Strategic Innovations by European Electricity Transmission System Operators (TSOs) for navigating the Energy Transition

A thesis submitted for the degree of Doctor of Philosophy (PhD)

by

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Declaration of Originality

I declare that this thesis is my own work, and that the work of others is appropriately referenced and acknowledged.

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Abstract

The electricity industry is undergoing far-reaching transformations. While the primary focus has been on decarbonizing supply and electrifying end uses, the challenges faced by grid operators, particularly Transmission System Operators (TSOs), have so far received less attention. TSOs play an essential role in maintaining the security and quality of electricity supply and are central to the energy transition. Despite being regulated monopolies shielded from direct competition, TSOs face numerous challenges, necessitating proactive future-proofing through investments in innovation and new technologies, organizational changes, and innovative business models.

This thesis explores how TSOs approach innovation to counter these challenges, what drives their efforts, and how they see their role evolving in the future. It employs a mixed-methods approach, combining a qualitative benchmarking analysis to create a comparative assessment of TSOs' innovativeness, in-depth interviews with innovation leaders to provide more detailed perspectives, and quantitative modeling of the impact of disruptive technology on their business.

In particular, it creates a comprehensive dataset of projects and initiatives being undertaken by TSOs across key technologies, identifying factors that might influence their innovativeness. It examines how TSOs perceive their evolving roles. Additionally, it conducts economic analysis on the impact of disruptive innovations like battery electricity storage.

Finally, the thesis identifies strategies for future-proofing TSOs, emphasizing among others: decentralized innovation approaches, digital innovations, grid-enhancing technologies, sustainability, collaboration and integration with other network operators, alongside regulatory adaptations to support innovation and investment in new technologies.

TSOs must embrace innovation to effectively drive and implement the energy transition in a timely manner, ensuring the achievement of climate goals. This necessitates strong regulatory support and strategic adaptability.

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Table of Contents

1 Introduction 15
1.1 Project motivation 17
2 Background and Literature Review 22
2.1 Who are the Transmission System Operators (TSOs)? 22
2.2 TSO roles and activities 30
2.3 Key challenges for TSOs 31
2.3.1 Operational challenges 33
2.3.2 Technological challenges 43
2.3.3 Corporate Affairs & Stakeholder Management challenges 47
2.3.4 Focus on key sectorial trends 52
2.4 The interplay between regulation and innovation 57
2.5 Innovation within TSOs 59
2.6 Summary 61
3 How European TSOs approach innovation: evidence from benchmarking analysis 62
3.1 Introduction 62
3.2 Background on Business intelligence tools for decision-making support 62
3.2.1 Benchmarking analysis 65
3.3 Methodology 68
3.3.1 Benchmarking European TSOs on six key technologies 68
3.3.2 A conceptual framework for analyzing TSOs business model innovation 72
3.3.3 Benchmarking International TSOs on additional eleven key technologies 78
3.4 Results: Transmission System Operators innovativeness 86
3.4.1 European TSOs innovativeness across six key technologies 86
3.4.2 The impact of National regulatory frameworks for innovation of TSOs on their innovativeness 91
3.4.3 International TSOs innovativeness across eleven additional key technologies 94
3.5 Discussion 109
3.6 Summary 112
4 How European TSOs approach innovation: evidence from interviews 113
4.1 Introduction 113
4.2 Background on Relevant literature on innovation 113
4.2.1 Business model innovation theory 114
4.2.2 Disruptive innovation theory 117
4.2.3 The organizational dimension of innovation 119
4.3 Methodology 124
4.3.1 Contextualizing the interviewees 126
4.4 Results: Insights from some European electricity TSOs 129
4.4.1 Innovation Approach and Technology Trends 130
4.4.2 Best practices 134
4.4.3 Special focus on Non-wires alternatives (NWAs) 138
4.4.4 Main challenges perceived by TSOs 139

4.4.5 Views on the evolution of the TSO ... 140
4.5 Discussion ... 144
4.6 Summary ... 145
5 The impact of battery electricity storage on TSOs ... 146
5.1 Introduction ... 146
5.2 Background on batteries and interconnectors ... 147
5.2.1 Interconnection investment models and income mechanisms ... 147
5.2.2 Non-wires alternatives ... 151
5.2.3 Power system modelling ... 152
5.2.4 Literature review ... 153
5.3 Methodology ... 156
5.3.1 The EuroMod power market model ... 157
5.3.2 Calculating cross-border interconnectors congestion rent ... 159
5.3.3 Scenarios for battery storage uptake ... 160
5.3.4 Scenarios with reduced cross-border transmission capacity ... 164
5.3.5 Calculating battery storage profitability ... 166
5.4 Results: Batteries vs Interconnectors ... 166
5.4.1 Validity of modelling cross-border interconnectors congestion rent ... 166
5.4.2 Impact of battery storage uptake on cross-border interconnectors congestion rent ... 169
5.4.3 Impact of reduced transmission capacity on cross-border interconnectors congestion rent ... 171
5.4.4 Impact on electricity generation costs and prices ... 174
5.4.5 Economic viability of battery uptake scenarios ... 176
5.5 Discussion ... 178
5.6 Summary ... 181
6 Conclusions ... 183
6.1 The TSO Paradox: conservative but eager to expand their scope ... 183
6.2 Batteries vs interconnectors: a tale of two visions ... 184
6.3 How to future-proof TSOs ... 185
6.4 No future-proof TSOs without a fit for the future Regulation ... 188
6.5 Main takeaways of the thesis ... 189
6.5.1 What is new? – Summary of Contributions ... 189
6.5.2 Why does it matter? – Key recommendations for TSOs and regulators ... 192
6.5.3 What is missing? – Limitations and Future Work ... 199
7 References ... 205
Appendices ... 232
Appendix 1 Global Overview of TSOs ... 232
Appendix 2 European TSOs revenue breakdown ... 242
Appendix 3 European regulatory frameworks for innovation of TSOs ... 244
Appendix 4: Interview guides ... 250
Appendix 5: International Benchmarking Analysis Results ... 252
Appendix 6: Comparative benchmarking charts ... 255

List of figures

Figure 1 European Transmission operators overview. 27

Figure 2 Overview of European TSOs. 28

Figure 3 Overview of the twenty main challenges faced by TSOs 33

Figure 4 Key trends shaping the electricity industry 53

Figure 5 The methodology used and the main steps of the analysis. 69

Figure 6 The TSOs covered in the first phase of the study 70

Figure 7 The TSOs' geographical areas covered in the second phase of the study 79

Figure 8 Innovation Map for European TSOs 86

Figure 9 TSOs' average score for each technology grouped by geographical origin 94

Figure 10 TSO average ranking across key technologies 96

Figure 11 State Grid engagement level across the eleven technologies 99

Figure 12 Best-in-class TSOs across each technology. 100

Figure 13 The TSOs' geographical areas covered in the interview study 126

Figure 14 Interviewed European TSOs innovation teams size 127

Figure 15 Innovation 'tools' used by Interviewed European TSOs to support innovation within their organizations. 129

Figure 16 Main methods and practices for identifying technology trends and selecting specific technologies for innovation efforts, other than radar analysis or similar methodology. 131

Figure 17 Overview of TSOs' the main areas of focus, and the specific technologies that pertain to the digital domain or to energy/grid systems 133

Figure 18 Key Benchmarking Practices Among Interviewed TSOs. 135

Figure 19 How European TSOs envision their role evolving in the future across three distinct layers, and time horizon. 143

Figure 20: The relationship between the annual energy generated from wind and solar sources and the installed power capacity of storage as a fraction of peak demand..... 162

Figure 21 Scenarios on values for battery electricity storage capacity installed in 2030..... 164

Figure 22 EuroMod efficacy in representing the pertinent metrics of the study over the period 2017–2020. 167

Figure 23 Congestion rent in the three scenarios..... 170

Figure 24 Changes in absolute congestion rent across Europe with decreasing grid capacity 172

Figure 25 Congestion rent earned per GW of transmission capacity..... 173

Figure 26 Total electricity generation cost in the three battery storage uptake scenarios..... 174

Figure 27 Total electricity generation cost per different levels of cross-border transmission capacity 175

Figure 28 Short-run profit (arbitrage revenue) and maximum breakeven cost that this arbitrage revenue would allow for energy storage across the scenarios..... 177

Figure 29 The main solutions identified to future-proof TSOs..... 186

List of tables

Table 1 Overview of European transmission companies..... 25

Table 2 Current distribution of TSO arrangements across different world regions. 299

Table 3 The TSOs covered in this study 71

Table 4 Innovation scoring criteria for the six technologies considered in this study 75

Table 5: European TSOs business model innovation approaches and specific activities 76

Table 6 Business model innovation approaches scoring criteria 78

Table 7 The technologies and applications selected for the next phases of the radar analysis79

Table 8 Innovation scoring criteria for the eleven technologies considered in this study..... 85

Table 9 European TSOs innovation scores 91

Table 10 National regulatory frameworks for innovation of electricity TSOs breakdown..... 92

Table 11 Interviewed European TSOs using radar analysis or similar structured methodology to identify technology trends and select specific technologies for their innovation efforts. 130

Table 12 How European TSOs views the role of the TSO in the future. 141

Table 13 Benchmarking analysis of European TSOs 252

Table 14 Benchmarking analysis of American TSOs..... 253

Table 15 Benchmarking analysis of Asian TSOs..... 254

List of acronyms

ACER	Agency for the Cooperation of Energy Regulators
AI	Artificial Intelligence
AP	Aggressive Penetration
BC	Base Case
BNEF	Bloomberg New Energy Finance
CAPEX	Capital Expenditure
CEER	Council of European Energy Regulators
CEO	Chief Executive Officer
CSG	China Southern Power Grid Company Limited
DC	Direct Current
DERs	Distributed Energy Resources
DG	Distributed Energy Generation
DLR	Dynamic Line Rating
DSO	Distribution System Operator
EC	European Commission
ENTSO-E	European Network of Transmission System Operators for Electricity
ESO	Electricity System Operator
EU	European Union
EV	Electric Vehicle
GA	Global Ambition
GIS	Gas-Insulated Switchgear
HVDC	High Voltage Direct Current
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
ISO	Independent System Operator
IT	Information Technology
KEPCO	Korea Electric Power Corp.
NT	National Trends
NWA	Non-Wires Alternatives
RAB	Regulated Asset Base
REN	Redes Energéticas Nacionais
RG	Robust Growth
RTE	Réseau de Transport d'Électricité
SF6	Sulphur Hexafluoride
SO	System Operator
TEPCO	Tokyo Electric Power Company
TO	Transmission Owner
TSO	Transmission System Operator
TYNDP	Ten-Year Network Development Plan
UAV	Unmanned Aerial Vehicle
UK	United Kingdom
US	United States
VIU	Vertically Integrated Utility
WEC	World Energy Council

1 Introduction

In the last twenty years, power sector reforms, technological progress, climate change awareness, and progressive low-carbon policies have revolutionized the energy sector, impacting economic fundamentals, investment opportunities, and business strategies (WEF, 2017; Helm, 2017; Sioshansi, 2016). Most market players have restructured their portfolios and innovated their business models, with utilities repositioning along the value chain and embracing new technologies and services as well as acquiring new skills and capabilities (Biancardi and Di Castelnuovo, 2020).

Major transformations are currently impacting electricity grids as well, which form the backbone of our contemporary lifestyle, delivering quality of life and well-being. Traditional grids, designed for centralized generation near consumption centres, are evolving to include distributed, widely dispersed and intermittent renewable energy sources. Grids are transitioning from linear to meshed structures, integrating battery systems, electric vehicles with smart charging, virtual power plants, and demand-side response.

Historically overshadowed in mainstream discourse, power grids are gaining increasing attention through a series of strategic plans and publications from governments, global institutions, NGOs, and media (GGI, 2023; Breakthrough Energy, 2023). Examples include The Economist's cover article “Hug Pylons, Not Trees”, which advocated for public support of grid expansion to achieve climate objectives (The Economist, 2023) and the “Electricity Grids and Secure Energy Transitions” report which projected that the global electricity grid must double in length by 2040 (IEA, 2023a).

In November 2023, the European Union proposed the EU Grid Action Plan, a 14-point policy action plan aiming to address challenges in expanding, digitalizing and better utilizing power grids. The plan outlines measures to facilitate the necessary investments for upgrading European electricity networks (European Commission, 2023a). Similarly, the US Department of Energy (DoE) announced billion-dollar investments in new transmission lines under President Biden’s "Investing in America" agenda. Supported by the Bipartisan Infrastructure Law and Inflation Reduction Act (IRA), this aims to develop thousands of miles of upgraded transmission

lines to reduce electricity costs, enhance reliability against extreme weather, improve energy security, create jobs, and promote renewable energy (DOE, 2023).

Despite growing recognition of the importance of electricity grids and increased attention to the challenges faced by grid operators (such as the diffusion of renewables, digitalization, decentralized energy resources, etc.), the focus on the strategic, organizational, and innovation challenges faced by transmission system operators (TSOs) remains limited. TSOs maintain the security and quality of the electricity system, essentially "keeping the lights on", and are pivotal in transitioning away from fossil fuels (Biancardi et al., 2021; WEC, 2020; ADL, 2018). Despite being regulated monopolies shielded from direct competition, TSOs must proactively future-proof their organizations. TSOs should invest holistically across innovation, embracing cutting-edge technologies, implementing transformative organizational changes, and innovative business models.

However, TSOs face a dilemma: innovating and modernizing grids while controlling costs to benefit ratepayers and shareholders. They also face public acceptance challenges, due to the 'Not In My Backyard' (NIMBY) syndrome, which may hamper or prevent infrastructure investments (i.e. building new overhead electric lines) (European Commission, 2019a).

