

# A Multidimensional Analysis of Existing Limitations for TSO-DSO Coordination

Maurizio Vassallo<sup>a</sup>, Adrien Bolland<sup>a</sup>, Alireza Bahmanyar<sup>a,b</sup>, Raphaël Fonteneau<sup>a</sup>,  
Anthony Maio<sup>a</sup>, Julien Callec<sup>c</sup>, Dorian Fourniret<sup>d</sup>, Damien Ernst<sup>a</sup>

<sup>a</sup>University of Liège, Belgium,

<sup>b</sup>Haulogy, Belgium,

<sup>c</sup>RTE, France,

<sup>d</sup>Gérédis, France.

**Abstract**—The growing penetration of distributed energy resources (DERs) has motivated a large body of literature on transmission system operator (TSO) and distribution system operator (DSO) coordination. Yet despite this research activity, pilot projects and commercial deployments remain much more limited. Existing reviews classify coordination schemes by architecture or market design, but provide limited insight into the practical barriers affecting deployment readiness. This paper introduces a multidimensional scoring framework that evaluates TSO-DSO coordination approaches across five dimensions: modeling assumptions, operational dynamics, validation at scale, communication requirements, and regulatory constraints. The framework is applied to 47 selected studies, divided into pilot and non-pilot works. Our analysis shows that pilot and non-pilot studies are similarly developed in modeling and operation, but diverge on validation, communication, and regulatory alignment. These results suggest that the primary bottleneck for deployment is not necessarily algorithmic complexity, but rather the lack of integration of non-technical and systemic constraints. The proposed framework highlights key research gaps and proposes directions for developing coordination methods better suited to commercial deployments.

**Index Terms**—TSO-DSO coordination, distributed energy resources, deployment barriers, power system operations, energy transition.

## I. INTRODUCTION

Power systems are undergoing a fundamental transformation. In the traditional top-down paradigm, transmission system operators (TSOs) ensured system-wide security, while distribution system operators (DSOs) managed networks passively. This structure is increasingly challenged by the growing penetration of distributed energy resources (DERs), including photovoltaic systems (PVs), electric vehicles (EVs), and battery energy storage systems (BESSs). While these technologies offer clear benefits, such as supporting decarbonization and lowering marginal costs, they also introduce significant operational challenges, notably bidirectional power flows and increased uncertainty in both demand and generation.

These challenges are driving the transition from traditionally centralized operation toward more distributed

paradigms, a shift sometimes referred to as a Copernican revolution [1]. As DERs increasingly participate in system operation, coordination between TSOs and DSOs becomes necessary to ensure efficient congestion and voltage management across network levels. Regulatory initiatives, including the European legislation [2] and the German Redispatch 2.0 [3], further accelerate this evolution by requiring DERs at the distribution level to participate in redispatch processes.

Consequently, TSO-DSO coordination has shifted from a theoretical concept to an operational necessity. Yet, the notion of coordination is not always clearly defined across studies. In this work, we define TSO-DSO coordination as the exchange of information and joint decision-making to improve network planning and operation. It typically aims to ensure network-wide security and lower-cost energy supply, and is achieved through various mechanisms, including software and hardware design, mathematical optimization, and market interactions. The existing literature proposes a wide range of coordination paradigms (e.g., centralized, decentralized, and hybrid) and technical approaches (e.g., joint planning processes, local markets, aggregators, operational envelopes) to reconcile the different objectives and operational timescales of TSOs and DSOs [4], [5].

However, despite numerous theoretical studies, very few have progressed beyond pilot projects to commercial deployment. This limited transition appears to be associated with multiple technical and non-technical factors. Existing reviews predominantly classify coordination schemes by architecture or market design, offering limited insight into practical deployment barriers. Without a structured way to assess deployment readiness, the field risks developing new methods under the same limiting assumptions that prevented earlier work from scaling.

TABLE I: Multidimensional scoring framework and distribution of characteristics across the reviewed literature.

