Power Syst. Res.	M. K. Arpanahi and M.-E. Hamedani-Golshan, "A competitive decentralized framework for Volt-VAr optimization of transmission and distribution systems with high penetration of distributed energy resources," *Electr. Power Syst. Res.*, vol. 186, p. 106421, 2020.
[28]	2021	JOURNAL OF LATEX CLASS FILES	M. Bragin and Y. Dvorkin, "TSO-DSO Operational Planning Coordination through" l1-Proximal" Surrogate Lagrangian Relaxation," 2021.
[29]	2016	IEEE Trans. Smart Grid	Z. Li, Q. Guo, H. Sun, and J. Wang, "Coordinated transmission and distribution AC optimal power flow," *IEEE Trans. Smart Grid*, vol. 9, no. 2, pp. 1228–1240, 2016.
[30]	2018	IEEE Trans. Power Syst.	Z. Li, H. Sun, Q. Guo, J. Wang, and G. Liu, "Generalized master–slave-splitting method and application to transmission–distribution coordinated energy management," *IEEE Trans. Power Syst.*, vol. 34, no. 6, pp. 5169–5183, 2018.
[31]	2020	Book	C. Madina *et al.*, "Technologies and Protocols: The Experience of the Three SmartNet Pilots," in *TSO-DSO Interactions and Ancillary Services in Electricity Transmission and Distribution Networks*, Springer, 2020, pp. 141–183.
[32]	2019	IEEE Trans. Smart Grid	A. Mohammadi, M. Mehrtash, and A. Kargarian, "Diagonal Quadratic Approximation for Decentralized Collaborative TSO+DSO Optimal Power Flow," *IEEE Trans. Smart Grid*, vol. 10, no. 3, pp. 2358–2370, 2019, doi: 10.1109/TSG.2018.2796034.
[33]	2020	Korea Software Congress (KSC 2020)	M. Munir, D. Kim, S. M. Kang, and C. S. Hong, *Intelligent Agent Meets with TSO and DSO for a Stable Energy Market: Towards a Grid Intelligence*. 2020.