Furthermore, the peculiar nature of their business (i.e. TSOs are regulated businesses), means that network companies seldom undertake investments in innovative technologies or new business solutions in the absence of sufficient incentives (Poudineh et al., 2017; Frame et al., 2018; Jamasb and Pollitt, 2011). More broadly, regulation influences every aspect of their operations, from system planning to strategic decisions and, to a certain extent, also the technologies that TSOs can experiment with or adopt. Additionally, the regulatory frameworks for network companies in many countries are primarily designed to incentivize cost efficiency. This often deters TSOs from undertaking projects that might be considered particularly innovative and, consequently, risky (Poudineh et al., 2017).

Some innovative technologies or solutions may actually reduce the need of physical construction of transmission lines; for instance, 'grid enhancing technologies' or 'non-wires alternatives' such as dynamic line ratings, battery storage or more interactive/intelligent grid management of balancing tools. This may prove counterproductive for TSOs as, in certain

countries, it reduces their regulated asset base (RAB), which represents one of the main revenue components (FSR, 2023). All of this highlights the need for policymakers and regulators to adopt consistent measures to accommodate innovation and guarantee system reliability and security.

Particularly relevant and indicative in this regard is the reform introduced by the Federal Energy Regulatory Commission (FERC), the U.S. authority regulating the interstate transmission and wholesale sale of electricity. FERC's Order No. 1920, issued in May 2024, mandates that transmission operators consider the use of alternatives to traditional infrastructure, as these technologies offer a critical opportunity to optimize the system, maximizing the capacity and flexibility of new infrastructure while enhancing grid reliability and affordability. This makes the consideration of alternatives to traditional infrastructure a part of routine transmission planning.

1.1 Project motivation

The motivation for this PhD project is to shed light on the underexplored domain of transmission system operators (TSOs) and on the approaches they are adopting towards innovation, with a specific emphasis on European TSOs. The project will particularly focus on their innovativeness, examining the strategic initiatives, operational practices, and technological innovations that TSOs are currently implementing and could adopt to future-proof their organizations. More broadly, this PhD project aims to explore the future of TSOs and their evolving role amid the energy transition, proposing solutions to future-proof their organizations.

While regulation is a fundamental aspect to TSOs, given their nature as regulated businesses, this PhD thesis does not focus extensively on the regulatory framework. Significant contributions have already been made regarding the regulation of the electricity network industry (Meeus and Glachant, 2018; Glachant, 2021). The Florence School of Regulation, in particular, is driving the European debate on electricity network regulation, aiming to develop the most effective regulatory framework that supports both the energy transition and innovation (FSR, 2023). The interplay between regulation and innovation in the electricity network industry have been extensively studied by Pollitt, (2024), Brunekreeft (2023),

Brunekreeft et al. (2021), Ribeiro and Jamabs (2024), Ribeiro et al. (2023), Poudineh et al. (2020, 2017), the European Commission (2019b), CEER (2020), Frame et al. (2018), Cambini et al. (2020, 2016), and Jamasb and Pollitt (2015, 2011, 2008). Similarly, many studies have, examined the influence of regulation on the energy sector (Schittekatte and Meeus, 2020; Cambini et al., 2020), on the energy transition (Schittekatte et al., 2021) and the impact of regulation on innovation in general (Blind, 2012).

Therefore, this study acknowledges the essential role of regulation in the innovation of TSOs. However, it aims to contribute new insights into the innovative strategies and practices of TSOs, a subject that has received comparatively less attention.

This study has four main objectives:

A. Evaluate the innovative efforts of TSOs across Europe and conduct a comparative analysis of their approaches.
B. Examine how European TSOs are perceiving the challenges that are occurring in the electricity industry and how they envision their role and business model evolving in the future.
C. Evaluate the potential impact of disruptive innovations on TSOs' traditional business.
D. Identify actions that can be adopted to make TSOs organizations more future-proof.

Chapter 1 introduces the ongoing transformations in the energy sector and emphasizes the need to understand the challenges faced by Transmission System Operators (TSOs), crucial for the energy transition's success, as well as to explore how TSOs are responding to these challenges, envision their future roles, and to examines strategies to future-proof their organizations amid the energy transition. Chapter 2 reviews the roles and trends of TSOs, providing an overview of their current functions and industry challenges. It examines who TSOs are, their primary responsibilities, and how industry challenges impact their operations. Chapter 3 presents a benchmarking analysis of how TSOs are approaching innovation, examining a sample of international TSOs with a focus on key technologies. Chapter 4 presents insights from in-depth interviews with an elite group of European TSOs, complementing the benchmarking analysis by exploring their approaches to innovation and perspectives on the future evolution of their business models. Chapter 5 focuses on the potential disruption to TSO

business models brought about by technological innovation, especially if these advancements are not proactively managed and if TSOs fail to respond strategically, with a particular emphasis on electricity battery storage. This chapter illustrates how unanticipated innovation can disrupt TSO operations and provides valuable insights for TSOs to future-proof their organizations. Chapter 6 summarizes contributions and concludes.

This PhD thesis makes five significant contributions to the literature on Transmission System Operators (TSOs) and the energy transition:

a) An updated overview of Transmission System Operators, detailing the organizational arrangements and unbundling structures adopted in different countries. (Chapter 2)
b) An overview of the main challenges and opportunities faced by Transmission System Operators. (Chapter 2)
c) An evaluation of the innovativeness of TSOs through the creation of a dataset of initiatives and projects being undertaken by TSOs and a benchmarking analysis. (Chapter 3)
d) An evaluation of how TSOs are responding to the challenges that are revolutionizing the electricity industry and their business, identifying best practices, along with an examination of their vision for their future role and business practices, based on in-depth interviews with an elite group of European TSOs (Chapter 4)
e) An assessment of the economic impact of technological innovations, particularly electricity battery storage, on the business of TSOs using an adapted power market simulation model (EuroMod) for this specific analysis. (Chapter 5)

The thesis builds on the following peer-reviewed journal papers:

- Biancardi, A., Staffell, I., 2024. How do electricity TSOs embrace innovation to navigate the energy transition? [R&R at Energy Strategy Reviews].
- Biancardi, A., Mendes, C., Staffell, I., 2024. Battery electricity storage as both a complement and substitute for cross-border interconnection. Energy Policy, 189, 114134. https://doi.org/10.1016/j.enpol.2024.114134

- Biancardi, A., Di Castelnuovo, M., Staffell, I., 2021. A framework to evaluate how European Transmission System Operators approach innovation. Energy Policy, 158, 112555. https://doi.org/10.1016/j.enpol.2021.112555

The following publications and presentations were produced as part of this PhD project, but do not provide content for this thesis:

- Biancardi, A., Di Castelnuovo, M., 2020. A new paradigm in the electricity sector: key trends and stock performance of European Utilities. European Energy & Climate Journal, 9(1), 31-43. https://doi.org/10.4337/eecj.2020.01.07
- Di Castelnuovo, M., Biancardi, A., 2020. The future of energy infrastructure. Challenges and opportunities arising from the R-Evolution of the energy sector in Gatti, S. and Chiarella, C. (Eds), Disruption in the Infrastructure Sector. Springer, 1st ed. 2020, 5-52. ISBN: 9783030446697
- Biancardi, A., 2023. Storage batteries as both complements and substitutes to cross-border interconnections. Milan, 8th IAEE European conference.
- Biancardi, A., 2020. What is the European electricity transmission companies approach to innovation? A novel analytical framework. Online, 5th AIEE Energy Symposium.
- Biancardi, A., 2018. The evolution of European TSO business model. Florence, Florence School of Regulation – Energy Innovation Academy.

The following publications were also produced while I undertook this PhD project, but fall outside the scope of it:

- Biancardi, A. [2023]. Space-based Solar Power: Just Science Fiction? ISPI – Italian Institute for International Political Studies. https://www.ispionline.it/it/pubblicazione/%20fotovoltaico-spaziale-solo-fantascienza-107577
- Biancardi, A., Di Castelnuovo, M., 2022. Italy's Energy Future at a Crossroads. ISPI – Italian Institute for International Political Studies. https://www.ispionline.it/en/publication/%20italys-energy-future-crossroads-36772

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- Biancardi, A., Di Castelnuovo, M., 2021. No Country for “Oil” Men. What Will the Future Hold for Big Oil? European Energy & Climate Journal, 10(1), 35-45. https://doi.org/10.4337/eecj.2021.04.04
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- Grubb, M., Bashmakov, I., Drummond, P., Myshak, A., Hughes, N., Biancardi, A., Agnolucci, P., Lowe, R., 2018. An exploration of energy cost, ranges, limits and adjustment process. Final report to the Institute for New Economic Thinking. https://www.ucl.ac.uk/bartlett/sustainable/sites/bartlett/files/an_exploration_of_energy_cost_ranges_limits_and_adjustment_process.pdf
- Ameli, N., Biancardi, A., Drummond, P., et al., 2017. Green growth and win-win solutions for sustainable climate actions. Stylised models of relative rates of return, technology co-benefit/spillover effects, multiplier and leverage effects for key sectors. European Commission, Green-Win D2.4 https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5b5a80c2b&appId=PPGMS
- Biancardi, A., Perissinotto, V., Pogutz, S., 2017. Egea – White Paper. https://assets.egea.it/documents/Documentazione/EGEA_Libro-bianco.pdf

2 Background and Literature Review

This chapter introduces Transmission System Operators, describing their roles, functions, and the main challenges they face. It reviews existing research on innovation within the transmission industry and examines the interplay between regulation and innovation.

2.1 Who are the Transmission System Operators (TSOs)?

Historically, utility companies that managed most power systems were vertically integrated. This meant they were responsible for the entire spectrum of activities, including developing, operating, and commercial functions. They built and operated generation plants, expanded and maintained power networks, managed transmission and distribution networks, and billed consumers for electricity. These companies held a monopoly over these services within a specific territory, allocated to them by a governmental authority.

While vertically integrated monopoly utilities are still common, over the last three decades, there has been a significant global trend towards liberalizing and restructuring the electricity industry with the aim to lower end-user prices, improve utility efficiency, and increase reliability. This shift has involved moving away from the traditional vertically integrated utility (VIU) model, unbundling various functions to separate competitive activities from those best managed as monopolies.

Specifically, because constructing multiple transmission or distribution networks is neither economically nor environmentally sustainable, network operation and planning should remain monopoly activities, a condition known as a ‘natural monopoly’. This is also why the transmission business is highly regulated (Perez-Arriaga, 2013). Conversely, power plants can compete to supply energy to consumers. These restructuring efforts have resulted in the establishment of Independent Transmission Owners (ITOs) and other independent organizations to manage system operations (Kirschen, 2024). For example, in the European Union, unbundling rules were introduced in 2009 as part of the EU's efforts to create a single internal electricity market, particularly through the so called “Third Energy Package”. These rules mandated the separation of electricity transmission and distribution from generation and supply activities to promote competition and prevent conflicts of interest (European Union, 2009).

However, these changes have not led to a single standardized arrangement. Instead, they have resulted in a variety of models for managing electricity transmission. These models can be categorized into four groups based on the degree of unbundling of transmission assets and the integration of the transmission operation (TO) function with the system operation (SO) function (Chawla and Pollitt, 2013):

1. Legally Unbundled Transmission System Operator (LTSO)
2. Independent Transmission System Operator (ITSO)
3. Independent System Operator (ISO)
4. Transmission Owner (TO)

The first option is the Legally Unbundled Transmission System Operator (LTSO), where a subsidiary manages the transmission grid while the parent company controls other segments. This arrangement allows for proper cost allocation for transmission but may result in favoritism towards the parent company's generators.

The Independent Transmission System Operator (ITSO) is a separate company that independently manages transmission, free from influence by other market players. This ensures fair competition and coordination in planning and investments but may face coordination challenges.

Another model is the Independent System Operator (ISO), which features distinct entities managing real-time operations and, in some cases, also maintenance of the transmission grid. When an ISO is in place, there are typically one or more Transmission Owners (TOs). The TO, which can be for instance the former vertically integrated utility, owns the physical transmission infrastructure and is generally responsible for its maintenance and the development of physical transmission assets. This setup allows for a clear division of responsibilities between the operation and ownership of transmission networks, aiming to enhance efficiency and transparency in the electricity market.

In Europe, most TSOs have undergone full ownership unbundling and now operate solely as electricity transmission businesses under the ITSO model (Meletiou et al., 2018). However, some countries have adopted the Legal Transmission System Operator (LTSO) model. For

instance, the French TSO, Réseau de Transport d'Électricité (RTE), is legally separated from its main shareholder and former vertically integrated utility (VIU), EDF[1].

Only a few European countries have adopted the ISO (Independent System Operator) model: in Ireland, the system operator Eirgrid is separate from the transmission owner ESB Networks; Northern Ireland uses a similar structure with SONI as the system operator and NIE Networks as the grid owner; in Russia, JSC SO UES operates the system independently from PJSC Federal Grid Company – Rosseti, the grid owner; Bosnia and Herzegovina follows this model with NOS BiH as the system operator and "Elektroprenos - Elektroprijenos BiH" a.d. Banja Luka (TransCo) as the grid owner. In Great Britain, the situation is similar but more complex: National Grid owns the transmission grid in England and Wales, while National Grid ESO operates as the system operator for the entire GB system, including Scotland, where the grid is owned by SP Energy Networks (part of the Scottish Power Group, owned by Iberdrola) and Scottish and Southern Electricity Networks (part of SSE plc). However, National Grid ESO is transitioning into a publicly owned, government-independent entity named the National Energy System Operator (NESO), which will be responsible for planning all energy networks, not just electricity.

