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How do electricity TSOs embrace innovation to future-proof their role in the energy transition?

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ABSTRACT

Access to electricity is the lifeblood of modern society. Electricity grids are undergoing transformative changes, driven mainly by decarbonization, decentralization and the integration of variable renewables. Transmission System Operators (TSOs) face increasing pressures from these changes, yet the scale and pace of innovation required to overcome them remain largely unexplored. This study uses interviews with innovation leaders at 11 European TSOs to investigate their approaches to managing the energy transition, focusing on innovation strategies, technology adoption, and future visions. We find that many TSOs adopt decentralized innovation strategies, involving business lines in defining innovation needs and exploring digital and grid technologies to improve efficiency and flexibility. TSOs are using cross-sector collaborations with various decision-making and benchmarking tools to improve performance and better manage emerging technologies like non-wires alternatives. While TSOs seek to adopt new technologies, regulatory constraints, excessive bureaucracy, technology immaturity, skills gaps, and organizational cultural inertia are raised as key barriers. We argue that proactive engagement in innovation, supported by collaboration and regulatory changes could improve TSO resilience and agility. We highlight the importance of integrating innovation into the core strategy of TSOs and the critical need to modernize regulatory frameworks, originally designed for a very different historical context, to eliminate outdated constraints and enable TSOs to more effectively future-proof their organizations.

1. Introduction

Electricity grids form the backbone of contemporary lifestyles, delivering quality of life and well-being. Transmission networks are essential for transitioning away from fossil fuels, enabling the electrification of industry, transportation, heating and cooling [1]. As countries rapidly build renewable capacity to meet climate targets [2], demand for new power lines grows [3], reflected in the phrase “no transition without transmission” [4].

Historically overshadowed in mainstream discourse, power grids are gaining increasing attention through a series of strategic plans and publications from governments, institutions, NGOs, and media [5,6]. Examples include The Economist’s cover article “Hug Pylons, Not Trees”, advocating public support for grid expansion to meet climate objectives [7], and the “Electricity Grids and Secure Energy Transitions” report projecting that the global grid must double in length by 2040 [1].

In 2023, the European Union proposed the EU Grid Action Plan, a 14-point policy to address challenges in expanding, digitalizing, better utilizing, and funding European electricity networks [8]. Similarly, the US Department of Energy announced billion-dollar investments in transmission under the Bipartisan Infrastructure Law and Inflation Reduction Act (IRA). These aimed to develop thousands of miles of upgraded transmission lines to reduce electricity costs and increase reliability against extreme weather, energy security, and jobs growth [9].

Transmission System Operators (TSOs) maintain electricity system security and quality of supply, essentially “keeping the lights on”; but they face substantial transformations [10–12]. Traditional grids, designed for centralized generation near consumption centres, now incorporate distributed, intermittent renewable energy sources. Grids are evolving from linear to meshed structures, integrating batteries, electric vehicles with smart charging, virtual power plants, and demand-side response. TSOs also face threats from cyberattacks, extreme weather, and public opposition to projects. They must balance grid upgrades against costs to ratepayers, while the rise of prosumers and micro-grids risks stranded assets and lost revenues.

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Despite growing recognition of electricity grids and the challenges faced by grid operators, there remains limited focus on the strategic, organizational, and innovation challenges facing TSOs. Although regulated monopolies are shielded from direct competition, TSOs must proactively future-proof their organizations, investing holistically across innovation, cutting-edge technologies, transformative organizational changes, and innovative business models.

This study explores TSOs' approaches to the energy transition and major transformations occurring in the sector, focusing on innovation: how they define strategies, set priorities, and direct their efforts. It examines both strategic and operational dimensions of innovation, including the technologies TSOs consider essential. The study investigates whether and how TSOs benchmark against peers and the organizational, operational, or technological areas they perceive themselves to excel. It also explores TSOs' views on key innovations, like non-wires alternatives (NWAs), identifies the main challenges they face, and how they envision their evolving role within a transforming energy landscape.

This study bridges innovation theory and the practical challenges of regulated energy systems by revealing how European TSOs strategically embrace innovation to navigate the energy transition. Using semi-structured interviews with professionals from TSOs' innovation departments, complemented by literature insights, this paper challenges conventional assumptions, advancing theoretical debates on innovation in regulated monopolies. It identifies transferable best practices and strategic innovations to help future-proof TSOs. This study does not assess the positions, feasibility, political implications, or merits of the innovations discussed. Instead, it seeks to represent the perspectives of innovation professionals leading European TSOs, offering a unique contribution by foregrounding expert views that are largely absent from existing academic literature.

Section 2 provides a literature review on innovation theory, including disruptive and business model innovation. Section 3 details the methodology, Chapter 4 presents our interview findings, and Chapter 5 concludes by discussing actions TSOs can take to improve their future readiness, study limitations, and policy implications.

2. Background

2.1. Relevant literature on innovation

Despite being regulated monopolies shielded from direct competition, Transmission System Operators (TSOs) are not immune to disruptive forces. To future-proof their organizations amid the energy transition, TSOs must commit to research and innovation, including investment in novel and uncertain initiatives [13]. TSOs should also innovate their business models by adopting new technologies and diversifying activities [11]. This approach, while sometimes overlooked, is important for companies to maintain their lead and adapt to the evolving industry landscape [14–16]. Organizational success and innovation depend on strategic decisions [17], with CEOs playing a key role in allocating resources towards innovation, supporting radical ideas, and creating unified transformation strategy [14,18].

Companies structure innovation efforts in various ways, including centralized teams, decentralized models allowing business units freedom within guidelines, or hybrid forms. Decentralized models align well with customer needs but may offer narrower perspectives than centralized approaches [19]. Including business units in the innovation process reduces cultural clashes and facilitates comprehensive innovation [14,19].

Academic literature differentiates between closed innovation, relying on internal resources, and open innovation, involving external partners such as suppliers or competitors. Open innovation, both inbound and outbound, addresses resource and competency gaps [20]. However, no single model fits all companies, and multiple models often coexist within an organization [14,19,20].

The coexistence of radical innovation and new business models creates challenges such as resource competition, balancing existing operations against uncertain innovations, and potential obsolescence of current models [14,15]. To navigate these issues, companies may develop radical innovations externally via "skunkworks" for autonomy or through spin-outs for independent operation, increasing agility [15,21,22]. Such ambidextrous structures allow organizations to pursue innovation while maintaining stability, providing dual focus from top management and exploiting synergies between the core company and its offshoots [23].

Companies can use corporate venture capital to access new trends and solutions without extensive internal development, investing in startups to acquire innovative technologies and refresh their culture [24–29]. This approach is a strategic tool for exploring new technologies and business models with minimal risk, enabling rapid learning and adaptation to technological change [30–33]. Corporate venturing via incubators and accelerators can target businesses from seed to rapid growth stages [31]. This strategy aims to balance innovation with ongoing operations [34–36]. Successful corporate venturing depends on selecting startups that align with company objectives, creating synergies, integrating venture capital into strategic planning, and ensuring financial sustainability through diversified investments [29].

2.2. Business intelligence tools for decision-making support

Business and technology intelligence supports informed decision-making and adaptation to industry changes, particularly by identifying technology trends and disruptions to future-proof business models [14,31,37,38].

Firms might conduct "scouting missions" for innovation insights [17], and use tools such as Gartner's Hype Cycle and ThoughtWorks' Technology Radar, despite limitations including broad categorization and vendor-specific focus [39]. Tools like the High Impact Technologies Radar and Innovation Radar broaden evaluations to digital innovations and startups, aiding assessment of technological and business model impacts, aligned with firms' strategic needs [31,39].

Benchmarking analysis is another important tool, enabling companies to learn from those who successfully managed uncertainty and disruptions [40,41]. It involves comparison with peers and sectors across metrics like finance, operations, sustainability, and innovation to adopt best practices and identify successful strategies [42–46]. This cost-effective method helps design new business models, identify performance gaps, achieve cost savings, improve efficiency, and develop an innovative culture [47,48]. It supports strategic planning and resource allocation [49] but must align with the organization's unique context [14,48]. The benchmarking process includes defining metrics, selecting subjects, collecting and analysing data, and implementing best practices [41], facing challenges like data comparability and resource management [50].

Innovation benchmarking evaluates innovativeness in countries and companies using tools developed by consulting firms and academic institutions [14,18,51,52]. BCG's "innovation to impact (i2i)" tool measures companies' innovation capabilities against an extensive database [53]. The Frost Radar™ assesses innovation and growth potential, considering scalability and R&D productivity [54]. For small and medium-sized enterprises, Copenhagen Business School provides a specialized tool to evaluate innovation and identify gaps between perceived and actual activities [55].

In electricity transmission, benchmarking is common, but complex and limited [56]. Notable initiatives include the Pan-European Cost-Efficiency Electricity and Gas Transmission System Operators Project, which assessed 46 TSOs from 16 European countries [57,58]. In Germany, Bundesnetzagentur benchmarked TSO efficiency as part of its revenue cap determination [59]. Global Transmission analysed 212 transmission system operators worldwide, covering network growth, operational and financial performance, transmission losses, power interruption metrics, revenue, profit margins, and capital spending from 2017 to 2021, with projections to 2027 [60]. To date, only Biancardi benchmarked innovation among TSOs, assessing engagement levels across six technologies for 12 European electricity TSOs [11].

In regulated monopoly industries such as TSOs, there may be scepticism about benchmarking's relevance [13]. However, when legal and regulatory teams observe peer organizations innovating, it often encourages them to follow, adopting a "safety in numbers" approach. Sharing peer innovation strategies internally can build a case for innovation, addressing concerns about pioneering in uncharted territory [13].

2.3. Who are the transmission system operators (TSOs)?

Electricity TSOs are central to the power sector, ensuring secure and reliable transmission from power plants to distribution networks, balancing real-time supply and demand, and integrating renewable energy to support the energy transition.

The EU's 2009 Third Energy Package introduced unbundling rules separating transmission and distribution from generation and supply. Intended to liberalize markets, reduce costs, and improve efficiency, these rules created diverse management arrangements across the EU.

Most European TSOs underwent full ownership unbundling and now operate solely as electricity transmission businesses under the Independent Transmission System Operator (ITSO) model [61]. Others, such as France's Réseau de Transport d'Électricité (RTE), follow the Legal Transmission System Operator (LTSO) model: RTE is legally separated from its main shareholder and former vertically integrated utility (VIU), EDF.[1] Some countries, including Ireland, adopted the Independent System Operator (ISO) model. Malta retains its vertically integrated structure due to its unique island status, exempt under EU rules.