Table A1. *Cont.*

Art. ID	Year	Publication	Reference
[34]	2020	Electr. Power Syst. Res.	A. Papalexopoulos, R. Frowd, and A. Birbas, "On the development of organized nodal local energy markets and a framework for the TSO-DSO coordination," *Electr. Power Syst. Res.*, vol. 189, p. 106810, 2020, doi: https://doi.org/10.1016/j.epsr.2020.106810.
[35]	2021	Int. Trans. Electr. Energy Syst.	V. K. Prajapati, V. Mahajan, and N. P. Padhy, "Congestion management of integrated transmission and distribution network with RES and ESS under stressed condition," *Int. Trans. Electr. Energy Syst.*, vol. 31, no. 2, p. e12757, 2021.
[36]	2016	CIGRE General Meeting 2016	A. I. Ramos Gutierrez and R. Belmans, "Distribution and Transmission system operator interactions in flexibility contracting," in CIGRE General Meeting 2016, 2016.
[37]	2019	CIRED 2019	M. Rossi *et al.*, "Testing TSO-DSO interaction schemes for the participation of distribution energy resources in the balancing market: the SmartNet simulator," 2019.
[38]	2020	IEEE Trans. Sustain. Energy	A. O. Rousis, D. Tzelepis, Y. Pipelzadeh, G. Strbac, C. D. Booth, and T. C. Green, "Provision of voltage ancillary services through enhanced TSO-DSO interaction and aggregated distributed energy resources," *IEEE Trans. Sustain. Energy*, vol. 12, no. 2, pp. 897–908, 2020.
[39]	2016	IEEE Trans. Smart Grid	A. Saint-Pierre and P. Mancarella, "Active Distribution System Management: A Dual-Horizon Scheduling Framework for DSO/TSO Interface Under Uncertainty," *IEEE Trans. Smart Grid*, vol. 8, no. 5, pp. 2186–2197, 2017, doi: 10.1109/TSG.2016.2518084.
[40]	2021	Int. J. Electr. Power Energy Syst.	P. Sheikhahmadi, S. Bahramara, A. Mazza, G. Chicco, and J. P. S. Catalão, "Bi-level optimization model for the coordination between transmission and distribution systems interacting with local energy markets," *Int. J. Electr. Power Energy Syst.*, vol. 124, p. 106392, 2021.
[41]	2020	IET Renew. Power Gener	D. Shukla, S. P. Singh, A. K. Thakur, and S. R. Mohanty, "ATC assessment and enhancement of integrated transmission and distribution system considering the impact of active distribution network," *IET Renew. Power Gener.*, vol. 14, no. 9, pp. 1571–1583, 2020.
[42]	2020	Energies	S. Skok, A. Mutapčić, R. Rubesa, and M. Bazina, "Transmission Power System Modeling by Using Aggregated Distributed Generation Model Based on a TSO—DSO Data Exchange Scheme," *Energies*, vol. 13, no. 15, p. 3949, 2020.
[43]	2020	Sustain. Energy	T. Soares, L. Carvalho, H. Morais, R. J. Bessa, T. Abreu, and E. Lambert, "Reactive power provision by the DSO to the TSO considering renewable energy sources uncertainty," *Sustain. Energy, Grids Networks*, vol. 22, p. 100333, 2020.
[44]	2019	18th Wind Integration Workshop	M. Staudt *et al.*, "Processes and Systems for Using Flexibility from Distribution Grid to Integrate a High Share of RES in a Resilient, Stable and Efficient Operated Energy Supply System."
[45]	2018	Energies	D. S. Stock, F. Sala, A. Berizzi, and L. Hofmann, "Optimal control of wind farms for coordinated TSO-DSO reactive power management," *Energies*, vol. 11, no. 1, p. 173, 2018.
[46]	2020	2020 International Conference on Smart Energy Systems and Technologies (SEST)	D. S. Stock, S. Talari, and M. Braun, "Establishment of a Coordinated TSO-DSO Reactive Power Management for INTERPLAN Tool," in *2020 International Conference on Smart Energy Systems and Technologies (SEST)*, 2020, pp. 1–6.
[47]	2019	IEEE Trans. Power Syst.	H. Sun *et al.*, "Review of Challenges and Research Opportunities for Voltage Control in Smart Grids," *IEEE Trans. Power Syst.*, vol. 34, no. 4, pp. 2790–2801, 2019, doi: 10.1109/TPWRS.2019.2897948.