Malta is the only exception to the unbundling rule. Due to its unique status as an island state with specific energy policy needs, Malta benefits from automatic derogations that allow it to continue operating as a vertically integrated utility.

In addition, most European TSOs are wholly or partly owned by state governments or state-controlled entities, though there are some privately owned TSOs as well. Furthermore, in most European countries, a single Transmission System Operator (TSO) holds a monopoly over the entire national transmission grid. However, there are exceptions, such as Germany, which has four TSOs, each responsible for a particular “control area”. Table 1 provides an overview of all European transmission operators and their organizational arrangement. To offer a comprehensive perspective, the table also includes information on the length of the grid under management, the latest revenue figures, the number of employees, and ownership details.

[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%).

Table 1 Overview of European transmission companies. The table shows if the TSO is member of ENTSO-E, its organizational arrangements, current grid length under management, the most recent figure for revenues from electricity transmissions, current number of employees and ownership. Abbreviations: VIU: vertically integrated utility; LTSO: Legally Unbundled Transmission System Operator; ITSO: Independent Transmission System Operator; ISO: Independent System Operator; TO: Transmission Owner; Trans.: Transmission; Obs. Observer; Int. International; NGET: National Grid Electricity Transmission; SSEN: Scottish and Southern Electricity Networks.

Country	TSO	ENTSO-E Member[2]	VIU	LTSO	ITSO	ISO	TO	Trans. line length (km)	Trans. revenues (€m)	Employees	Ultimate ownership	Origin of Ultimate Owner
Albania	OST	X			X			3395	102.0	779	State	Domestic
Austria	APG	X		X				6,948	1,880.0	730	State	Domestic
Austria	VUEN	X					X	350	n.a.	35	State	Domestic
Belgium	Elia	X			X			8,802	1,300.0	1,700	State	Domestic
Bosnia Herz.	NOS BiH	X				X		6,341	61.5	82	State	Domestic
Bosnia Herz.	TransCo						X	6,341	n.a.	n.a.	State	Domestic
Bulgaria	ESO	X		X				15,384	870.0	4,200	State	Domestic
Croatia	HOPS	X			X			7,774	418.0	1,155	State	Domestic
Cyprus	CTSO	X			X			1,319	n.a.	88	State	Domestic
Czechia	ČEPS	X			X			5,700	1,146.0	364	State	Domestic
Denmark	ENERGINET	X			X			7,440	1,181.0	2,174	State	Domestic
Estonia	Elering	X			X			5,270	125.9	291	State	Domestic
Finland	Fingrid	X			X			14,500	1,193.2	527	State	Domestic
France	RTE	X		X				105,800	6,131.0	9,586	State	Domestic
Georgia	GSE				X			4,383	97.0	1,400	State	Domestic
Germany	50Hertz	X			X			10,658	2,600.0	1,800	State	Foreign
Germany	AMPRION	X			X			11,000	4,829.4	2,700	Private	Domestic
Germany	TransnetBW	X		X				3,111	7,700.0	1,600	Mostly State	Domestic
Germany	TenneT Germany	X			X			10,741	7,001.0	4132	State	Foreign
Great Britain	NGET[3]						X	7,200	3,200.0	2,349	Private	Int.
Great Britain	National Grid ESO[4]					X		16,520	4,450.0	928	Private	Int.
Great Britain	SP Energy Networks						X	4,320	457.0	2,600	Private	Int.
Great Britain	SSEN						X	5,000	769.2	1,305	Private	Int.
Greece	Ipto	X			X			13,404	286.0	1,600	State	Domestic
Hungary	MAVIR	X		X				4,897	1,380.0	815	State	Domestic
Iceland	Landsnet	X			X			3,000	156.1	161	State	Domestic

(continued)

[2] The European Network of Transmission System Operators for Electricity (ENTSO-E) is a key organization currently representing and coordinating 40 electricity transmission system operators (TSOs) from 36 countries across Europe. Established in 2009, ENTSO-E plays a vital role in the integration and coordination of the European electricity market. Its primary objectives are to ensure the reliable operation, optimal management, and sustainable development of the European transmission network.

[3] This table distinguishes between National Grid Electricity Transmission (NGET) and National Grid ESO, the transmission owner and the system operator respectively. The rest of this thesis treats them together due to data availability.

[4] In 2022, Ofgem and the UK Government decided to create a new independent body to enhance energy security, achieve net zero, and ensure long-term affordability of household bills. The Energy Act 2023 legislated the formation of the Future System Operator (FSO), which in January 2024 was named the National Energy System Operator (NESO). NESO will inherit the functions of National Grid ESO, including real-time electricity system management, and expand to cover strategic planning for both electricity and gas networks.

Country	TSO	ENTSO-E Member[5]	VIU	LTSO	ITSO	ISO	TO	Trans. line length (km)	Trans. revenues (€m)	Employees	Ultimate ownership	Origin of Ultimate shareholder
Ireland	EirGrid	X				X		6,800	1,013.8	640	State	Domestic
Ireland	ESB Networks						X	6,800	1,191.0	3,376	State	Domestic
Italy	Terna	X			X			72,600	3,186.7	5,400	State	Domestic
Kosovo	KOSTT				X			1,430	52.1	123	State	Domestic
Latvia	AST	X			X			5,613	158.0	534	State	Domestic
Lithuania	Litgrid	X			X			7,245	369.8	335	State	Domestic
Luxemburg	CREOS	X		X				945	n.a.	867	State	Domestic
Malta	Enemalta		X					561	n.a.	2,000	State	Domestic
Moldova	Moldelectrica	Obs.			X			4,725	63.0	1,330	State	Domestic
Montenegro	CGES	X			X			1,416	120.5	317	State	Domestic
Netherlands	TenneT TSO B.V.	X			X			14,694	2,297.0	2805	State	Domestic
North Macedonia	MEPSO	X			X			2,300	68.5	112	State	Domestic
Northern Ireland	SONI	X				X		2,309	126.6	96	State	Foreign
Northern Ireland	NIE Networks						X	2,309	n.a.	1,506	State	Foreign
Norway	Stattnet	X			X			11,563	1,461.0	1,789	State	Domestic
Poland	PSE	X			X			15,892	5,955.0	2,825	State	Domestic
Portugal	REN	X			X			9,409	665.5	748	State	Foreign
Romania	Transelectrica	X			X			8,904	528.2	2,037	State	Domestic
Russia	PJSC FGC-Rosseti						X	149,600	2,475.0	21,541	State	Domestic
Russia	JSC SO UES					X		149,600	n.a.	n.a.	State	Domestic
Serbia	EMS	X			X			9,992	329.9	1,350	State	Domestic
Slovenia	ELES, d.o.o..	X			X			3,114	264.3	569	State	Domestic
Slovak Republic	SEPS	X			X			3,125	454.6	558	State	Domestic
Spain	Redeia	X			X			44,000	1,625.0	2,420	State	Domestic
Sweden	Svenska Kraftnät	X			X			17,000	4,340.0	1,209	State	Domestic
Switzerland	SWISS GRID	X			X			6,700	1,249.0	853	State	Domestic
Turkey	TEİAŞ	Obs.			X			74,916	748.0	16,300	State	Domestic
Ukraine	Ukrenergo	X			X			21,800	1,623.0	7,500	State	Domestic

Figure 1 provides an overview of European transmission operators and their performance in terms of employees/km of transmission line under management and revenue (EUR)/km of transmission.

[5] The European Network of Transmission System Operators for Electricity (ENTSO-E) is a key organization currently representing and coordinating 40 electricity transmission system operators (TSOs) from 36 countries across Europe. Established in 2009, ENTSO-E plays a vital role in the integration and coordination of the European electricity market. Its primary objectives are to ensure the reliable operation, optimal management, and sustainable development of the European transmission network.

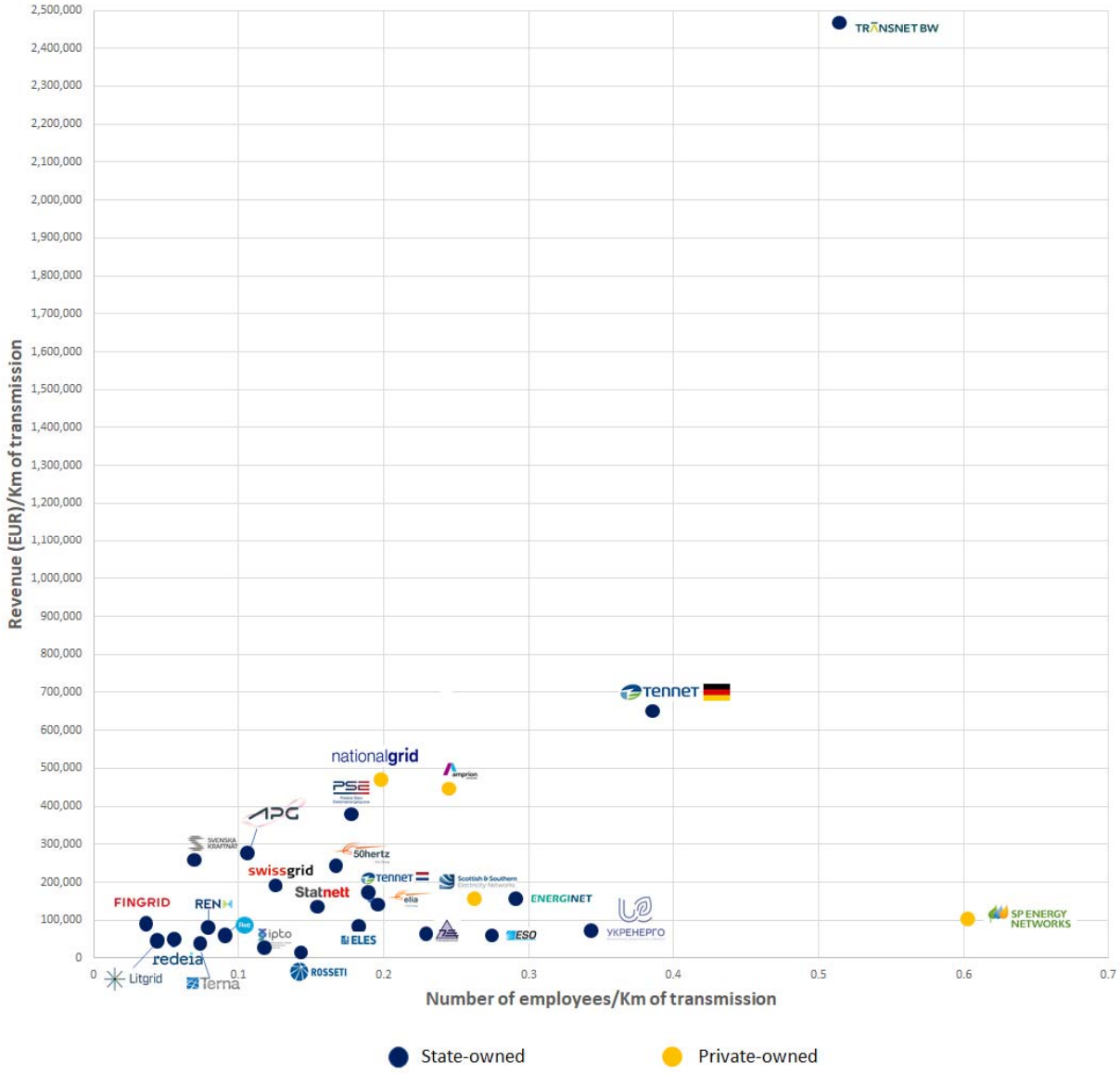


Figure 1 European Transmission operators overview in terms of employees/km of transmission and revenue (EUR)/km of transmission. Figures for National Grid were obtained by combining the respective figures for NGET with those for National Grid ESO.

There are also instances where transmission and distribution can be managed by the same entity. One example in Europe is ELES, the Slovenian Transmission System Operator which merged with SODO, the electricity distribution system operator, in October 2023. ELES now manages both transmission and distribution networks in Slovenia. A similar arrangement exists in countries that have chosen to separate the roles of system operator and transmission owner,

by adopting the ISO model. In these countries, transmission owners often also own part or all of the distribution grid, allowing them to manage a significant portion of the entire electricity infrastructure. Additionally, certain TSOs also manage the gas grid, overseeing the transportation of natural gas alongside electricity.

Figure 2 provides an overview of European transmission operators, their organizational arrangement and their business scope.