Most European TSOs are primarily state-owned, although some are privately held. Typically, a single TSO monopolizes each country's national transmission grid, but exceptions exist, such as Germany, which has four TSOs, each overseeing a specific control area. Appendix 1 summarizes Europe's transmission operators and their organizational arrangements, including grid length, revenue, employee numbers, and ownership details.

In some cases, such as ELES[2] in Slovenia, the same entity manages both transmission and distribution. Similarly, in countries using the ISO model, transmission owners often control substantial parts of electricity infrastructure, including the distribution grid. Some TSOs, including REN in Portugal and Energinet in Denmark, also manage natural gas transport, handling multiple types of energy infrastructure. Fig. 1 provides an overview of European transmission operators, their organizational arrangement and business scope.

2.4. The interplay between regulation and innovation

Regulation is critical for supporting innovation among TSOs due to their natural monopoly status [61–63]. Regulatory designs that incentivize TSOs to innovate underpin the energy transition's success [64–67]. National Regulatory Authorities (NRAs) must address distortions in investments in innovative technologies and overcome barriers to TSO innovation [11,62,63].

Major barriers to TSO innovation include unclear mandates [58,68,69] and regulatory focus on cost-efficiency over innovation [66,70–72]. The uncertainty of innovation outcomes makes network companies wary of investing in risky experimental activities [67]. Regulatory frameworks favour CAPEX-intensive solutions over OPEX, discouraging TSOs from adopting cheaper options like virtual power lines, dynamic line rating, or demand-side response. These technologies reduce conventional infrastructure investment, achieving similar benefits but lowering TSOs' financial returns [62,63]. Typically, CAPEX is remunerated through rate-of-return or cost-plus regulation, guaranteeing recovery and returns once approved by the regulator, and is included in the Regulatory Asset Base (RAB). In contrast, OPEX is compensated on a current or capped basis, earning no such return. Thus, cheaper solutions appear less attractive compared to higher-cost, higher-profit options.

To address this, the TOTEX-based approach, combining CAPEX and OPEX, incentivizes companies to choose efficient spending combinations [63]. However, this approach is still rarely adopted among NRAs [57].

Some NRAs introduced innovation-stimulus mechanisms offering utilities financial incentives to increase innovation investments and reduce risks associated with immature technologies [73]. Jamasb categorize these as [65]: (i) RAB-based; (ii) WACC-based; (iii) cost pass-through; and (iv) competition-based. Another categorization distinguishes between input-based and output-based approaches. Input-based approaches integrate innovation costs into the RAB or offer higher returns, promoting targeted innovation but potentially shifting risk to consumers. Output-based approaches reward only successful innovations through price or revenue increases, presenting verification and measurement challenges [64,66,74]. Poudineh suggest that regulatory frameworks should vary by innovation stage, using input-based approaches for early stages like R&D and pilots, and output-based approaches for later stages, utilizing "trial and error" and recognizing technology maturity differences [66].

Cambini found innovation-stimulus mechanisms effectively promoted smart grid investments [64], while Ribeiro and Jamasb identified positive impacts on patent applications [75]. Biancardi identified higher WACC premiums, additional budgets, extra revenues from successful innovations, and financial incentives as factors boosting TSOs' innovativeness [11]. Ribeiro and Jamasb also noted the cost pass-through approach, first adopted by the UK's Ofgem in 2005, catalysed innovation [75]. Brunekreeft proposed dedicated budgets for digitalization and innovation with pre-agreed costs and timelines [76]. Ribeiro and Jamasb confirmed their effectiveness, finding European Commission-funded projects, such as in smart grids, positively impacted network operators' innovation investment [75].

Regulators can also stimulate innovation using regulatory experiments like sandboxes, allowing small-scale exceptions to existing rules. Schittekatte examined sandboxes in Italy, the Netherlands, and Great Britain, highlighting varied implementations and potential to support Europe's green transition [77]. Insights from these countries could shape broader regulatory discussions. Beckstedde reviewed 72 sandbox projects across eight European countries, developing best practices to increase sandboxes' effectiveness [78].

2.5. The broader TSOs innovation environment

TSO innovation is driven by more than regulation; it involves various organizations, stakeholders, initiatives, national and supra-national strategies, and public and private funding. International initiatives like Mission Innovation (MI) and the Green Powered Future Mission (GPFM) support global energy transition goals and encourage TSOs to adopt advanced technologies [79]. Within Europe, the EU Technology and Innovation Platform Smart Networks for Energy Transition (ETIP SNET) drives transmission industry innovation and promotes knowledge exchange. Its R&I Implementation Plan (IP) 2025+ outlines urgent R&I needs to be addressed through European and national funding programmes [80].

When choosing innovation areas, TSOs follow their own strategies and ENTSO-E's Research, Development, and Innovation (RDI) Roadmap

[1] Established in 2005 as a limited company and a wholly owned subsidiary of EDF, RTE's capital was transferred in 2016 to CTE (Coentreprise de Transport d'Électricité), which is jointly owned by EDF (50.1 %), the Caisse des Dépôts (29.9 %), and CNP Assurances (20 %).

[2] ELES merged with SODO, the distribution system operator, in October 2023.

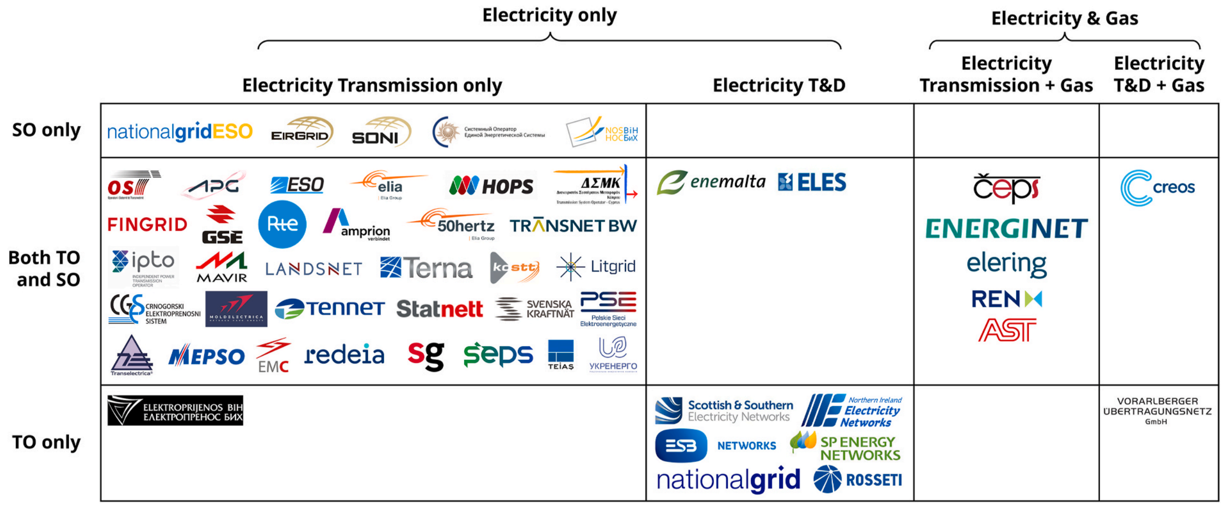


Fig. 1. Overview of European TSOs. Abbreviations: SO: System Operator; TO: Transmission owner.

2020–2030, a legally mandated guide for TSOs and stakeholders [81]. This sets priorities based on technology trends, operational needs, and market developments, with regular updates. An annual Implementation Plan targets key topics to transform project ideas into reality [81]. ENTSO-E found that of 117 TSO projects, 40 % are funded by TSOs and 37 % by Horizon Europe programmes, demonstrating the importance of the EU's key research funding programme in TSO innovation [81]. However, the report notes only partial alignment between TSO RD&I activities and Horizon Europe calls, suggesting better alignment with ENTSO-E's Roadmap could accelerate innovation.

EU Network Codes also incentivize TSOs and stakeholders to invest in innovative solutions to meet evolving grid requirements. For example, the 2024 Network Code on Demand Response proposed by ENTSO-E and the EU DSO Entity [82] supports decarbonization and strengthens energy system resilience. The code removes barriers to demand response and distributed energy resources (DERs) accessing markets [83], broadening participation in flexibility services. The proposed Energy Market Design (EMD) Reform [84] encourages innovation among network operators by strengthening investment signals for renewables, promoting demand response, and improving consumer protection. It promotes advanced technologies for better grid management, renewable integration, and system efficiency. The 2023 EU Grid Action Plan aims to stimulate TSO innovation [81]. It recommends ENTSO-E and the EU DSO Entity jointly update Technopedia to improve information on smart grid technologies for project promoters and regulators [82]. Updates will be shared at future Smart Electricity Grid Summits.

The EU's "Digitalizing the Energy System Action Plan" aims to transform the electricity grid through investments in digital technologies like smart IoT devices, 5G, a pan-European energy data space, and digital twins [85]. For TSOs, this improves grid efficiency and resilience, supports advanced simulations, and improves data exchange with Distribution System Operators (DSOs). The strategy drives innovation, collaboration between digital and energy sectors, consumer empowerment, and progress towards EU climate goals. The EU Data Act creates a unified framework for cross-sector data sharing, to promote innovation, improve grid management, and integrate renewable energy [86].

2.6. Innovation within TSOs

Limited research exists on TSO innovation and their evolving roles in the energy sector. TSOs must balance stability, cost-efficiency and innovation; so better forecasting and stakeholder engagement are recommended for managing the energy transition [12]. European TSOs are generally conservative [11], but are expanding beyond traditional roles by diversifying into new technologies and services to improve grid stability [10]. ENTSO-E highlights TSOs' R&D to increase grid flexibility and operations, calling for further research into storage and eco-design [81].

ENTSO-E's Technopedia provides detailed information on technologies to improve Europe's electricity transmission grid [87]. Compass Lexecon, WindEurope, and ACER advocate for regulatory reforms to facilitate adoption of "grid optimization technologies" or "grid enhancing technologies" in system planning [62,88,89]. These increase transmission capacity and integrate renewable energy, offering cost-effective ways to manage variability.