Dimension	Sub-dimension	Characteristic	Score	Total	Non-Pilot	Pilot
Modeling	Transmission network	DC formulation	0	29 (76%)	23 (77%)	5 (63%)
		AC formulation	1	9 (24%)	7 (23%)	3 (37%)
	Distribution network	DC formulation	0	6 (16%)	5 (17%)	1 (13%)
		AC formulation	1	32 (84%)	25 (83%)	7 (87%)
	Phase balance	Balanced system	0	31 (82%)	26 (87%)	5 (63%)
		Unbalanced system	1	7 (18%)	4 (13%)	3 (37%)
	Reactive power	Not considered	0	11 (29%)	9 (30%)	2 (25%)
		Considered	1	27 (71%)	21 (70%)	6 (75%)
Operation	Temporal resolution	Single timestep	0	12 (32%)	10 (33%)	2 (25%)
		Hours	1	18 (47%)	15 (50%)	3 (37%)
		Minutes	2	5 (13%)	3 (10%)	2 (25%)
		Seconds	3	3 (8%)	2 (6%)	1 (13%)
	Uncertainty management	Deterministic	0	20 (53%)	17 (57%)	3 (37%)
		Scenarios	1	15 (40%)	10 (33%)	5 (63%)
		Robust optimization	2	3 (8%)	3 (10%)	0
Validation	Network size	Small	0	18 (47%)	16 (54%)	2 (25%)
		Medium	1	11 (29%)	7 (23%)	4 (50%)
		Large	2	9 (24%)	7 (23%)	2 (25%)
	Network type	Not mentioned	0	1 (3%)	1 (3%)	0
		Standard test-case	1	22 (57%)	22 (74%)	0
		Real network	2	15 (40%)	7 (23%)	8 (100%)
Communication	Infrastructure	Not considered	0	27 (69%)	27 (82%)	0
		Considered	1	12 (31%)	4 (18%)	8 (100%)
	Data standardization	Not considered	0	29 (74%)	29 (94%)	0
		Considered	1	10 (26%)	2 (6%)	8 (100%)
	Privacy	Not considered	0	22 (56%)	22 (71%)	0
		Considered	1	17 (44%)	9 (29%)	8 (100%)
Regulation	Regulation incompatibility	Not considered	0	28 (72%)	28 (90%)	0
		Considered	1	11 (28%)	3 (10%)	8 (100%)
	Objective alignment	Not considered	0	24 (63%)	23 (77%)	1 (13%)
		Considered	1	14 (37%)	7 (23%)	7 (87%)
	Strategic behavior	Not considered	0	30 (83%)	26 (93%)	4 (50%)
		Considered	1	6 (17%)	2 (7%)	4 (50%)

To address this gap, the main contributions of this paper are the following: *i)* we introduce a scoring system according to five dimensions: modeling, operation, validation, communication, and regulation, *ii)* we discuss and highlight limitations across each dimension, *iii)* we compare pilot and non-pilot studies, *iv)* we discuss why pilots have not transitioned to commercial deployment.

The remainder of the paper is structured as follows. Section II describes the multidimensional framework and presents an analysis of the limitations within the literature. Section III introduces the pilot and non-pilot categorization and presents an assessment using the proposed scoring methodology. Section IV analyzes why pilot projects have not yet transitioned to commercial deployment. Section V discusses the limitations of this work. Section VI concludes the work by summarizing key findings and proposing future research directions. Finally, the appendix presents details on the review methodology and the scoring mechanism.

## II. ASSESSMENT OF COORDINATION LIMITATIONS ACROSS FIVE DIMENSIONS

To analyze deployment barriers, we structure the assessment around five dimensions: modeling, operation, validation, communication, and regulation. This approach extends the classification in [6] by explicitly incorporating modeling assumptions and validation constraints alongside systemic factors. We apply this multidimensional framework to evaluate the limitations of existing TSO-DSO coordination approaches by analyzing 47 selected studies, following the methodology detailed in Appendix A. Table I details the considered sub-dimensions, associated scoring criteria, and the distribution of characteristics across the analyzed literature, pilot, and non-pilot studies. For each characteristic, the table reports both the number of papers and the corresponding percentage within each category.

### A. Modeling

This dimension evaluates the mathematical simplifications used to represent power systems. Assessment focuses on network representation (AC or DC), phase imbalance, and reactive power constraints.

The literature favors computational tractability over physical realism. At the transmission level, linear DC formulations dominate, while distribution networks are generally modeled using AC power flow. Beyond power flow equations, the vast majority of studies assume balanced distribution systems, often ignoring local constraints, which may lead to optimistic estimates of available flexibility. The necessity of this computational trade-off is evident in pilot projects. For example, in CoordiNet [42], a hybrid approach based on simplified DC models is used for maintaining tractability during market clearing and is followed by an AC power flow validation to ensure feasibility.

### B. Operation

The operation dimension covers temporal granularity (ranging from a single snapshot to sub-minute resolution) and stochasticity management.

There is a temporal mismatch between theoretical simulations and actual grid operations. Most studies rely on hourly resolution, neglecting intra-hour dynamics such as frequency deviations and rapid voltage variations that are critical to system security. This coarse temporal representation fails to capture the fast-acting nature of DER flexibility, limiting the ability to assess its true operational value. Beyond temporal resolution, uncertainty management remains insufficiently addressed, with most studies relying on deterministic frameworks. Since DER generation and demand are inherently stochastic, deterministic approaches risk producing overly optimistic coordination schemes and potentially infeasible under real operating conditions.

### C. Validation

Validation reflects the scale of the tested network, categorized as small (<500 nodes), medium (500-2000 nodes), or large (> 2000 nodes), and the test network used (e.g., synthetic or real-world networks).

The literature primarily validates coordination schemes on small or medium-scale synthetic topologies rather than real networks. Real-world experiments, such as the SmartNet project [38], encountered significant computational limits when performing simulations of integrated TSO-DSO topologies at scale, necessitating the development of simplified network representations to maintain tractability without sacrificing important physical characteristics [12], [35].