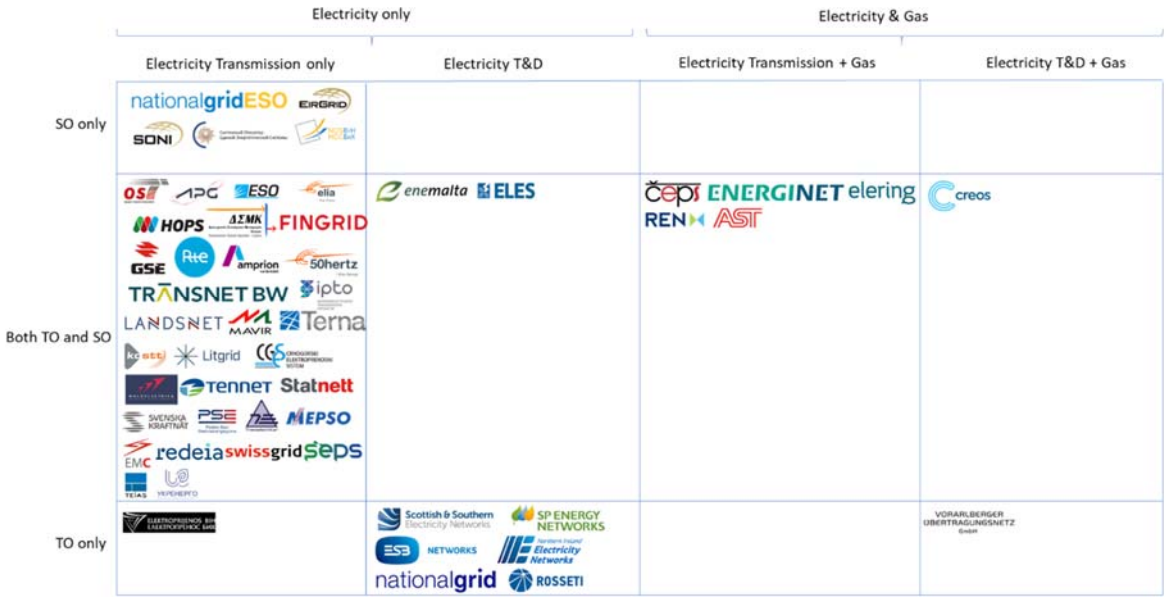


Figure 2 Overview of European TSOs. Abbreviations: SO: System Operator; TO: Transmission Owner.

Across different geographies worldwide, there are significant variations in the organization of TSOs. In the United States, for instance, Independent System Operators (ISOs) or Regional Transmission Organizations (RTOs) are commonly responsible for managing the high-voltage electricity transmission grid across extensive geographic regions. These entities are typically independent and operate on a not-for-profit basis. Numerous transmission companies, instead, own the physical transmission assets and undertake tasks such as grid expansion and maintenance in their respective areas of service. Similar organizational arrangements are observed in Canada, Australia, and several Latin American countries; in these regions, the ISO model is often adopted.

Furthermore, unlike in Europe, unbundling is not always mandatory, and there are regions where vertically integrated utilities operate both transmission, distribution and generation of electricity. In particular, the vertically integrated utility model, is still the prevalent model in Middle East and in Africa.

Table 2 provides an overview of the current distribution of TSO arrangements across the world.

Table 2 Current distribution of TSO arrangements across different world regions. VIU: vertically integrated utility; LTSO: Legally Unbundled Transmission System Operator; ITSO: Independent Transmission System Operator; ISO: Independent System Operator; TO: Transmission Owner;

Region	N° of countries	N° of transmission companies	VIU	LTSO	ITSO	ISO	TO
Africa	15	15	10	0	5	0	0
Asia	22	66	18	2	26	4	16
Europe	44	55	2	6	34	5	8
Middle East & North Africa	18	19	16	1	2	0	0
Central & South America	13	48	3	1	2	7	35
North America	2	127	7	0	0	10	110
Total	**114**	**330**	**56**	**10**	**69**	**26**	**169**

Comparing the figures, Table 2 suggests that North America, particularly the United States, has the highest number of transmission companies. This category includes transmission companies that operate as cooperatives, a model that emerged from the need to electrify rural areas during the New Deal era. Before the 1930s, rural regions had limited access to electricity because private utilities deemed it too costly and unprofitable to extend services to these sparsely populated areas. To address this disparity, President Franklin D. Roosevelt established the Rural Electrification Administration (REA) in 1935, offering low-interest loans to cooperatives and other entities. Rural residents formed member-owned cooperatives, allowing them to secure affordable and reliable electricity. These cooperatives, governed democratically and operated on a non-profit basis, played a crucial role in transforming rural America, fostering economic development, and improving the quality of life. Today, they continue to serve millions, adapting to modern energy challenges and technological advancements while maintaining their foundational community-focused principles (NRECA, 2024).

This thesis has analyzed the transmission system operation segment across 114 countries and covering 330 transmission grid operators. Appendix 1 provides an overview of these companies. The rest of this thesis, instead, will mainly focus on European TSOs.

2.2 TSO roles and activities

Electricity TSOs play a crucial role in the power sector by ensuring the security of supply in their regions, transmitting electricity reliably and securely from power plants to distribution networks, and maintaining grid stability. They balance supply and demand in real-time and facilitate the integration of renewable energy sources, thereby enabling the energy transition. In Europe, TSOs are also the pillars upon which the European Union aims to create a single European energy market, for instance, by increasing interconnections between countries which, in turn, enhances the reliability of the grid.

TSOs have diverse functions, which can be categorized using several schemas proposed in the literature: Primary vs. Secondary service (Rivier et al., 2013); Short vs. Long term (Rious et al., 2008; Stern, 2014); Hardware vs. Software (Glachant et al., 2015); System vs. Transmission operation (Pollitt, 2012). TSO's also categorize their activities between: (i) asset/infrastructure management; (ii) controlling/operating the electricity system (system operation); and (iii) facilitating the functioning of the electricity market (see TenneT, 2019a; Elia, 2019).

TSOs can also be categorized based on geographical criteria, distinguishing between *domestic activities* and *international activities* (Terna, 2019; Elia, 2019). Ideally, TSOs can take a position in international businesses (i.e. owning and managing transmission grids abroad), especially when these countries present low risk and stable political and regulatory frameworks. The logic is to use TSOs' own expertise to improve foreign country electricity infrastructure, for instance, by building, owning and operating a transmission grid, because the country in which TSO decide to invest in lacks these knowledge and skills.

The schema of '*regulated*' and *'non-regulated' activities* is also useful (Di Castelnuovo and Biancardi, 2020). Regulated activities are governed by relevant legislative and regulatory provisions and generate "regulated revenues" covered by a tariff set by the National Regulatory Authority (NRA). These mainly relate to the development of new CAPEX to enable energy transmission and OPEX for the correct functioning of the system. In some cases, TSOs may carry

out activities which generate regulated revenues in other regulated businesses, notably: transmission and distribution of natural gas or distribution of electricity. 'Non-regulated' activities conducted by TSOs are not covered by the tariff and are instead conducted in a competitive regime. Examples include Operation & Maintenance (O&M) conducted for third parties, Engineering, Procurement and Construction (EPC), investments in telecommunications (e.g. fibre optic) and the provision of services to telecommunications operators using own electricity infrastructures and assets, private interconnectors (financed through third parties), design, production, commercialization and repair of power transformers, energy efficiency solutions, or consultancy.

Across TSOs of 13 European countries (Belgium, Bulgaria, Denmark, France, Germany, Greece, Italy, Netherlands, Portugal, Romania, Spain, Sweden, UK), about 87% of revenues, on average, are generated by domestic regulated activities related with transmission of electricity, 7.5% are generated by other activities performed within domestic boundaries (both regulated and non-regulated) and only 6% come from international activities (both regulated and non-regulated). These data indicate that TSOs tend to be mostly engaged in regulated activities. The share of domestic revenues from transmission of electricity for individual TSOs varies from 22% for National Grid (UK) up to 100% for TenneT (Netherlands and Germany), ESO (Bulgaria) and Transelectrica (Romania). Appendix 2 offers a full breakdown of the revenues generated by the European TSOs, including the sources used.

2.3 Key challenges for TSOs

Due to megatrends and industry-wide transformations, grid operators are navigating significant challenges. Specifically, the synthesis of literature from various sources has identified 20 key factors that are reshaping the business of TSOs. Analyzed sources include, but are not limited to: ETC (2023), Eurelectric (2022), IEA (2023a; 2023b), EC (2023a), Breakthrough Energy (2023), ENTSO-E (2022), WEF (2023), McKinsey (2022), Jansen and Newman (2022), Poudineh (2022), Glachant et al., (2021); WEC (2020), WindEurope (2020), and IRENA (2020a, 2020b, 2019a).

These challenges were categorized based on their time frame (short or long-term), origin (external or internal to TSOs), and domain (operational, technological, corporate affairs & stakeholder management).

These challenges are often interconnected and their categorization is not rigid as they often share aspects common to other categories, indicating a fluidity in how they are perceived and addressed. Furthermore, the difference between short-term and long-term challenges is not about urgency, but rather their duration; while all these challenges demand immediate attention, some are temporary in nature and thus classified as short-term, whereas others are more enduring or long-standing. In other words, the challenges identified as long-term effectively constitute actual long-term trends.

Figure 3 illustrates the twenty challenges and the following section provides a detailed description of each. The chapter then focuses specifically on challenges classified as external and long-term, examining their potential impacts on TSOs and highlighting the main strategic opportunities and obstacles they pose.

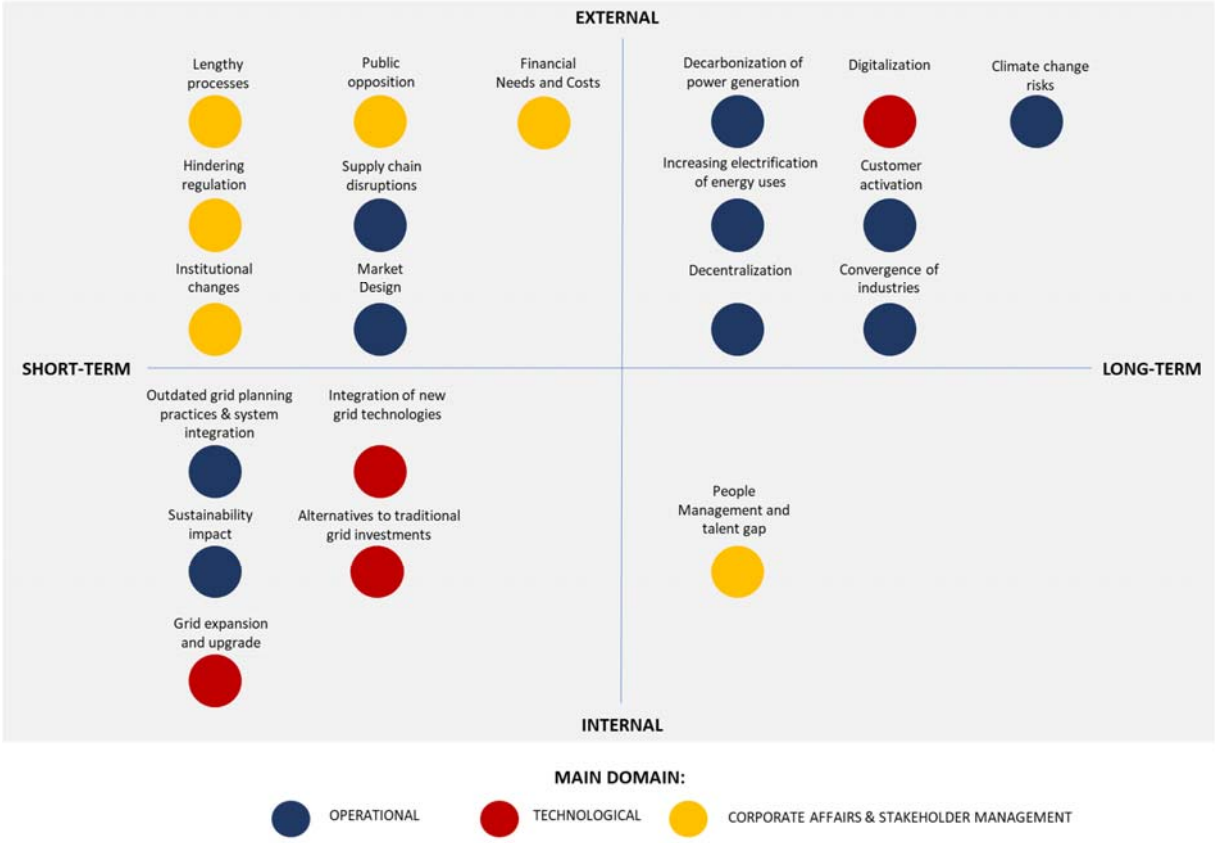


Figure 3 Overview of the twenty main challenges faced by Electricity Transmission System Operators categorized based on their time frame (short or long-term), origin (external or internal to TSOs), and domain (operational, technological, corporate affairs & stakeholder management). Colours indicate different domain.

2.3.1 Operational challenges

2.3.1.1 Decarbonization of power generation

In order to meet EU climate goals, wind and solar generation capacity must increase from 400 GW in 2022 to at least 1,000 GW by 2030, including a large build-up of offshore renewables up to 317 GW, to be connected to shore (European Commission, 2023a).

Decarbonizing the power sector is essential for addressing climate change, yet it introduces issues for grid operators. Renewable energy sites, frequently situated in remote locations such as offshore areas or deserts, in fact, contrast with traditional generation sites that are typically located near demand centers like cities and industrial areas. This geographical mismatch requires the construction of new transmission lines. Wind and solar technologies, then, typically

produce less power per unit than traditional fossil fuel generators, leading to a higher number of connections for the same output (IEA, 2023a). In addition to that, most of new renewable power projects are being connected directly to the distribution grid. Therefore, we are shifting from a system with a few large generators near load centers towards a more complex system, where large power plants are strategically located where renewable energy is most abundant and complemented by numerous small generators distributed locally, thus blending centralized infrastructures with decentralized and distributed resources.

The intermittent nature of renewables adds further complexity to grid management. A key solution to address this issue is the expansion of the grid through the construction of new cross-border and within-border interconnectors. These enable the use of diverse resources across large areas and allow the redistribution of surplus clean energy to meet varying demands, aiding in grid balance, emissions reduction, and achieving renewable energy goals (Joos and Staffell, 2018; Grams et al., 2017). Integrating new energy storage, whether co-located with renewables or standalone, is also crucial for enhancing flexibility but further complicates the grid. Similarly, demand-management systems play a vital role in modulating energy demand and supply balance, thereby enhancing grid stability and efficiency.