"Non-wires alternatives" (NWAs) are low-carbon, cost-effective, easily-installed technologies and business solutions that provide flexibility to system operators, helping defer traditional infrastructure upgrades [90,91]. NWAs are resilient to load growth uncertainty, avoiding stranded costs if demand does not rise [92,93]. Electricity storage, especially lithium-ion batteries, is an important NWA, providing market stability and cost-effective management of network constraints [94–96]. Integrating NWAs into system planning is widespread through the US, especially at distribution level, where operators are incentivized to use them, but less common in Europe due to regulatory barriers [62,63,97]. Unlike the US, where vertically integrated utilities manage grid assets and DERs, European unbundling rules separate system operation from electricity supply and generation, limiting flexibility in adopting NWAs [98].

Several innovations target increasing operational complexity, such as declining system inertia caused by rising shares of variable renewable generation [99]. Accurate real-time inertia data allows grid operators to optimize inertial reserves, ensuring cost-effectiveness, efficiency, and reducing renewable curtailment [88].

TSOs are developing cooperations with market actors like DSOs and Balance Responsible Parties (BRPs) [81,92]. They are creating platforms and market products to utilize distributed and decentralized flexibility resources to help stabilize the grid and balance supply and demand, which are becoming more volatile [100,101]. An example is UVAM (Mixed Virtual Aggregated Units), introduced by Italy's Terna in 2018, aggregating distributed resources like renewables, storage, and demand response into a single entity, allowing market participation and balancing services provision.

TSOs are also exploring innovative measures to address rising grid balancing costs [99]. The UK National Grid ESO's new Balancing Reserve (BR) service, introduced in 2024, allows day-ahead procurement of Regulating Reserve through daily auctions, reducing costs while improving efficiency and system security [102]. At the cross-border level, the Electricity Balancing Guideline promotes shared balancing resources and harmonized imbalance netting, expanding balancing areas and integrating capacity markets to reduce overall costs [87,99,103]. Additionally, TSOs can lower balancing costs by providing real-time imbalance data, enabling participants to perform "passive balancing" and adjust schedules based on price signals, decreasing the need for balancing reserves [99,104]. Real-time data publication varies across Europe, with the Netherlands and Belgium updating every 1–2 min, Britain after 30 min, and Germany a month later, hindering rapid BRP responses [99].

3. Methodology

This study used interviews to explore the opinions of innovation professionals at European electricity TSOs, covering how innovative TSOs are, how they may evolve, and the main challenges they face. It provides a deeper and previously under-explored perspective on the industry's changing landscape. This study adopted an exploratory approach, distinct from descriptive, explanatory or evaluative methods, using open-ended questions within a topic with limited existing literature. Its aim was to clarify the complexities provide a basis for future research, as suggested by Saunders [105].

3.1. Data collection

Data were obtained through semi-structured interviews, guided by specific themes and questions. This allowed themes and patterns to develop naturally based on participants' unique experiences and interpretations [105]. The method's flexibility and interviewee anonymity were chosen to support open and honest discussions, beyond the conventional corporate discourse and publicly available data [106].

Interviews were conducted with eleven European TSOs (Fig. 2). TSOs were selected using purposive sampling to create a homogeneous group of top-ranking innovation professionals while maintaining diversity across several strategic dimensions. Selection criteria included TSO size, geographical coverage across Europe, and innovation maturity as assessed through public information such as participation in EU-funded innovation projects or presence of formal innovation units (e.g. Refs. [11,81,87]). Additional factors considered included ownership structure, regulatory schemes, electricity generation mix (e.g. nuclear or coal), renewables penetration, and electric vehicle uptake in the TSOs' region. This aimed to capture diverse viewpoints while identifying shared insights among participants.

Interviewees within each TSO were recruited from heads of innovation or similar roles. Individuals were selected for their expertise, central positions within their organizations, and deep understanding of the field. While the sample size is relatively small, it represents an 'elite' group previously overlooked in research, and thus is appropriate for gaining in-depth understanding of expert views and reasoning [107].

All interviews complied with relevant laws, institutional ethics guidelines, and General Data Protection Regulation (GDPR) principles. Interview data were anonymized at source, enabling participants to freely express their views. Informed consent was obtained at the beginning and end of every interview, and through participant information sheets provided beforehand. Participants were reminded at each stage that involvement was voluntary and they retained the right to decline or withdraw at any time without consequence. Interview guides (see Appendix 2) steered discussions, but interviews were allowed to proceed organically according to participants' interests and priorities.

Interviews were conducted via Microsoft Teams from November 2023 to February 2024 and lasted 45–60 min (median 50 min). Interviews were not recorded or transcribed to maintain anonymity; instead, detailed notes were taken manually.

One limitation of this approach is that not all perspectives may be represented due to the small sample size and exploratory nature. The number and duration of interviews may not fully capture the complexity of the numerous topics discussed. Additionally, the limited sample size precludes statistical analysis across the entire TSO population, restricting this study to qualitative insights. Despite these limitations, this work establishes empirical novelty by providing novel qualitative data from an elite group [108]. Also, qualitative research often prioritizes depth over breadth [109]. Guest note "saturation begins after six in-depth interviews and is definitely evident after 12 interviews" [106]. Thus, this study's sample (11 subjects) may be considered "extremely valuable and represent adequate numbers" when studying "hard-to-access populations" such as corporate elites [110].

Finally, a potential concern is that interviewees' specific roles mean their viewpoints may be opinionated or biased. However, as this expert group has not previously been consulted in academic research, a strength of this study is voicing their perspectives, providing a novel contrast to established regulatory and academic views.

3.2. Contextualizing the interviewees

The represented TSOs contain diversity in the size of innovation units (Fig. 3). These range from small groups with only 1–6 people dedicated to innovation such as REN (Portugal) and Fingrid (Finland), to much larger teams of 70–100 people such as National Grid ESO (GB) and RTE (France).

While some innovation departments are larger, team size alone should not lead to assumptions that these TSOs dedicate more effort to innovation. Interviewed TSOs employ a broad array of tools to support

TSO	COUNTRY
Austrian Power Grid (APG)	Austria
Elewit (Redeia)	Spain
Elia	Belgium and Germany
Fingrid	Finland
Ipto	Greece
Terna	Italy
National Grid ESO	England, Wales and Scotland
REN	Portugal
RTE	France
Swissgrid	Switzerland
Transelectrica	Romania

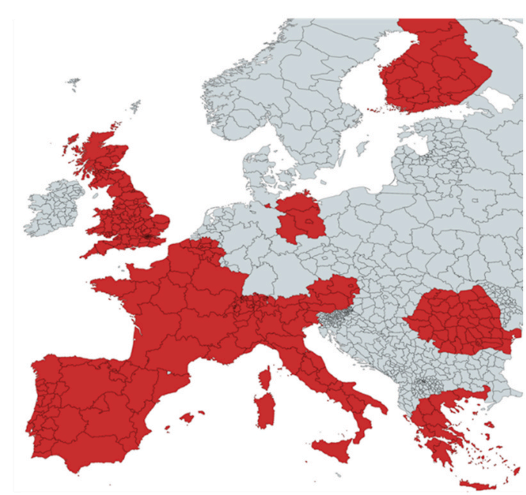


Fig. 2. The TSOs' geographical areas covered in this study.

TSO Name	Country	Innovation team size	TSO's total employees	% (of total)
APG		6–7	~ 730	~ 1.0%
redeia elewit		18–20	~ 2,420	0.5–1.0%
elia Elia Group		~ 15	~3,500	~0.5%
FINGRID		1–6	~ 527	~1.0%
ipto		~ 25	~ 1600	~1.5%
nationalgrid		~ 68	~3,277 (2,349 in NGET, and 928 NG ESO)	~2.0%
REN		~ 4	~748	~0.5%
Rte		~100	~ 9,586	~1.0%
sg		~10	~ 853	~1.0%
Terna Driving Energy		~60	5,300–5500	~1.0%
Transelectrica		~9	~ 2,042	<0.5%
	Average	**29**	**2,700**	**1.0%**

Fig. 3. Interviewed European TSOs innovation teams' size. The right-most column calculates the innovation team size as a percentage of the entire organization workforce. Information were collected from desktop research and interviewees.

innovation, including traditional internal research and development (R&D). They also participate in EU-funded projects that offer collaboration opportunities with diverse networks of stakeholders spanning other TSOs, research centres, startups, and academia. TSOs also frequently engage in spontaneous project collaborations with peers. An example is Equigy, a European crowd-balancing platform using blockchain to integrate DERs into the electricity market, founded by a consortium of European TSOs, including Swissgrid, TenneT, and Terna.

Additionally, TSOs use Centres of Excellence (CoEs) or Technology Labs to promote innovation. Notable examples include Terna's Mobility Lab; Elia's CoE for Artificial Intelligence, Extended Reality, Internet of Things, Robotics, Drones, and Automation; National Grid's AI CoE; and RTE's agreement with The SuperGrid Institute to create a CoE for power electronics.

Other tools include Open Innovation programs designed to attract and develop collaborations with their innovation ecosystem. These initiatives range from programmes targeting specific challenges to broader schemes selecting the best ideas from potential partners for collaboration with TSOs. Examples include the 'Terna Ideas' programme, Elewit's 'challenge (m).' programme, Elia's Innovation Challenge, Fingrid's Innovation Challenge, and National Grid's Innovation Event and open call for regulator-funded initiatives. Some programmes also target internal employees, aiming to nurture corporate intrapreneurship and innovation culture. Examples include Redeia's Elewit Intrapreneurship Programme, REN's Innovation Leaders programme, and Terna Ideas, which invites proposals from both internal and external sources.

Following such initiatives, TSOs incubate selected ideas and startups in incubators or accelerators. Examples from interviewed TSOs include Redeia's Venture Client Programme and Elia Group's Incubation Factory: The Nest. Additionally, some TSOs use corporate venture capital (CVC), involving mergers and acquisitions (M&A), and investments in innovative startups. Prominent CVC examples include National Grid Partners, Redeia's Elewit Venture Capital, and Terna Forward. Recently, Terna invested in Wesii S.r.l., an Italian startup using AI-equipped aircraft and drones for inspection and remote-sensing in the renewable energy sector.

TSOs also pursue joint ventures and partnerships to address knowledge gaps and challenges alongside startups, research centres, universities, and innovative firms. These collaborative efforts complement the tools mentioned above. Fig. 4 shows which TSOs employ selected innovation tools.