### D. Communication

This dimension identifies requirements for data exchange, digital protocols, and privacy measures.

Although information and communication technology (ICT) is recognized as the central nervous system of future smart grids, it remains comparatively underexplored in much of the academic literature. Requirements for data standardization and privacy compliance are largely ignored in theoretical studies. Conversely, pilot projects like SmartNet [38] and PLATONE [40] frequently expose the inadequacy of existing data frameworks, often requiring the deployment of supplementary IoT hardware and secure communication protocols.

### E. Regulation

The regulation dimension captures institutional constraints, including misaligned incentives, regulatory incompatibilities, and strategic behavior.

Regulatory and market-related aspects are among the least addressed dimensions, despite their importance for real-world implementation. In particular, TSOs and DSOs may compete for the same DERs, where actions beneficial for

transmission-level balancing can conflict with local distribution constraints [54]. Existing frameworks, moreover, lack adequate incentives for DSO participation [42], [47]: regulated tariffs compensate capital expenditures (CapEx) but not the operating expenses (OpEx) required to procure flexibility, which constitutes a structural barrier beyond technical design. Finally, strategic behavior is almost entirely neglected, and the assumption of cooperative actors risks producing mechanisms vulnerable to manipulation.

### F. Summary of research gaps

The multidimensional analysis highlights distinct patterns in how the literature addresses aspects relevant to TSO-DSO coordination deployment. For modeling and operation, the field exhibits relatively low variance: most studies converge toward a common set of assumptions, including DC transmission, AC distribution, balanced systems, reactive power consideration, hourly or single-time step resolution, and no uncertainty handling. In contrast, validation, communication, and regulation display notably higher variability, with aspects such as large-scale real-network validation, communication infrastructure, interoperability, and regulatory integration frequently omitted.

## III. PILOTS AND NON-PILOTS RESULTS

To investigate the high variability identified in the previous section, the analyzed literature is partitioned into pilot projects and non-pilot studies.

A paper corresponds to a pilot project when it satisfies three conditions: (i) real-life implementation involving actual TSOs and DSOs; (ii) physical infrastructure and measured data; and (iii) direct influence on operational decisions; whether in real-time, intraday, or day-ahead processes. Studies using real-world network data without operational integration are classified as case studies instead.

Following the scoring methodology detailed in Appendix B, each paper is evaluated across the five dimensions and normalized to its maximum possible score. Figure 1 presents these average normalized results, utilizing 95% confidence intervals (CIs) calculated via a Student's t-distribution to correctly account for the smaller sample size of pilot projects.

Differences between pilot and non-pilot studies are negligible when considering modeling and operation dimensions. The overlapping CIs indicate that both groups face similar trends in modeling physical systems and managing temporal dynamics. This suggests that real-world implementations do not necessarily rely on more advanced mathematical or operational representations; instead, they operate under the same simplifying assumptions and computational trade-offs as theoretical studies. In contrast to these shared technical challenges, notable differences appear in the validation, communication, and regulation dimensions. While simulation-based studies typically assume idealized information exchange and simplified institutional environments,

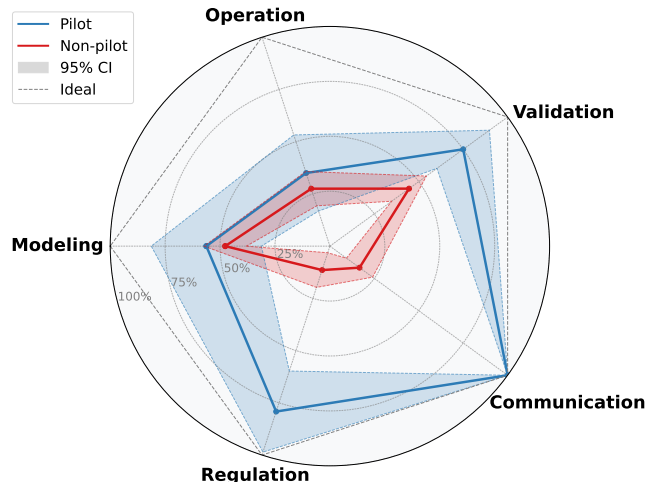


Fig. 1: Average normalized scores across the five dimensions for pilot and non-pilot studies.

pilot projects are forced to explicitly navigate data interoperability, stakeholder conflicts, and regulatory misalignment.

This asymmetry suggests two interrelated observations. First, pilot projects have largely integrated the state of the art from existing academic studies in modeling and operation, not relying on fundamentally more advanced algorithms or temporal resolutions. Second, theoretical studies tend to neglect validation, communication, and regulation, even though these dimensions are critical for pilot execution and, eventually, commercial deployment. As a result, coordination mechanisms that perform well under idealized simulation assumptions may face major challenges during real-world deployment, particularly at large scale or under imperfect communication and regulatory conditions.