Another issue with power sector decarbonization arises as renewable energy sources, which usually connect to the grid through inverters, become more prevalent. Unlike traditional synchronous generators in fossil fuel and hydroelectric power plants, these sources contribute less inertia to the grid, making it more vulnerable to frequency fluctuations and heightening the risk of instability. The situation is further exacerbated by the gradual phasing out of traditional, especially fossil fuel-based, generators from the market. Indeed, renewables' rise, environmental policies, and market changes threaten the viability of traditional flexibility-providing conventional generators (RMI, 2018; Fell and Kaffine, 2018; Genoese and Egenhofer, 2015).

Finally, as we progress towards a fully decarbonized system operating around the clock, managing higher levels of renewable energy penetration will become more challenging compared to current levels. This involves not just capitalizing on renewable resources during sunny and windy periods but ensuring consistent, sustainable energy supply throughout all times of day and year.

2.3.1.2 Increasing electrification of energy uses

Despite difficulties in forecasting European electricity demand due to changing population trends, geopolitical shifts, possible deindustrialization in some regions, and the adoption of digital and energy efficiency technologies, the outlook for electricity demand is clearly positive and expected to rise. Particularly, electricity consumption in the EU is expected to rise by about 60% by 2030 (European Commission, 2023a), fueled by its growing use in transportation, heating, cooling, and industry alongside the potential for electrifying low-carbon hydrogen production. This surge is marked by record electric vehicle (EV) sales (BNEF, 2023) and a significant increase in heat pump and air conditioner sales (EHPA, 2023).

The strategy to 'electrify everything' and simultaneously generate electricity from renewables is crucial for achieving climate goals. Using clean electricity instead of fossil fuels will also reduce total energy consumption due to its inherently higher efficiency, thus increasing energy security.

While these shifts offer significant growth opportunities, they also present major challenges for TSOs, especially in handling the increased strain from emerging technologies on grid capacity. This situation impacts grid stability and requires a deep understanding of electric vehicle (EV) charging behaviors, along with heating and cooling consumption patterns. Ultimately, these dynamics may cause higher peak loads and potential congestion on the grids.

Additionally, our increasing dependence on electricity amplifies the risks associated with power outages. Such disruptions can severely impact communication, safety systems, life support devices, food storage, and temperature control, especially in urban areas. This situation highlights the critical importance of ensuring electricity security as a paramount priority.

2.3.1.3 Decentralization

As mentioned earlier, the escalating deployment of decentralized and distributed resources, such as electric vehicles, may lead to higher peak demands, particularly if unmanaged. Furthermore, the increase in distributed renewable generation introduces unpredictable and sometimes reversed energy flows. Additionally, many decentralized resources, like rooftop solar panels, connect to the distribution grid, falling outside TSO control, complicating energy behavior visibility and forecasting.

The transition towards decentralized electricity and behind-the-meter storage is turning customers into 'prosumers' or 'prosumagers,' who both generate and store their own power (Green and Staffell, 2017). While this transformation can enhance system security, it may also lead to increased network charges if these are calculated on a volumetric basis (Friedrichsen et al., 2015). Moreover, the rise of energy communities and microgrids, which primarily rely on the main grid for backup, adds further complexity to the system.

Decentralized resources represent a potential crucial source of grid flexibility (Spyrou et al., 2021), and customer participation in energy markets, as encouraged by the EU's Clean Energy Package, can greatly benefit TSOs. In this regard, initiatives like Equigy, leveraging blockchain technology to enable consumer devices such as batteries or heat pumps to balance the grid, highlight the importance of consumer participation and the potential for decentralized players to contribute to grid flexibility (Jones, 2023). This shift, however, necessitates enhanced coordination between TSOs and Distribution System Operators (DSOs), who must now manage networks and integrate decentralized resources effectively. The emerging competition between TSOs and DSOs for the same flexibility resources underscores the need for stronger coordination and data sharing for the safe, reliable, and cost-effective use of flexibility services (Hadush and Meeus, 2018; Burger et al., 2019; Gerard et al., 2018).

The shift towards a decentralized system and greater emphasis on distribution could imply a reduced role for TSOs vis-à-vis DSOs. Yet, advancements in managing distributed resources and the need for enhanced transmission to support rising electricity demand from decentralized sources may alter this view. For example, the recent announcement of the commercialization of ultra-fast EV charging stations directly connected to the high-voltage transmission network actually highlights a potential increase in demand for charging infrastructure directly linked to the transmission network (Technovedas, 2024; National Grid, 2022). This could, in turn, make the transmission network even more crucial in the evolving energy landscape.

Additionally, while the system's decentralization represents an incontrovertible trend, the potential resurgence of interest in next-generation nuclear technologies, including nuclear fusion, along with advancements in carbon capture and storage technologies, may significantly transform the developmental trajectories of network architecture (EM, 2023; Giuliani et al., 2023). Such transformations could lead to a recalibration towards increased centralization,

culminating in the establishment of a hybrid architecture that incorporates both centralized and decentralized elements.

2.3.1.4 Outdated grid planning practices and system integration

Grid planning need to be profoundly revised, through improved coordination not only between grid and generation planning but also between transmission grid and distribution grid planning, as well as coordination between the electricity grid and other energy vectors like gas and hydrogen planning.

Traditional grid planning approaches, where generation projects precede grid development, have become outdated. In the past, for large hydro or coal projects, their development typically exceeded the time required to build the transmission grid. However, this dynamic has shifted, and the development of renewable energy projects now often outpaces the construction of transmission lines (IEA, 2023a). Therefore, it's imperative to update grid planning practices in order to ensure that transmission assets are in place concurrently with the development of renewable energy sources.

Firstly, grid planning must account for regions without grid access, as they risk missing out on deploying renewable resources without proactive grid infrastructure investments. Also, new resources, such as offshore wind or renewables in remote areas, may require dedicated grid development. Therefore, grid planning must anticipate these infrastructure investments.

Second, cross-border grid planning coordination is essential for managing the complexities of energy transitions, especially with the growth of variable renewable generation. Collaborative efforts among countries in grid and renewables planning are necessary to optimize resource sharing and handle bidirectional power flows.

Enhanced coordination between distribution and transmission grid planning is also crucial to address the complexities and potentials at the distribution level. Traditional planning, where power flows from generation centers to demand centers, is ill-suited for future grids with distributed generation, flexibility resources, and potential bidirectional power flows. Additionally, coordinated planning across transmission and distribution is necessary to explore technology-neutral solutions, including non-wires alternatives (NWAs) like storage and microgrids. In particular, the integration of NWAs into system planning is increasingly common

in some countries, as well as the incorporation of flexibility services from Distributed Energy Resources (DERs).

More broadly, grid planning studies must adapt by incorporating robust scenario development that encompasses diverse development paths, including climate policy and links to sectors like transport, heating, industry, and emerging energy sources such as natural gas and hydrogen. To accommodate increased renewables and electrified demand, including green hydrogen production from electrolysers, long-term scenario planning must address a wide range of actors, interactions, and uncertainties, creating a more comprehensive landscape. This detailed scenario analysis informs public discourse and evaluates the costs and benefits of various technology pathways. In this regard, coordinating the expansion of electricity transmission lines, electrolysers, hydrogen pipelines, and storage infrastructure is essential.

Last but not least, grid planning studies should incorporate a comprehensive risk assessment, considering multiple threats like climate change, cybersecurity, supply chain security, geopolitical risks, social acceptance, and unpredictable events like pandemics. This advanced risk analysis is crucial for supporting investment decisions in projects that are beneficial under various risk scenarios, not just under typical operating conditions.

2.3.1.5 Supply chain disruptions

Building grids involves integrating diverse components and technologies, including cables, lines, transformers, substations, and control systems. Scaling up the manufacturing of these components to meet demand can be a significant challenge.

Furthermore, supply chains for essential materials like copper and aluminum, crucial for manufacturing grid components and new lines, are susceptible to risks of scarcity and disruptions. This challenge extends to critical elements such as semiconductors used in specific grid applications.

Recent years have witnessed numerous barriers and bottlenecks in global supply chains. Events like the COVID-19 pandemic and Russia's invasion of Ukraine significantly disrupted technology supply chains, impacting the grid technology sector. These disruptions led to surging energy and material prices, shortages of critical minerals, semiconductors, and other components, adding extra hurdles to the energy transition.

In general, global supply chains for grid infrastructure remain vulnerable to geopolitical tensions and regional conflicts, potentially impeding the use of components from certain countries. For example, in December 2023, UK National Grid decided to remove components from its electricity transmission network supplied by China-backed Nari Technology due to cybersecurity concerns, following consultation with the National Cyber Security Centre in April (Mooney et al., 2023).

2.3.1.6 Climate change risks

Climate change impact all power system assets, from generation to transmission and distribution, to end-consumers. For instance, hydropower generators grapple with changing water inflow patterns, while droughts threaten supply and prices in summer, and winter precipitation and icing cause blockages. Thermal and nuclear plants face operational hurdles during heatwaves due to higher temperatures for cooling. Coastal and inland flooding also jeopardize most generation assets. Moreover, climate change significantly threatens the grid's physical security. Elevated risks include severe storms that can damage transmission and distribution lines, poles, transformers, mainly due to falling trees and branches. Extreme cold spells and higher temperatures can lead to power outages, reduce transmission capacity, and stress underground cable joints and insulation, particularly in urban areas or during droughts. The growing wildfire seasons also pose a serious risk, causing multiple faults across grid components and thermal derating of overhead lines. Additionally, substations are at risk of becoming inaccessible due to wildfires, floods, and high winds and potentially suffering flood damage.

In 2021 alone, grid-related technical failures, due to higher temperatures and extreme weather events, resulted in global economic losses of at least USD 100 billion (IEA, 2022). The majority of these losses stem from disrupted business productivity, supply chain interruptions, and potential equipment damage. Beyond financial implications, it's crucial to note that such power outages can lead to loss of life due to the inability to provide heating or cooling. These interruptions, in fact, impact critical infrastructures, affecting water and food supply, access to medical assistance, financial services, telecommunications, and mobility. Consequently, they pose risks to health, well-being, safety, and daily activities, constraining overall productivity.

In the future, climate change risks are set to escalate, as forecasted by the Intergovernmental Panel on Climate Change (IPCC). Europe can expect an increase in extreme heat, fire weather, heavy precipitation, and severe windstorms. Additionally, the Mediterranean and Western & Central Europe are likely to experience more frequent droughts, heightening the risk of wildfires. Northern Europe, on the other hand, faces the prospect of increased precipitation and flooding.

Several strategies can be adopted to enhance power grid resilience against climate change and weather events. Installing underground cables offers protection against weather risks, though they're vulnerable to heatwaves. Strengthening overhead infrastructure is also vital, involving reinforced poles and rerouted lines away from trees to mitigate wildfire and wind damage. Enhancing transformer cooling systems and using insulated conductors help combat heatwaves. Leveraging digital technology like AI, robots, drones, and satellites is crucial for disaster recovery and damage prevention.

Lastly, Eurelectric (2022) emphasizes the importance of innovative strategies such as Enel Grids' "4R", focusing on robust infrastructure, swift readiness, agile response, and effective recovery. These approaches are crucial for enhancing grid resilience as they provide novel solutions to manage these challenges effectively.

2.3.1.7 Sustainability impact

Electricity grids are essential for the energy transition and achieving climate goals. Providing access to quality and reliable electricity also brings other numerous, often hard-to-quantify, positive externalities. These benefits include driving economic growth, creating jobs, enhancing education and health outcomes, and increasing income levels, especially in some areas. However, the development of new power infrastructure also presents specific challenges related to sustainability and biodiversity preservation.

Like any major infrastructure project constructing new power lines and grid infrastructure may significantly impacts biodiversity and environmental sustainability. Such projects often lead to habitat loss and fragmentation, disrupting ecosystems and affecting wildlife. The construction activities can disturb and displace animals, forcing them into less suitable habitats. Birds are particularly at risk, facing hazards from collisions and electrocution. Environmental

degradation, including soil erosion and water pollution, is another consequence of these constructions. The visual impact and alteration of landscapes can also affect human enjoyment of natural areas whereas the construction of new power lines may lead to the displacement of local communities and the expropriation of land, posing significant social and ethical challenges.

Mitigating these impacts, which is absolutely crucial to secure TSOs' social license to operate and avoid public opposition, requires strategic planning and sustainable practices. This involves choosing minimally disruptive routes, using construction methods that preserve habitats, and implementing wildlife corridors. Post-construction, restoring habitats is crucial for maintaining ecological balance alongside energy development.

Last but not least, electricity grid operators are major consumers of sulfur hexafluoride (SF6), the insulator of choice in high-voltage power transmission equipment, including circuit breakers and gas-insulated switchgear (GIS) and, more broadly, in electrical substations, due to its excellent arc-quenching and dielectric properties which allow to reduce plant size. The problem with SF6 is that it is potent greenhouse gas, with a global warming potential 23,500 times that of CO_2 and leakages, which can occur during maintenance and disposal operations, often represent the main source of TSO's direct emissions (Terna, 2022). In light of emerging eco-friendly alternatives, several regions, including the EU, are now contemplating the complete ban of SF6 in grid equipment.