4. Results and discussion

This section outlines TSOs' approaches to the energy transition and sector's transformations. It focuses on innovation, from strategy to implementation and future planning. It begins with how TSO innovation strategies are defined, including identifying technology trends and prioritizing innovations, laying the foundation for understanding how TSOs structure their efforts. It then covers benchmarking to assess progress, learn from peers, and highlight perceived excellence. strengths. Non-wires alternatives (NWAs) are then used as a case study to explore how TSOs engage with a key class of innovation in practice. Finally, the section explores the challenges and evolving role of TSOs, placing innovation within a broader strategic and sectoral context. This structure offers a comprehensive understanding of how innovation is perceived, managed, and applied within TSOs, and how it shapes their role in a changing energy system. Points are illustrated with interview quotes shown in italics, and are not attributed to maintain anonymity.

4.1. Innovation approach and technology trends

4.1.1. Approaches, tools and techniques used by TSOs to select innovation focus areas

Among the TSOs interviewed, over half adopt a centralized approach to innovation, using a dedicated innovation unit (or centralized R&D

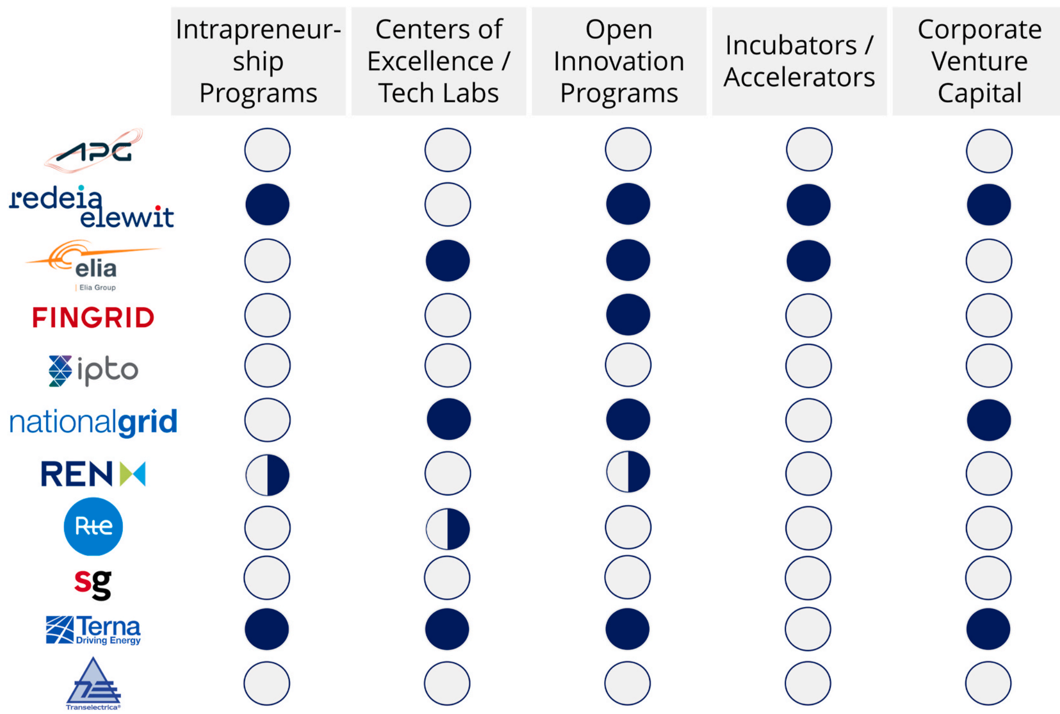


Fig. 4. Innovation 'tools' used by Interviewed European TSOs to support innovation within their organizations. R&D, Supranational projects (e.g. EU-Funded projects) and other collaborations are excluded. Full circle indicates initiatives that are fully implemented and in operation. Half-circle indicates initiatives that are either partially implemented or operating on a restricted scale, according to the available data. Empty circle indicates no initiative/no information available. Information were collected from desktop research and interviewees.

department) to decide focus areas and projects to undertake. In contrast, three of the 11 TSOs employ a hybrid approach, blending centralized planning with decentralized input from business units to align RD&I activities with business needs. A further two TSOs predominantly utilize a decentralized approach, where innovation initiatives originate directly from business units.

TSOs have developed various methodologies to identify technological trends and select focus technologies. Over half adopt the radar methodology, corroborated by interactions with other organizations, or have developed other structured methodologies. The remaining TSOs primarily rely on their networks and interactions, or do not use specific methodology. Interviewees using the radar methodology highlighted key pros and cons of it (Table 1).

TSOs also described additional practices they employ to map emerging technology trends and select technologies for innovation efforts (Fig. 5).

Table 1
Interviewed European TSOs using radar analysis or similar structured methodology to identify technology trends and select specific technologies for their innovation efforts.

Pros	Cons
"[the radar allows us] to have a good map, a complete overview of where we are."	*"We elaborated the radar for the first time in 2023 as a hype."*
"The radar has the goal to disseminate technological knowledge throughout our company, fostering innovative thinking and advanced problem-solving approaches among all employees."	*"Discussing a single point on the radar could extend to an hour, leading to an information overload and you can't discuss with the management people 100 points."*
"The goal [of using the radar] is to direct investments in the technologies that the system needs."	*"Potentially [the radar] can also be used to spot all the little new innovations that are linked to a specific technology cluster."*
"[the results from the radar help us to] reconsider the priorities."	*The last consultation phase involved "about 550 participants who provided feedback."*

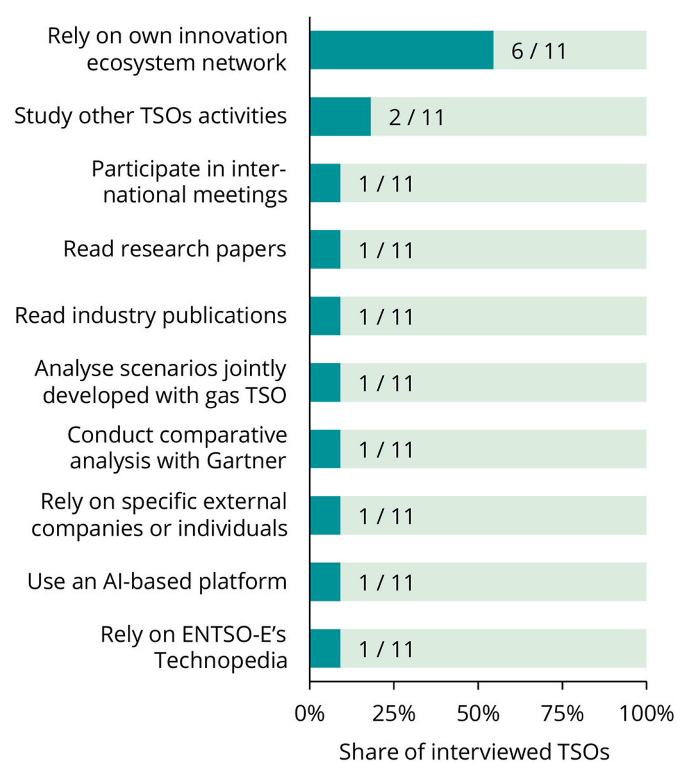


Fig. 5. Main methods and practices for identifying technology trends and selecting specific technologies for innovation efforts, other than radar analysis or similar methodology. Bars indicate how many of the interviewed TSOs reported using these additional practices.

4.1.2. Current focus of innovation efforts among European TSOs

Common innovation areas are prioritized by interviewed TSOs (Fig. 6). Most reported a focus on 'System Operation', emphasizing operational efficiency and stability. 'Digitalization' was the second-highest priority, reflecting the importance of integrating digital solutions and managing increasing data volumes: *"One of the biggest problems I have and that I will have in the future is the fact that there is a huge number of data that is coming our way. The ability to rationalize that data and to select what data we need to make what decisions will be crucial. Since I work in real time, I have to be able to understand how to minimize the impact of computing power, understanding what calculations I absolutely have to make in real time and what I can do at another time"*.

Regarding specific technologies, 'AI (including Generative AI)' was the most cited, underscoring its crucial role in fostering digital innovation. Other digital areas highlighted were 'Digital Twins', 'Robotics', 'Advanced Computing (including Quantum)', and 'Cybersecurity'. For energy/grid technologies, 'DLRs' and 'Storage' were most frequently mentioned: *"If we have more and more renewables, we need to build and build like hell, that is why we need complementary solutions like DLR"*.

Sustainability and eco-design, including SF_6 alternatives, were less common themes among interviewed TSOs. Likewise, only two TSOs identified hydrogen as a focus area. This is largely due to TSO managing both electricity and gas grids or its prominence in the national political agenda: *"having both facilities in the same company we can decide the best practice or the best process or the best technology in order to accomplish the challenges. I think it's better to have both together compared with separated organizations"*. The other interviewee on this topic stated: *"We maintain a technologically neutral stance, indicating that our priorities are not dictated by a preference for one technology over another. Instead, our role requires us to address the evolving needs of the electrical system in the forthcoming years. Thus, our approach is shaped by national strategy as well as our capacity to support the system's requirements"*.

4.2. Best practices

4.2.1. Use of benchmarking techniques among TSOs

Interviews revealed varied approaches to benchmarking among TSOs, ranging from detailed analysis to informal information gathering (Fig. 7). Three-quarters cited participation in sector-specific forums (e.g. ENTSO-E) as their primary benchmarking method: *"these working groups make position papers, so there is already a comparison on technology that is then synthesized in a document and then it is used in a common way"*.

These forums also facilitate interactions with other TSOs, providing insights into how peers approach technologies, address challenges, and learn from their collective experiences: *"we have our big brothers, who are really ahead of us and we can learn quite a lot from them"*.

Two TSOs also conducted formal benchmarking analyses through external partners, such as consultancy firms and academic institutions: *"we commissioned a benchmarking with a few TSOs, on R&D innovation process to know where we were on this mapping and what we were doing quite well and where we were lagging behind. Most of the time we do that before designing our new roadmap for innovation"*.

Some TSOs also utilize peer websites for insights: *"when we face a new issue or we see that we need to develop something new, we study what the other TSOs have done or how they are approaching that issue just to see if we can draw some inspiration from them or if someone is ahead of us and we can then learn something"*.