## IV. FROM PILOT TO COMMERCIAL DEPLOYMENT

Although pilot projects score significantly higher on validation, communication, and regulatory alignment, they still struggle to transition into widely deployed operational systems. In particular, pilot projects exposed a range of frictions that impacted their experiments. These include computational tractability forcing simplified models; low-voltage visibility suffering from weak DSO incentives; communication requiring far more engagement than expected; market design suffering from illiquidity and fragmentation; and forecasting errors undermining operations. Even in dimensions where pilots score reasonably well by our metrics, that level of integration may still be insufficient for robust, commercial deployment. For instance, no pilot in our review has demonstrated long-term stability under high degrees of unbalanced loading, sub-minute volatility, or widespread communication latency.

In summary, pilots demonstrate feasibility under controlled conditions, not robustness against real-world variability. They remain intermediate tests, and the gap to com-

mercial deployment likely requires simultaneous advances across all five dimensions, including those at which current practice may appear mature.

## V. DISCUSSION

The proposed multidimensional framework is intended as a diagnostic tool, not an absolute metric of deployment readiness, and several limitations must be acknowledged.

First, the analysis relies on peer-reviewed literature subject to publication bias. Successful methodologies are overrepresented, while operational failures, for instance, the scalability limits of AC formulations on large real-world networks, are rarely reported. Consequently, literature may underestimate the severity of practical deployment barriers, producing scores that reflect a best-case scenario rather than the typical reality faced by system operators.

Second, applying equal weights to all sub-dimensions assumes that a technical feature like three-phase unbalance carries the same operational weight as a regulatory constraint. Moreover, the normalized scores are sensitive to the choice and granularity of sub-dimensions, meaning that cross-dimensional comparisons (“modeling is more advanced than communication”) are not meaningful. Consequently, the relative scores across dimensions cannot be directly compared without explicitly acknowledging that the current framework captures a curated subset of sub-dimensions, rather than an exhaustive list of all requirements for a commercial solution.

Third, several deployment barriers are not included in the five dimensions. For example, emerging technical threats such as cybersecurity (e.g., false data injection, malicious intrusions) are omitted [55]. Furthermore, experiences from system operators such as RTE and Enedis indicate that effective coordination requires not only technical solutions but also an operational culture shift supported by dispatcher workflow integration [43], [44]. This socio-technical dimension is often overlooked in the literature. As a result, achieving a perfect score in a given dimension—for example, a pilot project that ticks all our communication sub-dimensions—may correspond to fulfilling only a small fraction of actual real-world operational requirements.

Fourth, the five dimensions are not strictly orthogonal: regulatory requirements on data privacy directly constrain communication architectures [6], and modeling assumptions affect the tractability of large-scale validation. Because these dimensions are interconnected, a low score in one area may restrict the progress of another, meaning that achieving real-world deployment requires a coordinated, simultaneous advancement across all dimensions rather than isolated technical fixes.

Despite these limitations, the framework goes beyond a classical literature review by providing a structured, visual, and quantitative analysis through which research assumptions can be compared against deployment conditions. Rather than simply listing existing approaches, it explicitly

highlights the gap between theoretical development and real-world readiness, and offers a reproducible basis for identifying where future research efforts are most needed.

## VI. CONCLUSION

This paper presented a multidimensional analysis of existing TSO-DSO coordination literature to characterize key barriers that limit the transition from theoretical frameworks to commercial deployment. The analysis is performed over five dimensions: modeling, operation, validation, communication, and regulation.

The results reveal an asymmetry in research attention. Modeling and operation exhibit relatively low variability across the literature, with most studies converging toward similar assumptions. Validation, communication, and regulation, in contrast, display notably higher variability, with frequent omission of these aspects.

Moreover, the comparison between pilot and non-pilot studies further refines this picture. Pilot projects address validation, communication, and regulatory aspects more explicitly, while relying on modeling and operational assumptions similarly to those adopted in academic studies. However, pilot projects should not be interpreted as deployment-ready solutions. They represent an intermediate level to commercial implementation.

At the same time, the apparent convergence observed in modeling assumptions should not necessarily be interpreted as full maturity of the field. Current approaches rely on tractable formulations and simplified operational settings, which may be limiting as coordination moves toward commercial deployment with higher uncertainty, stronger coupling between transmission and distribution networks, and faster operational timescales.

Overall, the proposed framework provides a structured way to identify where deployment-oriented considerations remain underrepresented and to compare how different studies address operational realism beyond purely algorithmic performance. More broadly, the results suggest that progress toward large-scale TSO-DSO coordination will likely depend on simultaneous advances across all five dimensions.

## REFERENCES

- [1] L. Aleixo et al., “A general framework for active distribution network planning,” English, in *CIGRE Symposium*, Apr. 2013, p. 8. [Online]. Available: <https://api.semanticscholar.org/CorpusID:56082552>.
- [2] European Commission, *Directive 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU (recast)*, Official Journal of the European Union, 2019. [Online]. Available: <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019L0944&from=EN>.
- [3] *Netzbaugesetz Übertragungsnetz (NABEG) [grid expansion acceleration act]*, Federal Law Gazette (BGBl), Germany, 2019. [Online]. Available: <https://www.wind-energie.de/themen/netze/redispatch/>.
- [4] T. Alazemi et al., “TSO/DSO coordination for RES integration: A systematic literature review,” *Energies*, vol. 15, 2022. DOI: 10.3390/en15197312.