2.3.1.8 Customer activation

The combination of decentralization and digitalization enables customers to be active players in the market (Biancardi and Di Castelnuovo, 2020; Flores and Waddams, 2018; Crampes and Waddams, 2017). Electricity consumption, particularly in households has been highly inflexible to date (i.e. inelastic demand), but is now changing due to the introduction of smart metering and automation, along with the deployment of distributed energy sources and other potential solutions including smart contracts and flexibility markets platforms (Schittekatte and Meeus, 2020; Zinaman et al., 2015; He et al., 2013). The Clean Energy Package also emphasizes the central place of customers in the energy transition and promotes customer participation in a wider range of markets, with new technologies and greater access to information. Demand participation is encouraged in wholesale electricity markets and new initiatives to make use of

demand flexibility as a resource in ancillary service markets are also envisaged (ENTSO-E, 2019a; Hogan, 2013). New solutions are also emerging to make flexibility provided by decentralized resources (e.g., electric vehicles, water heaters) a new market product. For instance, Spyrou et al. (2021) proposed an innovative approach for managing imbalances: an auction that allows resources with imbalance risk to hedge their production by purchasing flexibility options. These options are provided by grid-connected resources capable of offering physical flexibility. Consequently, TSOs may significantly benefit from higher demand side flexibility.

However, it's important to note that TSOs, particularly in Europe, do not directly engage with end customers. Therefore, harnessing demand flexibility requires strong coordination with DSOs (Hadush and Meeus, 2018; Beckstedde and Meeus, 2023). Furthermore, the emergence of new business models and technological innovations, such as energy communities and microgrids, simultaneously democratizes the energy sector and challenges TSOs by relegating their role to that of a mere backup in times of electricity demand from the grid, as previously discussed in the context of decentralization,

2.3.1.9 Market Design

When addressing decentralization, the increase of resources connected at the distribution level, beyond TSOs' direct control, along with greater market activity, complicates TSOs' real-time balancing of supply and demand. As highlighted in (Joos and Staffell, 2018) this necessitates larger markets for balancing and reserve both in geography and scale. Indeed, larger balancing areas will help integrate renewables, by leveraging on different weather patterns and cancel each other forecast errors, while opening balancing markets to smaller and alternative providers also increases competition and should thus improve efficiency. In particular, the possibility to tap into the flexibility potential offered by distributed energy resources seems to be crucial to both the TSO and the DSO, in order to solve problems related to frequency control (TSO only), congestion management (both TSO and DSO), and voltage control (both TSO and DSO) (Burger et al., 2019).

If the transmission system operators were hitherto the only buyer of flexibility services for balancing, with the transition to a decentralized energy system it is likely to see the emergence (first on a voluntary basis and then on a mandatory basis) of local balancing markets where

DSOs can procure flexibility services, thus playing an increasingly active role in the smart management of distribution networks. An interesting example here is provided by Piclo, a London-based start-up which has successfully developed a platform for trading flexibility on the distribution network in a trial which involved six Distribution Network Operators (DNOs) in Great Britain.

2.3.1.10 Convergence of industries

There is an ongoing convergence of different industries towards the electricity sector with potential profound implications for the industry as a whole. This trend extends beyond well-known sectors such as automotive, ICT (Information and Communication Technology), O&G (Oil and Gas), and finance. The building and construction industry are pioneering smart buildings and cities, incorporating energy-efficient solutions and renewable energy sources, thereby necessitating closer collaboration with the electricity sector. Similarly, the manufacturing sector is moving towards the electrification of processes and the integration of energy management systems to reduce carbon footprints, to name a few other examples.

Network companies, particularly at the distribution level, traditionally shielded by monopoly status, may soon encounter heightened competition, notably from non-energy actors. This cross-industry convergence also challenges the traditional relationships between Transmission System Operators (TSOs) and key stakeholders. For instance, in 2017, the German IT company Ponton launched Enerchain, a blockchain-based project designed to facilitate wholesale energy transactions without relying on a Power Exchange (Andoni et al., 2019; PwC, 2016). However, this evolving landscape also presents opportunities for new industry partnerships, drawing on the diverse skills and expertise that companies from these converging sectors can offer.

2.3.2 Technological challenges

2.3.2.1 Digitalization

Digitalization is revolutionizing power systems, enhancing efficiency and aiding decarbonization. It provides operators with sophisticated tools for forecasting, fault detection, demand response, and real-time grid management. Smart grid technologies, as the IEA suggests, could cut renewable energy curtailment by over 25% by 2030.

In remote or underserved regions, digital tools are facilitating the expansion of clean, decentralized energy through mini-grids and community projects. Technologies such as smart inverters and digital platforms are key for efficient electricity management, reducing peak-time issues, and enabling distributed resources to support grid balance.

Advanced monitoring systems, like SCADA, streamline grid operations and reduce response times. Innovations in automation enhance outage prevention and mitigation. Integrated systems, leveraging analytics and AI, forecast demand and identify grid vulnerabilities for proactive reinforcement. Sensors on grid infrastructure improve maintenance and durability. Furthermore, the use of drones and satellite technology for inspecting power lines offers safer and more effective alternatives to conventional methods.

Yet, the proliferation of these technologies brings associated risks, notably data breaches and cyberattacks. The interconnectedness of modern grids amplifies these risks, potentially leading to major disruptions and significant financial losses. For example, the UK's 2023 National Risk Register estimates a 5% to 25% likelihood of a cyberattack on critical infrastructure, with potential losses reaching hundreds of millions of pounds (HM Government, 2023). With the rise of digitalization, cyber incidents have increased globally, presenting serious threats to the electricity sector where large-scale power outages can have severe consequences. Addressing these challenges is crucial, necessitating both prompt, effective responses and proactive measures to safeguard the expanding and increasingly digital power systems.

Furthermore, the digital transformation necessitates a comprehensive overhaul of business operations, including the implementation of new software and hardware for big data, mastering machine learning artificial intelligence, new technologies like robots and drones. Additionally, it necessitates recruiting skilled personnel. In other words, this transformation is not only technological but also organizational, requiring a strategic approach to effectively harness the potential of digitalization in the energy sector.

2.3.2.2 Grid expansion and upgrade

Over the past years, there has been a notable expansion of the global electricity grid, particularly in emerging markets and developing economies. In particular, around 1.17 million kilometers of new transmission lines have been constructed in the last decade. A major player

in this expansion is China, which has installed more than 500,000 kilometers of transmission lines alone, accounting for over one-third of the global increase, prominently featuring Ultra-High Voltage (UHV) lines. These UHV lines are crucial for connecting areas rich in renewable energy sources with major consumption hubs.

However, to further increase the proportion of electricity in the global energy mix and to seamlessly integrate renewable energy sources in line with climate objectives, significant expansion is necessary. According to the International Energy Agency, the world's grid length needs to more than double by 2050. Specifically, global transmission lines, which measured 5.3 million kilometers in 2021, must extend to 12.7 million kilometers by 2050 (IEA, 2023b). In addition to the lines and cables, corresponding infrastructure such as substations, switchgear, transformers, and control and protection equipment also need to scale up accordingly.

A substantial portion of this expansion involves the development of cross-border interconnectors. For instance, the EU has set ambitious interconnection targets for each Member State, with a goal of 15% of each state’s installed electricity generation capacity by 2030. As of 2021, Europe had 80 GW of cross-border transmission capacity, with plans to augment this by an additional 50 GW by 2030 and a further 43 GW by 2040 (ENTSO-E, 2020a). Interconnections play a key role in grid stability, energy security, and flexible power management. Beyond their technical benefits, cross-border interconnections also have significant geopolitical impacts, fostering energy exchange and strengthening international relations. They promote regional cooperation and serve as instruments of 'electricity diplomacy,' symbolizing and facilitating mutual dependence and prosperity (Westphal et al., 2022).

Beyond expansion, there's an urgent need for replacement and modernization of the existing grid infrastructure. By 2050, it is projected that two-thirds of the world's grid length in 2021 will need replacement due to the aging of components, especially in developed economies (IEA, 2023a).

2.3.2.3 Integration of new grid technologies

In recent years, the grid industry has witnessed some important innovations. One of these, has been the rising adoption of High Voltage Direct Current (HVDC) technology. This is especially

evident in the development of meshed HVDC offshore grids that connect offshore renewable energy sources, like wind farms, across various regions. HVDC technology offers numerous benefits, including reduced transmission losses, enhanced grid stability, and vital black-start capabilities essential for grid recovery. Although HVDC currently represents about 2% of the global transmission line length, its usage is growing rapidly. This expansion is driven by the construction of long-distance lines in countries such as China and Brazil, and by the deployment of submarine cables in Europe (IEA, 2023a).

Other important innovations taking place at grid level include so called “Grid Optimization Technologies” or “Grid Enhancing Technologies” (GETs), such as dynamic line ratings (DLRs), static VAR compensators (SVCs), STATCOMs, static synchronous series compensator (SSSC), Flexible AC Transmission Systems (FACTS), grid forming converters and HVDC (mentioned earlier), all technologies that offer the opportunity to optimize grid capacity, prevent overloads, and ensure stable electricity flow (WindEurope, 2020; ENTSO-E, 2020b).

Moreover, advancements in transmission materials are underway, with innovations like Aluminum Conductor Composite Core (ACCC) and superconductors. ACCC has already proven effective in increasing efficiency, while superconductors hold the promise of further enhancing transmission efficiency (Consentec, 2021).

Another important area of innovation concerns alternatives to SF6-based technologies.

Clearly, the examples provided represent just a fraction of the numerous innovations occurring within the grid industry. A comprehensive analysis of all such advancements is beyond the scope of this study.

It's crucial to emphasize that TSOs often need time to integrate and master new technologies, with thorough testing on their grids essential to ensure reliability. A key example here is the alternatives to SF6. Should there be a ban on SF6 for high and extra-high voltage applications, establishing realistic transition periods will be key to maintaining industrial operations while moving towards more sustainable practices.

2.3.2.4 Alternatives to traditional grid investments

Traditional grid infrastructure - wires, poles, and substations - is challenged by the rapidly growing deployment of “non-wires alternatives” (NWAs). These are low-carbon, cost-effective and easily installed technologies and business solutions that, individually or in combination, provide valuable flexibility services to system operators (Dyson et al., 2018; Navigant, 2017).

Incorporating flexibility services from NWAs into grid planning, like for instance distributed energy resources (DER) Management Systems, might optimizes grid, aiding congestion management and recovery from faults.

Globally, different regions are implementing varied strategies to utilize these services. The UK and US have established markets for flexibility services, with US utilities actively managing DERs as non-wire alternatives. The EU is advancing through pilot projects and regulatory measures to enhance TSO and DSO coordination and explore flexible market mechanisms, with notable examples like Italy's use of DERs in ancillary services (IEA, 2023a).

Additionally, NWAs can enhance transmission capacity utilization, helping to defer extensive upgrades and they can remain resilient to uncertainty of load growth, avoiding stranded costs if load does not increase (IRENA, 2020a, Kirschen and Strbac, 2018).

Intuitively, while aiding TSOs in reducing the need for extensive grid expansion, these alternatives might also require significant innovation in their approach to grid planning and operation.

2.3.3 Corporate Affairs & Stakeholder Management challenges

2.3.3.1 People management and talent gap

Attracting and retaining skilled personnel poses a significant challenge for grid operators, a situation intensified by the impending need for substantial grid expansion.

Additionally, there's a pressing need to incorporate completely new skills to deal with technological advancements and the rise in automation. In this regard, TSOs must emphasize reskilling of existing workforce and offering on-the-job training to stay abreast of evolving demands.

Most importantly, the advent of smart tools and the broader trend towards grid digitalization, while reducing the labor intensity of grid operation and maintenance, concurrently elevate the demand for IT expertise. As grids become increasingly digital, there is an escalating need for utility workers proficient in information technology. In some cases, the digital transformation encompasses a cultural shift, a change in mindset across the whole organization.

To attract such talent, then, companies need to offer competitive compensation packages, aligning with what other industries offer. Additionally, as grid companies transform into more integrated energy ecosystems, there's a growing emphasis on collaborative skills. This represents a shift not just in technical capabilities, but also in organizational culture and approach.

Another major issue that grid operators must contend with is the phenomenon known as "the great resignation" (and related concepts such as “quiet quitting,” then “loud quitting,”, “quasi-quitting,” “boomerang employees,” “rage applying,”). This term refers to the widespread trend of employees voluntarily leaving their jobs, driven by various factors such as the search for better opportunities, a desire for greater flexibility, or a reevaluation of work-life balance. This trend, accelerated post-pandemic, has put additional pressure on companies, including those in the utilities sector, to reevaluate their employee value propositions. Leaders need to identify which factors most impact their organization and adapt by creating flexible, employee-centric work environments to attract and retain talent (Fuller and Kerr, 2022). This includes offering remote or hybrid work options, focusing on employee well-being, and providing opportunities for continuous learning and career advancement. For grid operators, addressing "the great resignation" is not just about filling vacancies but also about building a resilient and future-ready workforce that can adapt to the rapidly changing energy landscape.

2.3.3.2 Public opposition

Local resistance, often rooted in concerns about visual impact, health, noise, biodiversity, or the 'Not in My Backyard' (NIMBY) syndrome, can impede infrastructure investments, such as constructing new overhead electric lines. This opposition frequently leads to delays in connecting new energy resources, prompting project reassessments, route alterations and elevated costs (European Commission, 2019a).

Successful grid deployment is largely dependent on societal support, highlighting the importance of proactive and effective stakeholder engagement right from the early stages of planning. Clear communication, comprehensive public consultations, and transparently demonstrating the tangible benefits of projects are fundamental to this process. Ensuring consistent and open dialogue throughout the project lifecycle is crucial for building and maintaining trust within the community.

Moreover, it's crucial to offer fair compensation to those affected, like landowners and local communities. Technically, underground cabling addresses visual and environmental concerns but tends to be more expensive. Innovative approaches, such as the U.S.'s NextGen Highways, which merge electric infrastructure with existing routes, thus exploiting existing right-of-way, provide an effective alternative that can significantly increase community support.