Finally, one TSO systematically analyses peer activities, producing

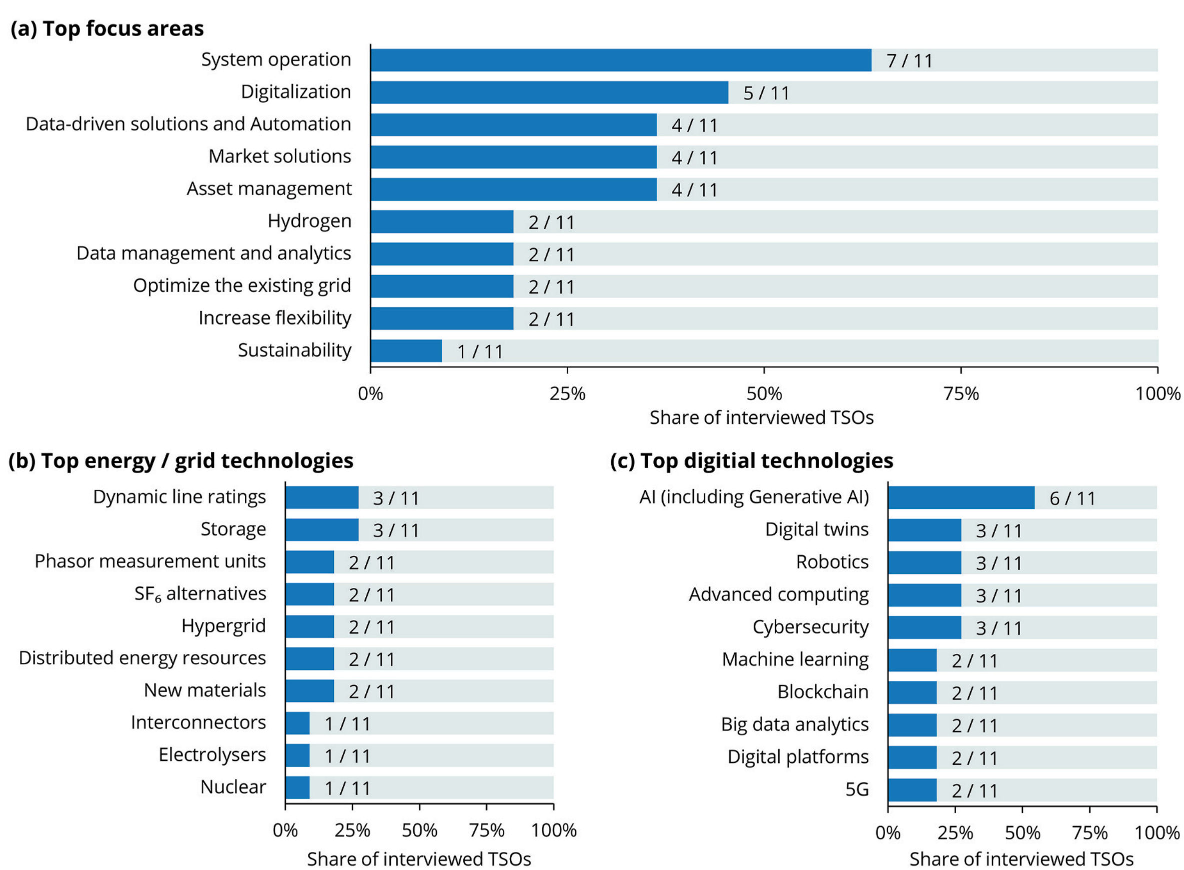


Fig. 6. Overview of the TSOs' main areas of focus, and the specific technologies that pertain to the digital domain or to energy/grid systems mentioned during the interviews. Bars indicate how many of the interviewed TSOs mentioned these areas and technologies. The number reported in the main area differs from the total number reported within specific technologies as these are only conceptually related (e.g. one TSO explicitly reported sustainability while SF_6 alternatives were reported by two TSOs).

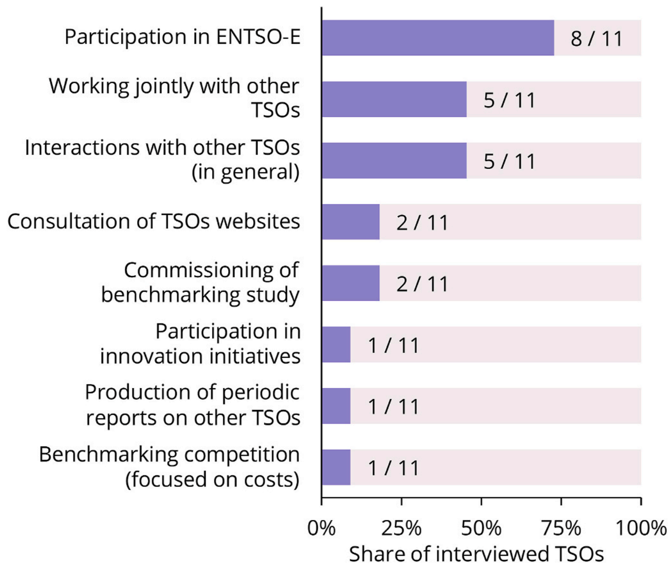


Fig. 7. Overview of the benchmarking practices used by TSOs. Bars indicate how many of the interviewed TSOs reported using these practices.

internal reports and updates. Notably, some TSOs employ benchmarking to confirm strategic direction or identify areas of underperformance, serving as a strategic alignment tool: *"we always question ourselves, are we on the right track, are we focusing on the right projects?"*.

4.2.2. Perceived excellence and best practices

Among the TSOs interviewed, several best practices emerged (Fig. 8). Adopting a decentralized innovation strategy, where business units actively define their needs or are meaningfully engaged, is considered a best practice by TSOs using it (five interviewed TSOs adopt hybrid or decentralized models to align innovation with business needs). This ensures projects closely align with actual business requirements: "*Until a few years ago, we used to follow a different approach where we only pulled the projects from the top to the business lines. Now, they suggest what are their needs and we realized that they are more willing to carry out projects and more involved from the beginning*". Another interviewee stated: *"one of the really best practice concepts, I think, is how the innovation team was structured, by having a so-called SPOC* [single point of contact] *per business domain, that manages all the business needs and the relationships to the main stakeholders and really understands what's the problem, what have we already done, what are we lacking, what could be improved"*. Similarly, another argued: *"we have somehow managed to distribute the R&D work quite good into the business units. So instead of having a centralized R&D department that take all the decision about innovation projects, all the decision making is also in the business side. So, we do R&D and innovation only where the needs, real needs are"*.

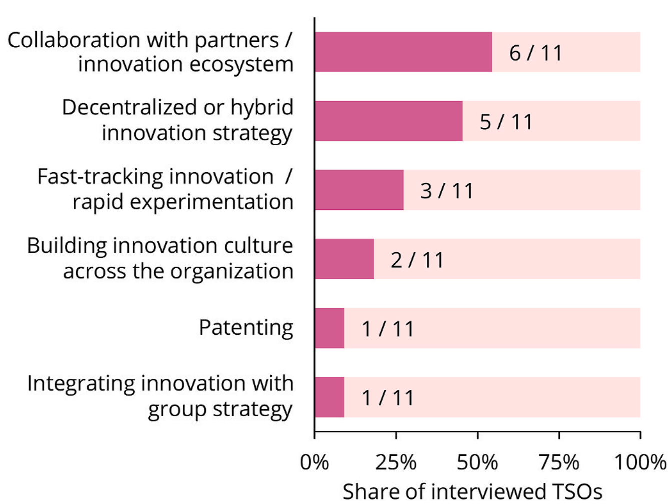


Fig. 8. Overview of the best practices for approaching innovation within TSOs. Bars indicate how many of the interviewed TSOs reported using these practices.

Conversely, one TSO highlighted its centralized innovation strategy, managed by the unit responsible for overall group strategy, as a success factor. This enables seamless integration of innovation initiatives into the group's broader strategic framework.

The most common theme, with six out of 11 interviewed TSOs considering it best practice, is collaboration with external specialized companies and other entities, relying on their broader innovation ecosystem network: "*We always strive to establish partnerships. I believe other companies also adopt this approach effectively by simply proposing, 'Okay, let's collaborate on something'*". This approach expands TSOs' capabilities and addresses specific challenges. Another interviewee stated: *"these kind of collaborations offer a significant leveraging effect. For every euro we invest, others contribute additional* funds, *effectively multiplying our investment three to four times. Each participant, including us, can only afford to contribute a limited amount, so by sharing the burden, we make substantial progress that wouldn't be possible individually"*. Similarly, another interviewee highlighted the importance of collaboration in areas where TSOs lack expertise: *"in some areas we are not the expert, then we have to take advantage of cooperation"*.

Additionally, three TSOs mentioned their ability to rapidly initiate innovation projects, bypassing complex and lengthy approval processes. Innovation literature emphasizes the importance of teams with decision-making autonomy and rapid experimentation to support innovation: *"Like all other TSOs usually in the past we had operated in a much more complex context made of internal procedures with several steps, agreements, approval of projects, budgets and so on. Our new procedure, instead, doesn't stop innovation, on the contrary, we do it in a fast manner in order to do innovation and see projects get done"*.

However, interviews revealed TSOs often face challenges due to their regulated nature, mandating adherence to complex, lengthy authorization procedures that could potentially stifle innovation. An equal proportion of TSOs highlighted their focus on building an innovation culture across their organizations: *"whereas some TSOs may neglect the importance of cultural aspects, we emphasize it"*.

One TSO also attempts to engage its entire workforce in innovation activities: *"we have created a structure based on which all the colleagues, potentially all the 5000 people, are involved in the innovation process"*. Interestingly though, patenting activity was mentioned by only one TSO as a best practice.

Finally, interviewees identified a wide range of technological innovation areas as best practices (Fig. 9). These include flexibility platforms and market solutions, emphasized by four TSOs, followed by asset management, condition monitoring, and renewable management, each highlighted by two TSOs. Other areas mentioned include frequency excursion management, defence systems, and inertia forecasting: *"we are definitely ahead in inertia forecasting […] we have more services* (e.g. *flexibility services) than anyone else in the world, we have developed many market solutions. Perhaps we have much more courage than others"*.

Additional areas include offshore wind technologies, submarine cable technology, electric vehicle infrastructure, power-to-gas, drones, artificial intelligence, robotics, digital substations, Digital Twins, and cybersecurity. This diversity highlights the broad spectrum of innovations TSOs are exploring and adopting as industry best practices. It reflects a complex interplay of factors, from unique geographical and morphological characteristics which dictate specific technical needs, to overarching political and national energy strategies shaping investment. Regulatory frameworks also play an important role, either enabling or constraining innovation in certain areas: *"a close relationship with the authorities is important because they are the ones who make the rules"*.