- [5] Y. Zahraoui et al., "Assessment of TSO-DSO coordination to enhance flexible grid operation," *Current Sustainable/Renewable Energy Reports*, vol. 12, Jul. 2025. DOI: 10.1007/s40518-025-00269-6.
- [6] C. Ziesemann et al., "Challenges and barriers to the implementation of TSO-DSO coordination concepts: Discussion paper," Aachen, Tech. Rep., 2023. DOI: 10.18154/RWTH-2022-11734.
- [7] S. Stanković and L. Söder, "Probabilistic reactive power capability charts at DSO/TSO interface," *IEEE Transactions on Smart Grid*, vol. 11, pp. 3860–3870, 2020. DOI: 10.1109/TSG.2020.2992569.
- [8] S. Skok, "Transmission power system modeling by using aggregated distributed generation model based on a TSO—DSO data exchange scheme," *Energies*, vol. 13, 2020. DOI: 10.3390/en13153949.
- [9] M. Radi et al., "Developing enhanced TSO-DSO information and data exchange based on a novel use case methodology," *Frontiers in Energy*, 2021. DOI: 10.3389/fenrg.2021.670573.
- [10] M. A. Bragin and Y. Dvorkin, "TSO-DSO Operational Planning Coordination through Surrogate Lagrangian Relaxation," *ArXiv*, 2021. DOI: 10.36227/TECHRXIV.13557242.V1.
- [11] A. Hermann et al., "A complementarity model for electric power transmission-distribution coordination under uncertainty," *European Journal of Operational Research*, vol. 299, pp. 313–329, 2022. DOI: 10.1016/j.ejor.2021.08.018.
- [12] J. Ringelstein et al., "A methodology for improved TSO-DSO coordination in grid operation planning," *Electric Power Systems Research*, vol. 211, 2022. DOI: 10.1016/j.epsr.2022.108445.
- [13] M. Habibi et al., "A privacy-preserving approach to day-ahead TSO-DSO coordinated stochastic scheduling for energy and reserve," *IET Generation, Transmission & Distribution*, vol. 16, pp. 163–180, 2022. DOI: 10.1049/gtd.12286.
- [14] M. Sarstedt and L. Hofmann, "Monetization of the feasible operation region of active distribution grids based on a cost-optimal flexibility disaggregation," *IEEE Access*, vol. 10, pp. 5402–5415, 2022. DOI: 10.1109/ACCESS.2022.3140871.
- [15] M. K. Arpanahi et al., "Non-cooperative operation of transmission and distribution systems," *IEEE Transactions on Industrial Informatics*, vol. 18, pp. 153–162, 2022. DOI: 10.1109/TII.2020.3041921.
- [16] T. Kolster et al., "Providing distributed flexibility for curative transmission system operation using a scalable robust optimization approach," *Electric Power Systems Research*, vol. 211, 2022. DOI: 10.1016/j.epsr.2022.108431.
- [17] M. Gupta and A. R. Abhyankar, "Amalgamating TSO and DSO energy markets through minimal data exchange-based framework," *Policy and Regulation IEEE Transactions on Energy Markets*, vol. 1, pp. 173–186, 2023. DOI: 10.1109/TEMPR.2023.3277751.
- [18] Y. Weng et al., "Asymmetrically reciprocal effects and congestion management in TSO-DSO coordination through feasibility regularizer," *IEEE Transactions on Power Systems*, vol. 38, pp. 1948–1962, 2023. DOI: 10.1109/TPWRS.2022.3193052.
- [19] M. Z. Degefa et al., "Challenges of TSO-DSO voltage regulation under real-time data exchange paradigm," *IEEE Open Journal of the Industrial Electronics Society*, vol. 4, pp. 75–84, 2023. DOI: 10.1109/OJIES.2023.3239946.
- [20] S. Nikkhah et al., "Distributed flexibility to maintain security margin through decentralised TSO—DSO coordination," *International Journal of Electrical Power & Energy Systems*, vol. 146, 2023. DOI: 10.1016/j.ijepes.2022.108735.
- [21] D. Sieraszewsk et al., "Multi-period hybrid AC/DC-OPF model for flexibility market clearing with seamless TSO-DSO coordination," *IEEE Access*, vol. 11, pp. 40093–40106, 2023. DOI: 10.1109/ACCESS.2023.3269423.
- [22] X. Sun et al., "Pricing for TSO-DSO coordination: A decentralized incentive compatible approach," *IEEE Transactions on Power Systems*, vol. 38, pp. 1869–1882, 2023. DOI: 10.1109/TPWRS.2022.3170436.
- [23] H. Laaksonen et al., "Advanced distributed energy resources and on-load tap-changer control principles for enhanced flexibility services provision," *IEEE Access*, vol. 12, pp. 161768–161785, 2024. DOI: 10.1109/ACCESS.2024.3488211.
- [24] M. Nejadmuri et al., "An uncertainty-aware two-stage optimization framework for coordinating energy and reserve markets in TSO-DSO interface in the presence of energy storage systems," *Journal of Energy Storage*, vol. 102, 2024. DOI: 10.1016/j.est.2024.114121.