2.3.3.3 Lengthy processes

A major challenge in the energy sector is the mismatch between the swift deployment of renewable energy projects and the slower development of necessary grid infrastructure. Renewable projects like wind and solar farms can be completed relatively quickly, often within five years, and EV charging setups can be established in under two years. However, the process of planning, permitting, and constructing new grid infrastructure is considerably more time-consuming, potentially taking up to 15 years (IEA, 2023a).

This discrepancy creates a backlog of renewable projects awaiting grid connection, turning these connections into significant bottlenecks for renewable energy deployment. Such delays in grid expansion and connections are not just slowing the energy transition, but also pose a risk to achieving the 1.5°C climate goal by impeding the timely integration of renewable sources into the energy mix.

Lengthy issues are not solely related to the time required for obtaining permits for constructing new lines and connecting renewable energy sources. They also encompass more internal dimensions within TSO organizations, which may impede innovation. Specifically, this pertains to the extended duration and complexity of procedures that TSOs, often public companies bound by procurement codes, must adhere to. Such processes risk slowing down innovation (European Commission, 2021). To encourage progress, it is essential that regulators sanction

streamlined procedures and facilitate the approval process for new projects and initiatives, especially those focused on innovation. More broadly, the future procurement function must evolve to serve as a strategic catalyst, enhancing organizational resilience and effectively adapting to rapidly evolving market dynamics (EY, 2021; ADL, 2023).

2.3.3.4 Hindering regulation

To ensure the effective deployment of new resources like offshore wind and renewables in remote areas, dedicated grid development is essential. Regions lacking grid access face the risk of not being able to harness renewable resources without proactive infrastructure investments. Therefore, regulatory adjustments are urgently needed to allow for anticipatory investments. In this context, the EU's market design reform proposal includes provisions that require national authorities to empower grid operators to make such investments (European Commission, 2023b). Delayed network upgrades, by the way, can result in socio-economic losses that exceed the initial expenses (IEA, 2023b).

As highlighted later in Chapter 3, current regulatory frameworks in some cases create disincentives or do not adequately incentivize investments in innovative technologies (FSR, 2023). Intuitively, a mis-aligned political and regulatory framework risks to hamper the energy transition and prevent society to grasp the benefits of such transition and pursue broader economic growth opportunities. Reforming these frameworks to better promote innovation is essential. Particularly, regulatory frameworks should grant TSOs the flexibility to explore options like NWAs without adverse impacts on their profitability.

Recognizing these needs, the European Commission through its Grid Action Plan proposed regulatory changes to increase renewable grid investments and efficiency through innovative technologies. The plan also advocates for updating Technopedia for technology comprehension (ENTSO-E, 2020b) as well as fostering operator cooperation, providing ACER guidance, facilitating EU funding access for smart grids, streamlining permitting, and harmonizing industry standards to ensure grid supply chain security (European Commission, 2023a).

2.3.3.5 Institutional changes

TSOs not only face strategic, operational, technological, societal, and regulatory challenges, but also institutional ones.

A key example here is the discussion about the so-called "Europeanization" of TSOs, referring to the process over recent years aimed at enhancing security and stability across the continent. This has involved, to some extent, divesting TSOs of certain functions and responsibilities, which have then been delegated to regional coordination bodies (Van Renssen, 2018; Meeus, 2020; Glachant et al., 2015).

Italy's longstanding discussions about merging gas and electricity TSOs (Reuters, 2020, 2012) and Germany's discussions to consolidate electricity transmission system operators through buyouts in a strategic effort to streamline energy transmission and enhance efficiency represents other two noteworthy examples of this kind of challenge (Bloomberg, 2023).

Finally, a more recent example is the UK's government's plan for renationalization of a critical segment of the National Grid, specifically the Electricity System Operator (ESO). This move is part of wider energy system reforms aimed at supporting the UK's net-zero emissions strategy. The rationale for this action stems from concerns that the current ESO model, operated by National Grid, might face conflicts of interest, potentially placing profit above environmental goals and impeding net-zero progress. Amid ongoing discussions about the future of the domestic gas network, including hydrogen integration, the UK government believed that transferring gas system operations to public ownership would enable a more effective gas phase-out. Furthermore, the UK regulator Ofgem suggested that National Grid should cede its ESO role due to these conflicts, leading to government plans for an independent public sector entity to ensure unbiased system management and align long-term investments up to 2050 (Ofgem, 2023, 2022). In response, the government recently transformed the system operator into a public corporation, named the "National Energy System Operator" (National Grid, 2024). Although it will be government-owned, it is designed to operate independently. This new organization will oversee and plan across all energy sectors, promoting a more coordinated and strategic approach to the nation's energy infrastructure.

2.3.3.6 Financial needs and costs

According to IEA (2023a), to achieve national climate targets, global grid investment must nearly double by 2030, reaching over USD 600 billion annually. This surge is necessary after years of stagnation and should focus on digitalizing and modernizing distribution grids, alongside significant investments in transmission.

Governments are now acknowledging the importance of dedicated funding to enhance grid investment, extending beyond grids to include flexibility and the integration of distributed energy resources (Reuters, 2023).

Financial accessibility, however, might be a significant concern in certain regions. The IEA (2023a) points out that in countries like India, Indonesia, and Korea, the financial health of utilities is a key issue. Meanwhile, emerging markets, especially in Sub-Saharan Africa, face challenges with access to finance and high capital costs.

In contrast, regions like Europe, the U.S., Chile, and Japan face fewer financial barriers, but investments are still capital-intensive and as Meeus (2020) noted, this could conflict with the need to manage costs and reduce ratepayer burden.

Intuitively, the overall costs and affordability of the energy transition impacts on its broader social acceptability.

2.3.4 Focus on key sectorial trends

Among the challenges described in the previous section, those classified as external and long-term are actually key trends that are reshaping the electricity industry, with significant implications for economic fundamentals, investment opportunities, and business strategies for all market players. Figure 4 illustrates these trends and their interconnections. Notably, from the original list of the challenges (see Figure 3), climate change was excluded, as it represents a pervasive and enduring challenge across all industries. Instead, the rest of this section concentrates on these six key trends, examining their potential impacts on TSOs and highlighting the main strategic opportunities and challenges they present.

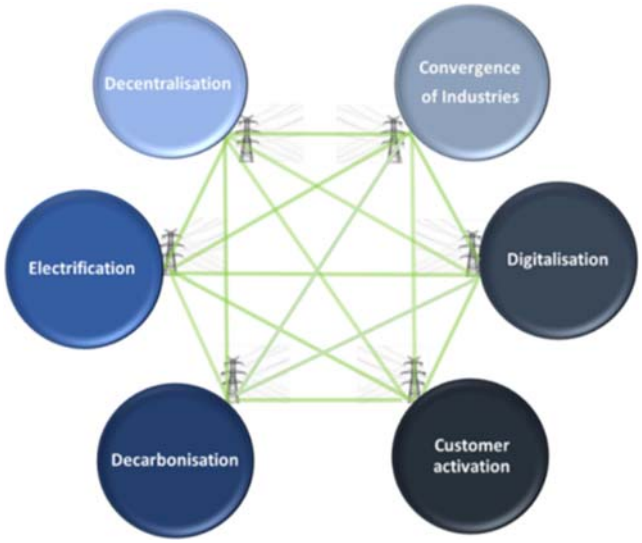


Figure 4 Key trends shaping the electricity industry – Source: (Biancardi and Di Castelnuovo, 2020)

2.3.4.1 Decarbonization

The previous section discussed how the rapid diffusion of renewables and their integration into electricity systems pose significant operational challenges for TSOs. These changes also present substantial opportunities. For instance, connecting large renewable power plants, such as offshore wind farms, offers a chance to expand the Regulated Asset Base of TSOs. Additionally, building new cross-border interconnectors can enhance the ability of countries with excess renewable capacity to export it, further contributing to decarbonization efforts. More broadly, the grid must be updated and reinforced to manage the increasing share of intermittent renewables in the system. This creates investment opportunities and reinforces the central role of TSOs, ensuring they maintain their pivotal position in the energy sector.

2.3.4.2 Digitalization

The increasing use of digital technologies in the grid will help manage its growing complexity, providing operators with sophisticated tools for real-time management and making tasks like inspection and maintenance safer and more effective (Nenova, 2019). Digitalization will also enhance power systems by improving energy forecasting, outage prevention and mitigation, fault detection and resolution, demand aggregation services, demand response, and active consumer participation (IEA, 2017). However, it poses significant challenges for TSOs, requiring an overhaul of business operations, new software and hardware for big data, and skilled

personnel. Additionally, new digital tools introduce risks such as data breaches and cyberattacks. The latter can cause major disruption as experienced after the attack to Western Ukraine's power grid in 2015 in which 30 substations were taken offline, leaving more than 230,000 people without electricity for up to six hours (Irena, 2019a). Lastly, digitalization could support the expansion of clean, decentralized energy through mini-grids, micro-grids, and community projects, potentially reducing the centrality of the transmission system, as less electricity would need to be transported and withdrawn from the grid.

2.3.4.3 Decentralization

The proliferation of small generation units, especially solar PV connected to the distribution grid, along with the rise of behind-the-meter storage systems, is driving a paradigm shift towards a more disintermediated and distributed energy supply. Customers can generate their own electricity, becoming "prosumers" (both producers and consumers of electricity), or even "prosumagers" who also store their electricity (Green and Staffell, 2017). Energy communities and microgrids further enhance the potential "democratization" of electricity generation and use, though they add to the system's complexity.

Decentralization might enhance overall system security because local disruptive events can only affect a small portion of the electricity system (Casertano, 2012). Additionally, while distributed energy resources (DERs) are crucial for providing the necessary flexibility as the share of intermittent renewables increases, stronger coordination and data sharing between DSOs and TSOs are essential but challenging to fully leverage this flexibility potential (Hadush and Meeus, 2018). Moreover, decentralization creates major challenges as increasing self-generation reduces the energy purchased from utilities and withdrawn from the grid. Since grid tariffs are usually volumetric (MWh charge)[6], this may raise network charges for remaining users, with unequitable redistribution effects among customers (Friedrichsen et. al., 2015). As these impact strengthen as more electricity is self-generated, this is sometimes referred to as the 'utility death spiral' (Schittekatte et al., 2018; Mountouri et. al., 2015). This puts pressure on

[6] According to ENTSO-E (2019a), on average, 60% of the TSO cost component was invoiced based on energy (i.e. on a volume, or MWh basis), while 40% was invoiced based on power (i.e. a capacity, or MW basis).

regulatory authorities which will struggle to guarantee the sustainability of network tariffs in the future (Helm, 2017; Küfeoğlu and Pollitt, 2018).

Finally, despite the potential diffusion of next-generation nuclear and energy-intensive carbon capture technologies, as well as the diffusion of ultra-fast EV charging stations connected to the high-voltage network, which could rebalance views on the future architecture of the electricity system in favor of a more hybrid system with both centralized and decentralized elements, should the decentralization of the system ultimately prevail, it could potentially reduce the role of TSOs. Intuitively, the diffusion of decentralized power generation and storage alone may reduce transmission requirements. Actually, the overall transmission grid requirements in Europe will likely depend on the eventual configuration of the Europe-wide electricity system, and the scale at which electricity supply and balancing resources of variable renewable generation will take place (Tröndle et al., 2020). A more decentralized and “autarkic” system will have lower transmission requirements but higher costs. Should European countries decide to share their renewable electricity supply sources at continental scale, this requires a large expansion of the transmission capacity (both at cross-border and sub-national level), but at a lower cost for final consumers (Green et al., 2016; Tröndle et al., 2020).

2.3.4.4 Customer activation

The combination of decentralization and digitalization empowers customers to be active market participants with new technologies and greater access to information. This trend suggests increased customer participation in wholesale and possibly balancing electricity markets, enabling grid operators to tap into demand flexibility as a resource (Spyrou et al., 2021). Consequently, TSOs may significantly benefit from higher demand-side flexibility. However, since TSOs in Europe generally do not engage directly with end customers, harnessing this flexibility requires strong coordination with DSOs (Hadush and Meeus, 2018; Beckstedde and Meeus, 2023).

For transmission companies, these changes present an opportunity to engage more deeply with DSOs and assist those with fewer financial, technical, and human resources to drive the change. On the other hand, the emergence of new business models and technological innovations, such as energy communities and microgrids, democratizes the energy sector and

simultaneously challenges TSOs. These innovations, in fact, may reduce the TSOs' role to a mere backup during peak electricity demand, as discussed in the context of decentralization.

2.3.4.5 Electrification (Increasing electrification of energy uses)

The increasing use of electricity in other sectors, primarily heat and transportation (BNEF, 2023, 2018; EHPA, 2023; IEA, 2018), brings about other relevant challenges and opportunities for TSOs. The rapid diffusion of electric vehicles (BNEF, 2020), may have a huge impact on the capacity required at certain times and locations. This, in turn, may have consequences for both adequacy and stability (Ofgem, 2018; McCulloch, 2018; Boßmann and Staffell, 2015). Hence, a greater understanding of EV charging patterns and technologies will thus be necessary to ensure their appropriate integration into the grid (especially distribution grid). Conversely, electrification could benefit TSOs as it will increase electricity consumption, and thus the need for transmission capacity investments which represent a source of revenues for TSOs. Furthermore, some experts argue that EV uptake could contribute to the integration of renewables into the grid, notably solar PV, since their demand may fit well with the production profile (BNEF, 2018). Great opportunities also derive from vehicle-to-grid (V2G) technologies: EVs drawing electricity from the grid or providing stored electricity back to help balance resources, meaning electric vehicles provide a good example of a potential demand side revolution (IEA, 2018; Eurelectric, 2018; Jochem et al., 2013).