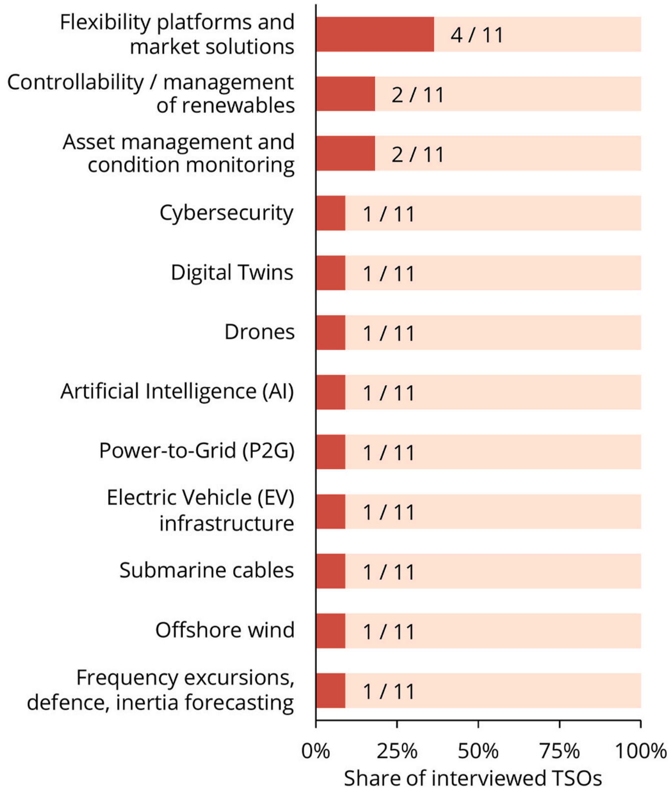


Fig. 9. Overview of the perceived technological areas of excellence among TSOs. Bars indicate how many of the interviewed TSOs reported these areas.

4.3. Special focus on non-wires alternatives (NWAs)

Interviews revealed European TSOs are familiar with NWAs, even if they do not explicitly use this term (Fig. 10). They generally view NWAs as opportunities, regarding some as valuable tools for addressing bottlenecks, congestion, and other issues. Network investments are substantial and time-consuming, and so solutions improving network utilization are welcomed: *"I have never heard that someone mentioned this as a threat. We are like guys who swim and the level of water is rising and rising so we need desperately everything to balance the grid. It's not only about the profitability but rather how to make the system stable"*.

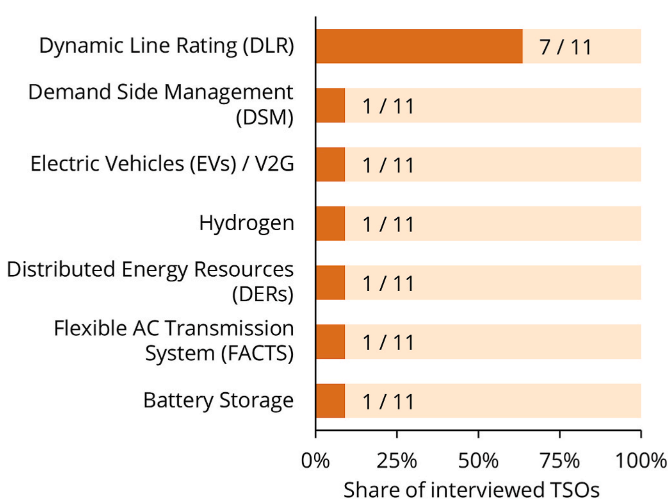


Fig. 10. Overview of the technologies considered as non-wires alternatives among TSOs. Bars indicate how many of the interviewed TSOs reported these specific technologies for current or future adoption.

Some highlighted the need for regulatory adjustments: "*The challenge lies in collaboration with regulators to ensure these advancements are reflected fairly in policies and incentives. Currently, the regulatory framework and incentives for NWAs are not well-established, which could pose a risk to their effective integration and benefit to society. Addressing this gap is essential for harnessing the full potential of NWAs in our evolving energy landscape*".

Some TSOs highlighted potential profitability risks from certain NWAs: "*I perceive as a greater threat individuals reducing their dependency from the grid, for instance, by equipping their homes with batteries and photovoltaic systems, through microgrids or energy communities, thus minimizing the need to connect to the grid except during specific circumstances, such as prolonged periods of winter with no wind or sunlight. I believe this scenario presents a more significant challenge*".

Most TSOs interviewed already integrate NWAs into their core strategy, some using them actively for grid planning: *"for us, during the recent planning period, DLR has been implemented as a key planning tool across multiple circuits for the first time. This marks the inaugural period where DLR is fully integrated into our planning process, and we anticipate its increased adoption in future planning cycles"*. Others consider NWAs only in specific contexts, as interim complementary solutions, or merely explore them.

Finally, wireless electricity, which can be considered the most extreme form of Non-Wires Alternatives, is mostly seen as a complex idea for the distant future: *"There is no appetite for this kind of thing. They are too large, too complex and they require huge investments"*. Some TSOs expressed concerns about risks to human and animal health, highlighting the need for further investigation and potential public opposition: *"you have to understand what the human risks are. People complain about the waves of the cell phones, you can imagine what happens with space solar power"*. Others were more optimistic, seeing potential for limited applications, such as providing electricity to remote off-grid areas, albeit far into the future: *"we wouldn't invest something in this, because then we have maybe 15 years ahead of us"*. "*Even if you have a breakthrough now, it would take decades before using it at scale because you have an existing system and if there is not a strong incentive to change your existing system, you would continue basically using that system*".

4.4. Main challenges and future evolution

4.4.1. Challenges perceived by TSOs

Key challenges frequently mentioned by interviewees concerned digitalization and integration of new grid technologies (Fig. 11). These involve technical hurdles: *"You need time to investigate these new technologies, to make it really tangible and useful for your business"* and *"we need a lot of double checks if we want to use new technologies. It must be 100 % perfect"*. They also involve a shift in cultural mindset: *"when you have a problem of a megawatt, you think you have to solve it with a megawatt, whereas the solution might be in megabyte. And you have difficulty understanding how you can solve it with a megabyte"*.

These two challenges, highlighted by nine of the 11 interviewed TSOs, are as prevalent as 'decarbonization of the power sector', which faces its own sub-challenges: maintaining system stability with more renewables, phasing out traditional flexibility sources, falling inertia, and accommodating more renewable connection demands: *"inertia is something that is critical for us. And we believe that if we don't have mechanisms to increase inertia or synthetic inertia or whatever, the system is impossible to work"*.

Eight TSOs mentioned challenges in attracting and retaining talent, recognizing the urgent need for new personnel to cope with these issues: "*people are those who enable everything we are talking about" […] "but, most of the time, these are not really experienced people, these are new people and technicians are really rare" […] "maintaining a skilled workforce is crucial, especially as technology advances at an accelerated* pace".

TSOs also highlighted the affordability of the energy transition, emphasizing the financial requirements for grid upgrades and risks of

Fig. 11. Overview of main challenges faced by TSOs. Bars indicate how many of the interviewed TSOs reported each challenge.

rising public opposition if the transition is perceived as unjust [111]. They noted supply chain risks exacerbated by geopolitical tensions and the need for greater system integration and coordination, particularly between TSOs and DSOs, and electricity and gas TSOs, with a focus on grid planning.

Table 2
How European TSOs views the role of the TSO in the future.

Central and key during the energy transition	Evolving into a back-up role
"People often are not aware that they need the grid. They just think, okay, we want to have a wind farm there, a photovoltaic park or device there, and that's it." *"I see the TSO like the main element or central element for the energy transition, playing a key role in facilitating the integration of renewable energy and the decarbonization of the system."* *"We have already realized that we are in the centre of everything. And [..] we are kind of enablers."* *"I think the role of TSOs is set to remain crucial, serving as the baseline of the energy sector."*	*"In the future, I think it will be a more and more distributed system, and the role of the TSO will be more a backup of the system, rather than being the backbone of the system. [..] We will rely less and less on the infrastructure per se."*

4.4.2. Views on the evolution of the TSO

All interviewed TSOs anticipate their role remaining central during the energy transition (Table 2). Only one predicts a limited backup role due to distributed resources (self-production and storage), meaning the TSO will only be needed occasionally to prevent shortages and ensure security.

Most TSOs foresee their role expanding beyond traditional boundaries, for instance seeking a stronger voice in sector discussions to influence regulation and evolution: *"Maybe there is a need for TSOs to have a bit louder voice in the room than in the past, because TSOs will have a central role there"*. Investing in storage is another emerging option: *"Now we have to think that everything is market-oriented, however, sometimes it could also be advantageous for TSOs themselves to have the opportunity to invest in storage solutions directly"*. Some TSOs also wish to directly engage with final consumers: *"the TSO already now is investigating how to bring benefits to the end user, although the classical energy system chain would have not allowed it somehow. That doesn't mean that in the future we are doing this alone and forget about the DSO, but we need to change our system, in the interest of the end consumer"*.

Some TSOs foresee closer collaboration with DSOs, potentially overcoming traditional separation via unbundling. Adapting regulatory frameworks is intuitively necessary for TSOs to expand their roles: *"the organization that we have nowadays between TSO and DSO (the unbundling) is a legacy of the way we were seeing the system back at the end of the 90s, a system that was designed in a way to optimize the costs, but it was built in the fossil fuels economy. That's not what we need for the future. The right question that we have now is how we could deliver all needed investment in CAPEX. In my opinion, we shall break quite soon these layers and going for network operators, TSOs and DSO to reach a kind of vertical integration at least at the grid level"*.