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Art. ID	Year	Publication	Reference
[48]	2020	IEEE Trans. Smart Grid	K. Tang, S. Dong, X. Ma, L. Lv, and Y. Song, "Chance-constrained optimal power flow of integrated transmission and distribution networks with limited information interaction," *IEEE Trans. Smart Grid*, vol. 12, no. 1, pp. 821–833, 2020.
[49]	2016	FCN Working Paper	J. Tran, R. Madlener, and A. Fuchs, "Economic optimization of electricity supply security in light of the interplay between TSO and DSO," 2016.
[50]	2019	CSEE J. Power Energy Syst.	J. Yu, Y. Guo, and H. Sun, "Testbeds for integrated transmission and distribution networks: Generation methodology and benchmarks," *CSEE J. Power Energy Syst.*, vol. 6, no. 3, pp. 518–527, 2020, doi: 10.17775/CSEEJPES.2019.03110.
[51]	2017	Appl. Energy	Z. Yuan and M. R. Hesamzadeh, "Hierarchical coordination of TSO-DSO economic dispatch considering large-scale integration of distributed energy resources," *Appl. Energy*, vol. 195, pp. 600–615, 2017, doi: https://doi.org/10.1016/j.apenergy.2017.03.042.
[52]	2020	Int. J. Electr. Power Energy Syst.	Y. Zhou, Z. Li, and M. Yang, "A framework of utilizing distribution power systems as reactive power prosumers for transmission power systems," *Int. J. Electr. Power Energy Syst.*, vol. 121, p. 106139, 2020.
[53]	2019	IEEE Trans. Power Syst.	G. D. Zotti, S. A. Pourmousavi, J. M. Morales, H. Madsen, and N. K. Poulsen, "A Control-Based Method to Meet TSO and DSO Ancillary Services Needs by Flexible End-Users," *IEEE Trans. Power Syst.* vol. 35, no. 3, pp. 1868–1880, 2020, doi: 10.1109/TPWRS.2019.2951623.
[54]	2021	Porto University	J. P. V. V. da Silva, "An optimization framework to estimate the active and reactive power flexibility in the TSO-DSO interface," 2021.
[55]	2021	Louvain University	I. Mezghani, "Coordination of Transmission and Distribution System Operations in Electricity Markets." UCL-Université Catholique de Louvain, 2021.
[56]	2019	Eur. J. Oper. Res	H. Le Cadre, I. Mezghani, and A. Papavasiliou, "A game-theoretic analysis of transmission-distribution system operator coordination," *Eur. J. Oper. Res.*, vol. 274, no. 1, pp. 317–339, 2019.
[57]	2021	CSEE J. Power Energy Syst.	A. Nawaz and H. Wang, "Distributed stochastic security constrained unit commitment for coordinated operation of transmission and distribution system," CSEE J. Power Energy Syst., vol. 7, no. 4, pp. 708–718, 2021, doi: 10.17775/CSEEJPES.2020.02150.
[58]	2021	IET Energy Syst. Integr.	P. Betancourt-Paulino, H. R. Chamorro, M. Soleimani, F. Gonzalez-Longatt, V. K. Sood, and W. Martinez, "On the perspective of grid architecture model with high TSO-DSO interaction," IET Energy Syst. Integr., vol. 2021, pp. 1–12, 2021.
[59]	2019		F. Silvestro et al., "Review of transmission and distribution investment decision making processes under increasing energy scenario uncertainty," 2019.
[60]	2017	CIRED-Open Access Proc. J.	F. Pilo, G. Mauri, B. Bak-Jensen, E. Kämpf, J. Taylor, and F. Silvestro, "Control and automation functions at the TSO and DSO interface–impact on network planning," CIRED-Open Access Proc. J., vol. 2017, no. 1, pp. 2188–2191, 2017.
[61]	2018	Appl. Energy	J. Liu, H. Cheng, P. Zeng, L. Yao, C. Shang, and Y. Tian, "Decentralized stochastic optimization based planning of integrated transmission and distribution networks with distributed generation penetration," Appl. Energy, vol. 220, pp. 800–813, 2018.

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Art. ID	Year	Publication	Reference
[62]	2021	Front. Energy Res.	M. Radi, G. Taylor, J. Cantenot, E. Lambert, and N. Suljanovic, "Developing Enhanced TSO-DSO Information and Data Exchange Based on a Novel Use Case Methodology," Front. Energy Res., vol. 9, p. 259, 2021.
[63]	2020	CIRED 2020 Berlin Workshop	F. D. M. Utrilla, D. Davi-Arderius, A. G. Martínez, J. P. Chaves-Ávila, and I. G. Arriola, "Large-scale demonstration of TSO–DSO coordination: the CoordiNet Spanish approach," in CIRED 2020 Berlin Workshop (CIRED 2020), 2020, vol. 2020, pp. 724–727, doi: 10.1049/oap-cired.2021.0209.
[64]	2020	CIRED 2020 Berlin Workshop	D. S. Stock et al., "Operational optimisation framework improving DSO/TSO coordination demonstrated in real network operation," in CIRED 2020 Berlin Workshop (CIRED 2020), 2020, vol. 2020, pp. 840–843, doi: 10.1049/oap-cired.2021.0241.
[65]	2020	CIRED 2020 Berlin Workshop	H. Chang and A. Moser, "Benefits of a combined flexibility utilisation between TSO and DSO for congestion management," in CIRED 2020 Berlin Workshop (CIRED 2020), 2020, vol. 2020, pp. 758–760, doi: 10.1049/oap-cired.2021.0218.
[66]	2020	CIRED 2020 Berlin Workshop	G. Gürses-Tran, A. Monti, J. Vanschoenwinkel, K. Kessels, J. P. Chaves-Ávila, and L. Lind, "Business use case development for TSO–DSO interoperable platforms in large-scale demonstrations," in CIRED 2020 Berlin Workshop (CIRED 2020), 2020, vol. 2020, pp. 672–674, doi: 10.1049/oap-cired.2021.0188.
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[68]	2021	Electr. Eng.	D. Marujo, G. L. Zanatta, and H. A. R. Floréz, "Optimal management of electrical power systems for losses reduction in the presence of active distribution networks," Electr. Eng., pp. 1–12, 2021.

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