- [25] C. Gu et al., "Distributed energy resource and energy storage investment for enhancing flexibility under a TSO-DSO coordination framework," *IEEE Transactions on Automation Science and Engineering*, vol. 21, no. 3, pp. 2961–2973, Jul. 2024, ISSN: 1558-3783. DOI: 10.1109/TASE.2023.3272532.
- [26] M. Kalantar-Neyestanaki and R. Cherkaoui, "Grid-cognizant TSO and DSO coordination framework for active and reactive power flexibility exchange: The Swiss case study," *Electric Power Systems Research*, vol. 235, 2024. DOI: 10.1016/j.epsr.2024.110747.
- [27] H. A. Mahmoud and A. E. Abdelgawad, "A robust unit commitment-based TSO-DSO coordination scheme for optimal generation scheduling," *Electric Power Systems Research*, vol. 243, 2025, ISSN: 03787796. DOI: 10.1016/j.epsr.2025.111512.
- [28] Y. Wen et al., "Quantifying and optimizing the time-coupled flexibilities at the distribution-level for TSO-DSO coordination," *IEEE Transactions on Power Systems*, vol. 40, pp. 5071–5085, 2025. DOI: 10.1109/TPWRS.2025.3563041.
- [29] R. Han et al., "Unified transmission-distribution coordination for secure and economical frequency support from distributed energy resources," *IEEE Transactions on Sustainable Energy*, p. 16, 2026, ISSN: 1949-3037. DOI: 10.1109/TSTE.2026.3668374.
- [30] S. Bruno et al., "Mapping flexibility region through three-phase distribution optimal power flow at TSO-DSO point of interconnection," in *2021 AET International Annual Conference (AET)*, 2021, p. 6. DOI: 10.23919/AET53387.2021.9627050.
- [31] S. M. H. Rizvi et al., "TDS-CoSim: A static co-simulation tool for integrated T & D snapshot analysis considering large penetration of DERs," in *2022 IEEE Industrial Electronics and Applications Conference (IEACon)*, 2022, pp. 67–72. DOI: 10.1109/IEACon55029.2022.9951837.
- [32] M. Panahzari et al., "A new market-based framework for increasing responsive loads in distribution systems," in *2023 13th Smart Grid Conference (SGC)*, 2023, p. 6. DOI: 10.1109/SGC61621.2023.10459317.
- [33] A. Churkin et al., "Impacts of distribution network reconfiguration on aggregated DER flexibility," in *2023 IEEE Belgrade PowerTech*, 2023, p. 7. DOI: 10.1109/PowerTech55446.2023.10202791.
- [34] M. I. Alizadeh et al., "Uncertainty-aware TSO-DSO coordination methodology for transmission voltages control," in *2023 IEEE Belgrade PowerTech*, 2023, p. 6. DOI: 10.1109/PowerTech55446.2023.10202827.
- [35] M. S. Miah et al., "Equivalent network representation for TSO-DSO interaction with present and future DERs, EV charging stations, and storage uptakes," in *2025 IEEE Kiel PowerTech*, 2025, p. 6. DOI: 10.1109/PowerTech59965.2025.11180571.
- [36] N. C. Martin and B. Fanzeres, "Multi-agent DSO-TSO active and reactive power flow coordination with a two-level decentralised ADMM," in *2025 IEEE Kiel PowerTech*, 2025, p. 6. DOI: 10.1109/PowerTech59965.2025.11180218.
- [37] B. Dindar et al., "Privacy-preserving flexibility provisioning with an optimization approach for enhanced TSO-DSO interaction in modern power systems," in *2025 21st International Conference on the European Energy Market (EEM)*, 2025, p. 6. DOI: 10.1109/EEM64765.2025.11050293.
- [38] SmartNet Project, *TSO-DSO coordination for acquiring ancillary services from distribution grids*. Florence School of Regulation, 2019. [Online]. Available: <https://smartnet-project.eu/wp-content/uploads/2019/05/SmartNet-Booklet.pdf>.
- [39] S. Potenciano Menci et al., "Functional scalability and replicability analysis for smart grid functions: The InteGrid project approach," *Energies*, vol. 14, 2021. DOI: 10.3390/en14185685.
- [40] I. Losa et al., "PLATONE: Towards a new open DSO platform for digital smart grid services and operation," in *CIREN*, Sep. 2021, pp. 2974–2978. DOI: 10.1049/icp.2021.1880.
- [41] V. Mladenov, "A flexibility market platform for electricity system operators using blockchain technology," *Energies*, vol. 15, no. 2, 2022, ISSN: 1996-1073. DOI: 10.3390/en15020539.
- [42] CoordiNet Consortium, "Roadmap towards a new market design including the implementation of standardised products for system services," CoordiNet Project (Horizon 2020), Tech. Rep., 2022.