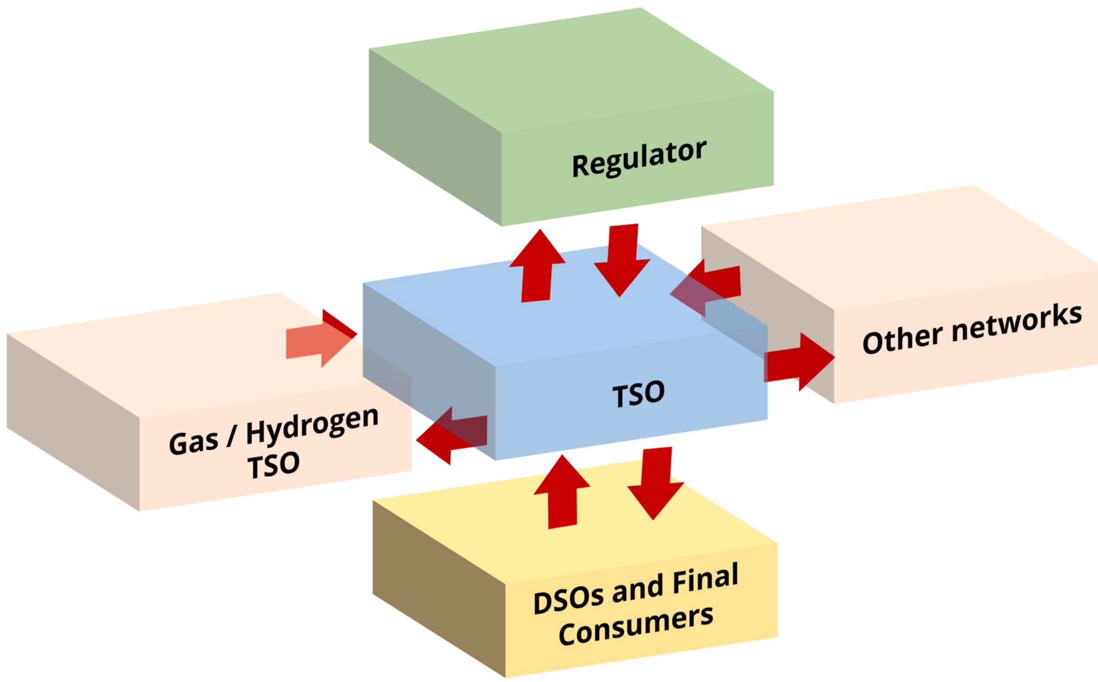
Four interviewed TSOs highlighted the need for a coordinated strategic approach to all energy infrastructures, playing a key role in sector coupling with gas and enabling the hydrogen economy: *"The idea is to create a strategic central plan for the whole country to understand how to develop the infrastructure to optimize through all the energy and infrastructural sectors"*. Additionally, one TSO suggested integration beyond grid planning and strategic coordination into ownership: *"I'm not a fan of big companies controlling everything, also the gas sector, because it's just a mess but we have to work together more closely in the future"* [...] *"you could also start imagining that you group together some of the TSOs, but at the moment the European Union is not that strong and ready for that. So, I guess the status quo will probably remain untouched for the next 10 to 15 years, unless something major happens"*.

Fig. 12 illustrates the TSOs' insights, differentiating between short-term and long-term evolution across three layers.

- The middle layer of TSO activities is widely expected to transform through increased intelligence and digitalization, incorporating flexibility solutions and extending horizontally through improved coordination with other sectors to optimize network development. This culminates with integrating electrical TSOs with other networks.
- The downstream layer of TSOs (distribution and end consumers), where some consider expanding operational scope by using flexibility from decentralized resources, potentially interacting directly with end consumers. This requires greater coordination with DSOs and emerging entities such as aggregators or balance service providers. Some suggest acquiring DSOs, though this runs contrary to current TSO/DSO collaboration practices.
- The upper regulatory layer, which must adapt to enable TSOs to address future challenges adequately.

5. Conclusions

This study explored a fundamental topic with limited attention in the literature: TSOs' innovation approaches. It examined how TSOs define



SHORT-TERM EVOLUTION	LONG-TERM EVOLUTION
• Stronger voice in sectoral discussions • Revision of current rules, particularly on permitting	• Adapting the remuneration formula for TSOs • Regulatory framework adaptation for NWAs • Regulatory framework adaptation for Storage • Reevaluating unbundling rules for TSOs and DSOs
• Increasingly smarter and digitalized • Business model adaptation • Increasingly relying on NWAs and other flexible solutions	• A stronger collaboration with gas TSO • Enabling sector coupling • Enabling the hydrogen economy • Coordinated and strategic approach to energy infrastructures development • Collaboration with other network operators (e.g. transport, water, etc.) to anticipate demand • Integration of network planning and ownership
• Closer collaboration with DSOs • Harnessing flexibility from distribution	• Shift towards more decentralized operations • New roles and challenges at distribution level • Engage with final consumers

Fig. 12. How European TSOs envision their role evolving in the future across three distinct layers, and time horizon. The arrows represent the forces and directions of change.

innovation strategies, set priorities, and benchmark against peers. It also investigated perceived strengths, TSOs' views on key innovations such as non-wires alternatives (NWAs), and the main challenges TSOs face regarding their evolving role in the transforming energy landscape. Drawing on interview insights, innovation literature, and the authors' reflections on translating findings into strategies, we identified transferable best practices and strategic innovations to prepare TSOs for future developments. In the following sections, we explain each solution by thematic area, providing tables summarizing strategic innovations and best practices, highlighting current practices, recommended changes, and potential benefits.

5.1. Best practices for future-proofing TSOs

5.1.1. How to promote innovation within TSOs

Interviews with TSO innovation leads showed that most TSOs currently use a centralized approach to define innovation strategies. However, best practice is to decentralize strategy development and project implementation, while keeping centralized oversight to track technological trends (Table 3). Some TSOs adopt diverse methods to encourage innovation, including technology labs, centres of excellence, open innovation programmes, incubators, accelerators, corporate venture capital, and mergers & acquisitions. Lagging TSOs should emulate these leading practices.

Successful innovation also needs CEO commitment, strategic prioritization, sufficient budgeting, and policy reviews to provide innovation managers resources for experimentation.

Best practice among some TSOs includes rapidly initiating innovation projects, effectively speeding up traditionally complex approval processes. Agility is important; granting teams autonomy and the ability to experiment quickly promotes innovation.

5.1.2. Technological innovation

TSOs must embrace digital innovations and modernize operations, as digitalization improves decision-making, resource optimization, renewable integration, and load management (Table 4). Innovations like real-time monitoring, predictive maintenance, and satellite technology improve infrastructure management and environmental considerations. Digital tools also promote project transparency and social acceptance. Interviews showed most TSOs prioritize digitalization, especially specific digital technologies. However, TSOs face challenges in adopting these technologies, including cultural adaptation, skilled talent recruitment, and increased cybersecurity risks. Resolving these issues is essential for fully realizing digitalization's benefits and ensuring resilient, future-ready grid operations.

To address rising infrastructure costs and congestion, TSOs should focus on grid-enhancing technologies and Non-Wires Alternatives (NWAs), such as Dynamic Line Ratings (DLRs), for cost-efficient transmission expansion. Interviews revealed most TSOs are familiar with NWAs and view them positively. However, regulatory frameworks often favour capital-intensive projects over quicker, cheaper NWAs, a mismatch that could redefine TSOs' roles as energy systems decentralize. Facing this evolving landscape, TSOs can cede certain responsibilities to private NWA operators or seek regulatory adjustments to participate in these markets.

Table 3
Recommendations for TSOs on how to foster innovation.

Practice	Current Limitation	Suggested Action	Impact
Decentralized or dual innovation governance	Most TSOs currently follow a centralized innovation model.	Adopt a decentralized approach for project implementation, complemented by centralized oversight for strategic alignment and trend analysis.	Ensures innovation projects are aligned with business needs while fostering agility and responsiveness.
Dedicated innovation structures (e.g., labs, incubators, corporate venture capital)	Not all TSOs have established structures to support innovation.	Institutionalize innovation through permanent structures and programs to test, scale, and fund new ideas.	Enables a sustained and systematic approach to fostering innovation.
Agile approval processes	Most TSOs face lengthy internal approval procedures that hinder innovation.	Streamline governance to accelerate internal decision-making and reduce delays in innovation projects.	Facilitates faster testing and deployment of new technologies.
Leadership commitment	Only some TSOs currently integrate innovation strategy with overall corporate strategy.	Ensure CEO-level prioritization of innovation, with strategic alignment and cross-functional support.	Provides credibility to the innovation team and reinforces organization-wide commitment.
Innovation budgeting	Some TSOs allocate very limited budgets for innovation.	Allocate adequate and protected innovation budgets to support experimentation and long-term initiatives.	Increases the ability to invest in and test new technologies.

5.1.3. Sustainability

Sustainability and eco-design, including SF_6 alternatives, emerged as priorities in only a few cases among interviewed TSOs. Nevertheless, TSOs should integrate sustainability across all operations (Table 5). Given their central role in the energy transition, TSOs should mitigate environmental impacts by embedding sustainability when planning and delivering new infrastructure, such as by assessing biodiversity and local community impacts. This improves social acceptance, reduces project delay risks, and safeguards their license to operate. Emphasizing sustainability may also attract and retain staff who prefer organizations committed to environmental and social challenges. More broadly, TSOs should treat sustainability as a strategic driver.

5.1.4. Collaboration and ecosystem engagement

This study highlights the importance of collaboration among TSOs, involving partnerships with technology firms, peers, universities, and research bodies to acquire essential knowledge for new technologies and quality service (Table 6). Collaboration, especially between TSOs and DSOs, improves data sharing. Adopting a data-driven strategy is important for client demands, system operations, asset management, and managing distributed resources. Sharing innovation among TSOs can reduce time and costs, promoting a collective approach to common challenges.

Integration with other network operators, including Gas/Hydrogen TSOs or water and highway infrastructure operators, could enable coordinated planning and development, optimizing resources and preventing bottlenecks. In the UK, for example, the regulator initiated the formation of the "National Energy System Operator", a public, government-owned yet independent entity, facilitating cooperation across networks to plan national energy infrastructure development. Even without such extensive changes, TSOs can identify efficient solutions, such as installing new lines alongside existing highways or railways. The $2.5 billion SOO Green HVDC Link project in the US is an example, using existing transport corridors for 2 GW of underground transmission to mitigate siting and permitting challenges [112].

5.1.5. Benchmarking and knowledge sharing

Benchmarking analysis helps TSOs identify areas for improvement, avoid overlooking critical aspects, and adopt best practices (Table 7). It provides insights into how peers address challenges like cybersecurity in an increasingly digital landscape. ENTSO-E could facilitate a continuous benchmarking and technology monitoring platform for TSOs to share experiences. Although ENTSO-E already produces RD&I Monitoring reports, expanding their scope to include a wider range of technologies and practices would improve information sharing. This would help disseminate successful strategies, avoid repeated mistakes, streamline processes, and save resources.

5.1.6. Changing TSO boundaries

Regarding TSOs' perspectives on their future role, the study highlights most TSOs' conviction about the continuing relevance and centrality of their role, particularly given the energy transition (Table 8). Some TSOs foresee an expansion of their operational scope and recommend revising outdated regulations, especially related to unbundling. Updating these rules would enable more direct engagement with consumers and allow oversight of DSOs, which may lack resources for

Table 4
Recommendations for TSOs around technological innovation.