- [Online]. Available: <https://www.edsoforsmartgrids.eu/eu-projects/coordinet/>.
- [43] EU-SysFlex Consortium, “European flexibility roadmap,” Tech. Rep., 2022. [Online]. Available: <https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5e92cd204&appId=PPGMS>.
- [44] OneNet Project, “Evaluation of OneNet demonstrators’ results,” OneNet Project (Horizon 2020), Deliverable D11.1, 2024. [Online]. Available: [https://www.onenet-project.eu/wp-content/uploads/2024/02/OneNet\\_D11.1\\_V2.0.pdf](https://www.onenet-project.eu/wp-content/uploads/2024/02/OneNet_D11.1_V2.0.pdf).
- [45] Z. Ruan et al., “Application of hierarchical TSO-DSO coordination in European pilot projects,” in *2025 21st International Conference on the European Energy Market (EEM)*, 2025, p. 7. DOI: 10.1109/EEM64765.2025.11050314.
- [46] BRIDGE Regulation and Data Management Working Groups, “TSO-DSO coordination,” European Commission (BRIDGE Initiative), Tech. Rep. Deliverable D3.12.f, Dec. 2019, Horizon 2020 BRIDGE Initiative. [Online]. Available: [https://h2020-bridge.eu/wp-content/uploads/2020/01/D3.12.f\\_BRIDGE-TSO-DSO-Coordination-report.pdf](https://h2020-bridge.eu/wp-content/uploads/2020/01/D3.12.f_BRIDGE-TSO-DSO-Coordination-report.pdf).
- [47] International Renewable Energy Agency, “Innovation landscape brief: Co-operation between transmission and distribution system operators,” International Renewable Energy Agency (IRENA), Tech. Rep., 2020. [Online]. Available: <https://www.irena.org/publications/2020/Jul/System-Operation-Innovation-Landscape-briefs>.
- [48] B. Herndler and I. Annex, “Lessons learned from international projects on TSO-DSO interaction,” *ISGAN (International Smart Grid Action Network)*, 2020. [Online]. Available: <https://www.iea-isgan.org/wp-content/uploads/2020/12/Lessons-learned-from-international-projects-on-TSO-DSO-interaction.pdf>.
- [49] Electric Power Research Institute, “TSO-DSO coordination functions for DER,” EPRI, Palo Alto, CA, Tech. Rep. 3002021985, 2022. [Online]. Available: <https://www.epri.com/research/products/000000003002021985>.
- [50] E. Lambert et al., “Practices and architectures for TSO-DSO data exchange: European landscape,” in *2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, 2018, p. 6. DOI: 10.1109/ISGTEurope.2018.8571547.
- [51] A. G. Givisiez et al., “A review on TSO-DSO coordination models and solution techniques,” *Electric Power Systems Research*, vol. 189, 2020. DOI: 10.1016/j.epsr.2020.106659.
- [52] A. Bytyqi et al., “A review on TSO-DSO data exchange, CIM extensions and interoperability aspects,” *Journal of Modern Power Systems and Clean Energy*, vol. 10, pp. 309–315, 2022. DOI: 10.35833/MPCE.2021.000770.
- [53] M. Power et al., “TSO-DSO interaction and coordination,” in *Distributed Energy Resources in Active Distribution Networks*, ser. CIGRE Green Books, C. Schwaegerl et al., Eds., Springer, 2025, ISBN: 978-3-030-91366-3. [Online]. Available: <https://link.springer.com/book/9783030913663>.
- [54] F. Najibi et al., “TSO-DSO coordination schemes to facilitate distributed resources integration,” *Sustainability*, vol. 13, no. 14, 2021, ISSN: 2071-1050. DOI: 10.3390/su13147832.
- [55] N. Rodríguez Pérez et al., “ICT architectures for TSO-DSO coordination and data exchange: A European perspective,” *IEEE Transactions on Smart Grid*, vol. 14, pp. 1300–1312, 2023. DOI: 10.1109/TSG.2022.3206092.
- [56] E. Mourão et al., “Investigating the use of a hybrid search strategy for systematic reviews,” in *2017 ACM/IEEE International Symposium on Empirical Software Engineering and Measurement (ESEM)*, 2017, pp. 193–198. DOI: 10.1109/ESEM.2017.30.