Practice	Current Limitation	Suggested Action	Impact
Digitalization	n.a.	Deploy smart tools for real-time monitoring, predictive maintenance, satellite imagery, etc.	Improves operational efficiency and situational awareness.
Foster a digital culture	Internal resistance to change; insufficient digital skills	Address internal resistance and invest in digital talent	Fosters a secure, adaptive, and digitally skilled organization.
Increase Cybersecurity	n.a.	Strengthen cybersecurity measures	Reduces risks of cyberattacks and increases electricity security
Non-Wires Alternatives (NWAs)	Low experimentation with NWAs and limited regulatory support.	Experiment with technologies like Dynamic Line Ratings (DLRs) to defer infrastructure investment.	Reduces the need for costly infrastructure expansions.
Grid-enhancing technologies	Underutilized existing asset optimization technologies.	Adopt solutions that optimize existing assets before investing in new infrastructure.	Maximizes value from existing grid assets and delays capital expenditure.

Table 5
Recommendations for TSOs around sustainability.

Practice	Current Limitation	Suggested Action	Impact
Eco-design & emissions	Continued reliance on SF_6 and limited consideration of emissions in infrastructure design.	Prioritize SF_6 alternatives and design infrastructure with low environmental impact.	Reduces environmental footprint and aligns with regulatory and societal expectations.
Biodiversity & communities	Environmental and social impacts often assessed late in the planning process or not comprehensively.	Assess environmental and social impacts early and systematically during project planning.	Builds public trust and reduces opposition to new infrastructure projects.
Workforce appeal	Sustainability is not widely used as a lever for employer branding in TSOs.	Promote sustainability commitments to attract, engage, and retain talent.	Enhances employer attractiveness, especially to younger and purpose-driven professionals.
Strategic embedding	Sustainability is often treated as a separate function rather than integrated into innovation strategy.	Embed sustainability as a foundational pillar of the innovation strategy.	Strengthens strategic alignment and long-term value creation through sustainable innovation.

Table 6
Recommendations for TSOs around collaboration and ecosystem management.

Practice	Current Limitation	Suggested Action	Impact
Cooperation with DSOs, tech firms, academia	Limited or fragmented collaboration frameworks and inconsistent data sharing practices.	Strengthen partnerships for co-developing solutions, sharing data, and conducting joint R&D initiatives.	Accelerates innovation, enhances interoperability, and reduces duplication of effort.
Cross-sectoral cooperation (gas, hydrogen, water, telecom, transport)	Few established mechanisms for joint planning or shared infrastructure use across sectors.	Explore integrated planning and shared infrastructure development, such as leveraging transport corridors.	Improves efficiency, reduces costs, and fosters holistic system integration across sectors.

technological advances, climate adaptation, and renewable energy integration. Some TSOs also propose exploring integration with other networks (gas, hydrogen, telecommunications), strategically and through ownership, to support this transition.

TSOs might also consider establishing a pan-European TSO or merging specific TSOs. Financially constrained TSOs could benefit by joining larger organizations, driving innovation and reducing fragmentation in industry practices. This strategy could improve efficiency and innovation in European electricity transmission, creating 'supranational champions'.

5.1.7. *Regulatory & policy support*

These transformative actions depend on regulatory adaptation (Table 9). TSOs should engage with regulatory bodies to communicate the benefits of regulatory changes. Interviews revealed that most TSOs face obstacles from prolonged authorization procedures due to their highly regulated nature. TSOs should collaborate with regulators to address this. Regulators should provide flexibility and agility, enabling TSOs to innovate and keep pace with technological advances.

More broadly, regulation is key to driving TSO innovation, particularly by designing incentives for investment in riskier, innovative ventures. TSOs should advocate for regulatory revisions to remove barriers and promote investment in new technologies. Misaligned regulations could hinder the energy transition and restrict broader economic benefits.

It is beneficial to have individuals within legal or regulatory departments who are interested in innovation, as they can advocate regulatory changes. Legal and regulatory professionals may hesitate to embrace innovation and persuade regulators [13]. Observing peers innovate, influence regulation, and regulator responses can reassure these professionals, promoting a "safety in numbers" approach [13].

Table 7
Recommendations for TSOs around benchmarking and knowledge sharing.

Practice	Current Limitation	Suggested Action	Impact
Bench-marking tools	Inconsistent use of benchmarking tools across TSOs; limited insight into peers' innovation performance.	Regularly compare performance, innovation efforts, and challenges with peer TSOs to identify gaps and best practices.	Drives continuous improvement and learning through structured comparison.
ENTSOs' role	ENTSOs' platforms have limited focus on real-time or forward-looking innovation and technology trends.	Advocate for ENTSO-E to expand platforms for monitoring technology trends and innovation activities.	Strengthens sector-wide awareness and coordination around emerging innovations.
Safety-in-numbers approach	Individual TSOs often lack leverage to influence regulation toward innovation.	Leverage collective evidence from peer TSOs to engage with regulators and promote innovation-friendly frameworks.	Increases regulatory confidence and reduces risk for individual TSOs experimenting with new solutions.

Table 8
Recommendations for TSOs around changing boundaries.

Practice	Current Limitation	Suggested Action	Impact
Expanded Operational Scope	DSOs with limited capacity may struggle to adapt to emerging challenges without TSO support.	TSOs should oversee or support DSOs with limited capacity to ensure consistent innovation and system adaptation.	Improves system-wide resilience and accelerates innovation at all grid levels.
European TSO partnerships	Innovation efforts across TSOs are fragmented, and collaboration is often limited to voluntary initiatives.	Consider mergers or establish pan-European TSOs to pool innovation capacity and reduce fragmentation.	Improves efficiency, strategic alignment, and innovation scalability across Europe.

Table 9
Recommendations for TSOs around regulation and policy.

Practice	Current Limitation	Suggested Action	Impact
Incentive redesign	Traditional regulatory frameworks favour capital-intensive investments over innovative or flexible solutions.	Collaborate with regulators to shift from capex-heavy models to innovation-enabling frameworks.	Encourages investment in flexible, digital, and customer-centric solutions.
Unbundling reforms	Current unbundling rules may restrict deeper collaboration between TSOs, DSOs, and consumers.	Advocate for updated unbundling rules that allow more flexible and collaborative TSO-DSO-consumer interactions.	Enables greater system integration and co-creation of value across grid levels.
Internal champions	TSOs often lack internal regulatory or legal staff with an innovation-oriented mindset.	Hire and empower regulatory/legal professionals who understand innovation and can navigate complex regulatory landscapes.	Improves TSOs' ability to innovate within regulatory constraints.
Policy advocacy	TSOs tend to react to policy changes rather than proactively shaping them.	Engage proactively in regulatory consultations and policy forums to influence innovation-friendly policies.	Strengthens the voice of TSOs in shaping a supportive environment for innovation.

5.2. Main limitations

We acknowledge several limitations of this study, outlined in the methodology section. First, the number and duration of interviews may not fully capture the complexity of the topics discussed. While the small sample size suits qualitative research, it prevents generalizable or statistical conclusions about the broader TSO population. Thus, this study is limited to generating exploratory, qualitative insights.

Another limitation concerns the interviewee profile. We acknowledge the perspectives derive from TSO employees involved with innovation, and we explicitly avoid commenting on the feasibility or merit of solutions proposed by some TSO interviewees, who do not represent their entire organizations. Debating the political implications of these solutions would exceed this study's scope, introduce author bias, and detract from this stakeholder group's perspectives.

Applicability of the findings must be considered given the diversity among TSOs; not only in national regulatory environments but also organizational size, structures, and resources. TSOs operate within varying national frameworks shaping their capacity to innovate, set priorities, and experiment. TSOs in more flexible or innovation-friendly contexts are better positioned to adopt new technologies and pilot initiatives. In contrast, rigid or risk-averse settings impose constraints, limiting the transferability of some identified strategies.

Interviewed TSOs vary considerably in the size and composition of their innovation departments, ranging from small teams (e.g., REN and Fingrid) to larger units (e.g., National Grid ESO and RTE). These disparities substantially affect the ability of TSOs to implement certain innovation strategies or replicate best practices identified in the study. While larger TSOs can launch complex innovation programmes or allocate extensive resources to cross-sector collaboration, smaller TSOs face constraints despite strategic intent. Recommendations discussed here should therefore be adapted to each organization's scale, capabilities, and institutional context.

However, overarching principles, such as regulatory agility, cross-sector collaboration, and organizational readiness, remain relevant across contexts. These findings should be interpreted considering such variability but offer an important reference for TSOs and regulators shaping innovation agendas. More broadly, they contribute an initial framework of strategic responses to sectoral transformation, forming a basis for future empirical research, policy dialogue, and international comparison.

5.3. Policy implications

This study provides important policy insights into how TSOs can become more effective agents of innovation in the changing energy landscape. Interviews with innovation leaders revealed that while many TSOs still rely on centralized approaches, greater innovation success comes from decentralized models that empower business units with strategic oversight. Regulatory frameworks should adapt accordingly, enabling agile decision-making, reducing reliance on capital-intensive incentives, and institutionalizing non-wires alternatives and grid-improving technologies as viable solutions.

Current incentive structures often favour traditional infrastructure investments, discouraging innovation. Regulators should consider approaches like TOTEX-based models, which set requirements and revenues based on efficiency, encouraging cost-effective solutions that lower consumer energy costs. Innovative mechanisms can reduce CAPEX bias by promoting total cost minimization and supporting OPEX-oriented solutions, including regulatory sandboxes [63]. Excessive internal bureaucracy within TSOs can further inhibit innovation. Streamlining procedures, especially at initial testing phases, is necessary to create an innovation-friendly environment.

Another policy implication is the need to modernize unbundling rules, as proposed by some TSOs. Policy should also support benchmarking, cross-sector partnerships, and sustainability integrated into innovation strategies; not as an add-on but as a core driver of long-term value.

TSOs should proactively engage in regulatory discussions, supported by internal champions familiar with both innovation and regulation. Regulators and policymakers have an important role in creating conditions that enable TSOs to experiment, collaborate, and lead the transition to a more adaptive, secure, and sustainable energy system.

CRediT authorship contribution statement

Andrea Biancardi: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Visualization, Writing – original draft. **Iain Staffell:** Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

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

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Appendix A. Supplementary data

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Data availability

The authors do not have permission to share data.

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