## APPENDIX

This appendix provides the supporting methodological frameworks for the study. Specifically, Appendix A details the literature review and paper selection process, and Appendix B formalizes the scoring algorithm used for the multidimensional analysis.

### A. Literature search and selection process

This subsection presents the methodology used to evaluate TSO–DSO coordination research papers and documents. The proposed framework is designed to quantify the gap between algorithmic development and real-world implementability.

1) *Literature search strategy*: the paper selection process follows a structured methodology, inspired by the approach proposed in [56]. To ensure broad coverage of the multidisciplinary nature of TSO-DSO coordination, multiple scientific databases and publishers are considered. The search process is conducted with the *Publish or Perish* software tool (©1997-2026, Anne-Wil Harzing), using Google Scholar, Scopus, and Semantic Scholar as primary search engines.

The primary search query was designed to capture the intersection of system operators and their coordination mechanisms:

(power OR electricity OR network OR grid OR DER OR “distributed energy resource”) AND (TSO OR “transmission system operator” OR “electricity transmission”) AND (DSO OR “distribution system operator” OR “electricity distribution”) AND (coordination OR cooperation OR interaction OR interface)

The search is restricted to publications from 2015 onwards, corresponding to the period during which the number of TSO-DSO coordination papers increased.

2) *Inclusion criteria*: Papers were included if they met all the following criteria:

- They are peer-reviewed publications or reports from recognized institutions.
- They provide an explicit discussion of TSO-DSO coordination or interaction mechanisms.
- They mention limitation(s) from Section II, either by explicit acknowledgment, methodological choices, or real-world evidence of implementation challenges.

3) *Paper filtering process*: The filtering process followed PRISMA guidelines and is fully detailed in Figure 2. From an initial pool of 886 records, the papers are progressively filtered: duplicate removal (305), metadata and title screening (172 candidates), abstract and conclusion screening (65 articles), and final eligibility assessment (47 publications). The selected publications are categorized in Table II.

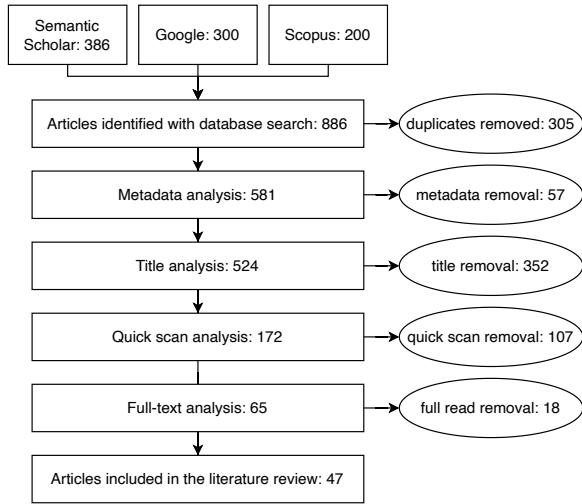


Fig. 2: PRISMA diagram of the paper selection process.

TABLE II: Summary of the 47 reviewed papers categorized by publication type, comprising 23 journal articles, 8 conference papers, 8 pilot projects, 4 technical reports, 3 reviews, and 1 book, with 68% published between 2022 and 2026.

Category	Articles
Journal	[7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29]
Conference	[30], [31], [32], [33], [34], [35], [36], [37]
Pilot	[38], [39], [40], [41], [42], [43], [44], [45]
Reports	[46], [47], [48], [49]
Review	[50], [51], [52]
Book	[53]

### B. Multidimensional scoring methodology

To support a structured comparison across the reviewed literature, each paper is evaluated along the five dimensions introduced in Section II according to the following scoring system.

For all scientific articles obtained from the process described in Appendix A, we assign an index to each paper (corresponding to its literature review entry) and define the set of indices as  $\mathcal{A}$ . This set is partitioned into three disjoint subsets: pilots  $\mathcal{P} \subseteq \mathcal{A}$ , non-pilots  $\mathcal{N} \subseteq \mathcal{A}$ , and other contributions  $\mathcal{O} \subseteq \mathcal{A}$ . Only the papers in  $\mathcal{P} \cup \mathcal{N}$  propose coordination schemes and are therefore included in the scoring analysis.

Let  $D$  denote the set of dimensions along which the papers are compared. For each dimension  $d \in D$ , we define the set of sub-dimensions  $I_d$ . These two sets correspond, respectively, to the first and second columns of Table I (*Dimension* and *Sub-dimension*).

For each paper  $p \in \mathcal{P} \cup \mathcal{N}$ , dimension  $d \in D$ , and sub-dimension  $i \in I_d$ , we define a discrete score  $s_{p,d,i}$  that depends on the characteristic of the paper for that dimension and sub-dimension. Its value corresponds to the

entry reported in the fourth column (*Score*) of Table I for the characteristic associated with the paper.

For each paper  $p$ , the scaled per-dimension score  $s_{d,p}$  is defined as

$$s_{d,p} = \frac{\sum_{i \in I_d} s_{p,d,i}}{\sum_{i \in I_d} s_{d,i}^{\max}}, \quad (1)$$

where  $s_{d,i}^{\max}$  is the maximum attainable score for dimension  $d$  and sub-dimension  $i$ .

Finally, the score of each paper group is given by the average scaled score over pilots and non-pilots:

$$S_{X,d} = \frac{1}{|X|} \sum_{p \in X} s_{d,p}, \quad X \in \{\mathcal{P}, \mathcal{N}\}. \quad (2)$$

This yields, for each group and dimension, a normalized score in  $[0, 1]$  that is directly comparable across the pilot and non-pilot subsets.