2.3.4.6 Convergence of industries

Finally, there is an ongoing convergence of different industries, notably automotive, ICT, O&G and finance, towards the electricity sector. With the advent of new technologies, business solutions, and new players, network companies, including TSOs, will face increasing pressure to adapt and innovate. They may encounter heightened competition, particularly from non-energy companies and IT firms, to the point where the traditional monopoly model might be questioned if they fail to evolve and keep pace. This convergence could also reshape the relationship between TSOs and traditional key stakeholders (Glachant, 2021). For instance, blockchain technology, which aims to enable wholesale energy transactions without the need for any Power Exchange (Andoni et al., 2019; PwC, 2016), could significantly alter industry dynamics.

At the same time, TSOs have the opportunity to forge new industry partnerships and collaborate with these emerging players to gain access to essential skills, particularly in ICT (IEA, 2017). This is essential as there is fierce competition for attracting talent, especially IT professionals. More broadly, these new actors can introduce innovative solutions expanding the range of tools available to TSOs for managing their grid.

2.4 The interplay between regulation and innovation

Being natural monopolies, TSOs typically operate under a regulatory framework which affects their incentives for investments in infrastructure and other operation decisions (Joskow, 2007, 2014; Égert, 2009). Since regulation plays such a crucial role for transmission companies, the adoption of a regulatory design that adequately stimulates and incentivizes TSOs to innovate is widely advocated as vital for the success of the energy transition (Poudineh et al., 2020, 2017; Jamasb et al., 2020; Cambini et al., 2020).

Key factors have been highlighted that may hinder innovation by network companies, and must be corrected by the regulators if not already properly taken into account. These include: lack of clarity of TSO mandate and its prerogatives on certain innovative fields (European Commission, 2019b; CEER, 2020, 2019a); the presence of a regulatory regime designed to favour mainly cost-efficiency improvements (Jamasb and Pollitt, 2008, 2011, 2015); a regulatory regime with a bias towards CAPEX which discourages the adoption of technologies that reduce the need for physical investments by lowering TSOs' financial return (e.g. virtual power lines, dynamic line rating, demand side response and other so called "non-wires alternatives") (European Commission; 2019a; Poudineh et al., 2020).

Network companies may not invest in innovative activities because innovation and experimentation have, by nature, an uncertain outcome, so they are perceived as "too risky" activities (Poudineh et al., 2017). TSOs' need to be encouraged and incentivized towards R&D&I to limit such distortion, for instance through introducing a statutory duty to invest in innovative activities and/or to reach some specific targets (e.g. a minimum percentage of yearly revenues to be invested in innovative activities) (European Commission, 2019b). Above all, network companies need to be incentivized through ad-hoc financial mechanisms that allow them to recover their innovation costs (Poudineh et al., 2020, 2017; Lo Schiavo et al., 2013).

One approach to mitigate innovation risks consists in integrating innovation costs into the Regulatory Asset Base (RAB) or offering higher returns (Bauknecht, 2011). This spurs innovation in targeted areas (Poudineh et al., 2020) with the drawback that no attention is given to whether the investments result in useful innovations, shifting risk to customers (Cambini et al., 2020). Alternatively, an "output-based approach" consists in devising the incentive mechanism such that the firm benefits only from successful innovation (e.g. raising the price or revenue cap for a firm that introduced a useful innovation) (Bauknecht, 2011). In this case, however, we might incur the problem of verifiability and measurability of the outcome (Poudineh et al., 2020; Cambini et al., 2020).

Poudineh et al. (2020) suggest that the design of innovation-friendly regulatory schemes should also account for the different level of risk involved at each stage of innovation. Besides the different level of maturity that may characterize new technologies, innovative solutions imply a "trial and error" process before their full adoption. One potential counter is to adopt an input-based scheme for innovation activities at the early stages of the spectrum (i.e. R&D and piloting) and an output-based scheme for less risky activities or more mature solutions (Poudineh et al., 2020, 2017; Cambini et al., 2020).

Another solution proposed is adopting regulatory experimentation methods like sandboxes, which permit small-scale exceptions to existing regulations. Schittekatte et al. (2021) studied sandboxes in Italy, the Netherlands, and Great Britain, highlighting their varied implementations and evolving nature. Despite differences, sandboxes show promise for aiding Europe's green transition, and insights from these countries could shape national and EU-level regulatory discussions, with coordinated efforts to integrate new technologies and business models into the energy sector. Similarly, Beckstedde et al., (2023) examined 72 approved sandbox projects across eight European countries, developing best practices on the topics of regulatory sandboxes and their implementation frameworks, which might contribute to increase the likelihood that sandboxes will effectively accelerate innovation.

Brunekreeft et al. (2021) proposed a framework to boost investment in digitalization and innovation, including market facilitation incentives, a digitalization budget with benefit-sharing, and experimentation budgets for innovative projects. This framework encourages projects that offer widespread benefits, driving innovation and efficiency across TSOs.

The Florence School of Regulation (FSR, 2023) proposed an incentive scheme to boost the efficiency and innovation of Europe's electricity transmission infrastructure. The scheme aims to reduce CAPEX bias by promoting total cost minimization and potentially more OPEX-intensive solutions. It suggests setting regulatory requirements and revenues based on TSOs' efficient solutions, encouraging cost-effective innovations that could lower consumer energy costs.

2.5 Innovation within TSOs

Limited research exists on TSO innovation and their changing roles in the energy sector. The 2020 World Energy Council report (WEC, 2020), co-authored with PwC, highlights the necessity for TSOs to balance stability, cost-efficiency, and innovation. It recommends better forecasting and increased engagement with societal stakeholders for managing the energy transition. TSOs are expanding scope beyond traditional boundaries by embracing new technologies and services, moving towards grid stabilization and diversification (ADL, 2018). ENTSO-E (2022) shows TSOs' R&D efforts on enhancing grid flexibility and operations, advocating for more research on storage and eco-design.

ENTSO-E's Technopedia initiative is a key resource, providing detailed information on technologies to improve Europe's electricity transmission grid (ENTSO-E, 2020b). It emphasizes the importance of "grid optimization technologies" for increasing transmission capacity and renewable energy integration, offering cost-effective ways to manage renewable variability and curtailment. WindEurope (2020) and ACER (2021) advocate for regulatory reforms to facilitate the adoption of "grid optimization technologies" in system planning. They call for a more dynamic planning process and better stakeholder cooperation, aiming to align transmission investments with the European Green Deal's objectives by promoting grid optimization and innovation.

Another innovation is the so-called “non-wires alternatives” (NWAs): low-carbon, cost-effective and easily-installed technologies and business solutions that provide valuable flexibility services to system operators and help defer and avoid traditional infrastructure upgrades (Dyson et al., 2018; Navigant, 2017). They are resilient to load growth uncertainty, avoiding stranded costs if load does not increase (IRENA, 2020a; Kirschen and Strbac, 2018). Electricity storage is a notable NWA, especially lithium-ion batteries, which provide market stability and

manage network constraints cost-effectively (Schmidt et al., 2017; Schmidt and Staffell, 2023; Kumaraswamy et al., 2020). Regulatory policies like the Clean Energy Package promote competitive markets by restricting network operators' ownership of batteries, yet TSOs are innovatively utilizing batteries, showcasing NWAs' role in energy system transformation (IRENA, 2020b).

Integrating NWAs into system planning is common in parts of the United States, particularly at the distribution level where grid operators are incentivized to utilize NWAs. This approach is less widespread in Europe (Power, 2022a) due to regulatory barriers, specifically unbundling rules mandating separation of system operation from electricity supply and generation activities (Steinbacher and Stanton, 2019). This contrasts with the US system, where vertically integrated utilities manage grid assets and have direct oversight of Distributed Energy Resources (DERs). This allows more flexibility to delay or bypass traditional grid expansion, leading to more efficient NWA utilization.

2.6 Summary

Transmission System Operators (TSOs) maintain the security and quality of the electricity system, essentially "keeping the lights on", and are pivotal for the energy transition. The role of TSOs as distinct entities responsible for network management and system operation emerged following the wave of liberalization and restructuring in electricity markets over the past thirty years. However, these changes have not resulted in a single standardized arrangement. Instead, they have led to the development of diverse models for managing electricity transmission.

Most European TSOs serve as both the owners and operators of their transmission grids, maintaining a monopoly over their respective national electricity networks. Only a few countries have chosen to separate these roles into two distinct entities. Most of their revenues come from regulated domestic activities related to electricity transmission.

Twenty challenges have been identified that TSOs are called to address. These challenges were categorized based on their time frame (short or long-term), origin (external or internal to TSOs), and domain (operational, technological, corporate affairs & stakeholder management). Out of the twenty challenges identified, six are key trends that are reshaping the entire electricity industry. These trends impact all market players, including Transmission System Operators (TSOs), presenting strategic opportunities for growth and innovation.

Being natural monopolies and highly regulated businesses, the regulatory framework under which TSOs operate affects their incentives for innovation. To date, there has been limited research on TSO innovation and their changing roles in the energy sector.

3 How European TSOs approach innovation: evidence from benchmarking analysis

3.1 Introduction

The previous chapter provided a general overview of who TSOs are, their roles, functions, and activities. It identified the challenges they face and the crucial interplay between regulation and innovation in these regulated businesses and provided an overview of the literature on innovation in the transmission industry. This chapter sheds light on how European TSOs are approaching innovation through a benchmarking analysis. I focus on benchmarking analysis as a valuable business intelligence tool for companies facing rapid transformations and significant uncertainties. This tool equips them to identify and anticipate disruptive innovations, identify emerging opportunities, compare themselves with peers, and adopt best practices to stay ahead and prepare for future changes. Initially, the analysis focuses on a sample of European TSOs and six key technologies. It also examines the regulatory frameworks of these TSOs to determine whether they impact their levels of innovativeness. The analysis is then expanded to include a broader international sample of TSOs and additional innovative technologies, omitting the examination of regulatory frameworks in this case.

This chapter is based upon the paper “A framework to evaluate how European Transmission System Operators approach innovation” (Biancardi et al., 2021). My role in this paper included the conceptualization – the development of the core idea and research questions – the choice of methodology, the analysis – data collection, elaboration, and visualization – and the writing. My co-authors provided support in supervision and writing – review and editing.

3.2 Background on Business intelligence tools for decision-making support

Rooted in military strategy and inspired by the ancient teachings of Sun Tzu, a Chinese philosopher and general, the modern concept of business intelligence focuses on the continuous monitoring of competitive trends, identification of new market opportunities, tracking of emerging technologies, and understanding the dynamics of significant business shifts.

While TSOs, as regulated monopolies, do not face the typical competitive threats present in other industries, the role of business and technology intelligence remains crucial. Indeed, business and technology intelligence is essential for informed decision-making and adapting to industry changes, particularly in identifying technology trends and disruptions to future-proof business models (AdL, 2023; Lyu et al., 2023; Bower and Christensen, 1995; Venzin and Konert, 2020).

Innovation literature highlights the critical importance of business intelligence, as disruptive innovations can create entirely new markets but also displace established players (Lyu et al., 2023; Bower and Christensen, 1995). The consequences of overlooking disruptive innovation can be severe, including loss of market share, reduced profits, and even bankruptcy. Conversely, embracing disruptive innovations offers significant opportunities for both new entrants and incumbents (Christensen, 1997; Christensen et al., 2015).

To address disruption proactively, it's vital to identify key indicators like emerging customer needs, new technologies, evolving regulations, and broader ecosystem factors. Employing tools such as ongoing industry trend monitoring, scenario planning, market research, and business intelligence is essential for this purpose, as noted by Venzin and Konert (2020). While precise future predictions are challenging, these tools help companies detect patterns and potential disruptions in advance.

Once key trends and potential disruptive innovations are identified, evaluating their potential to disrupt becomes crucial. While a universal quantitative method is lacking, certain criteria can guide this evaluation (Guo et al., 2019; Nagy et al., 2016). These include assessing whether the innovation enhances existing products or can replace them, understanding its market impact, and analyzing factors like value proposition, technological feasibility, competitive landscape, historical precedents, and testability with existing networks and prototypes (Bower and Christensen, 1995; Christensen et al., 2015). Crucially, the assessment should consider the viability of a sustainable business model and the transformational impact on the incumbent's value proposition, operations, culture, and broader societal and environmental implications.

Lyu et al. (2023) refer to this approach as "proactive discovery," emphasizing the importance of innovation teams engaging with thought leaders, experts from various fields, and employing

associative thinking to thoroughly explore the landscape of emerging technologies, ideas, or business models. A caveat to consider is that innovations appearing as simple advancements or combinations of existing technologies can have extensive impacts. As they evolve, unforeseen applications often emerge, diverging from initial expectations and challenging R&D leaders to predict the radicalness of these innovations (Lyu et al., 2023). Conversely, technologies proclaimed as revolutionary may face challenges and coexist with existing solutions for a time, as highlighted by Castelli et al. (2022). However, Adner (2023) also warns of the 'illusion of resilience,' where a slow initial substitution of old technology suddenly accelerates.

Additionally, Adner (2023) emphasizes that while businesses cannot completely avoid the risk of missing "unknown unknowns," they often fail by overlooking "unknown knowns", information that is available but not properly understood or contextualized. A proactive strategy involves anticipating significant future changes, such as a new technology or a partner's performance improving drastically while costs decrease similarly. If such changes are viewed positively, the risk of value inversion is reduced. Conversely, if they raise concerns, a closer examination becomes necessary. ADL (2023) suggests a similar technique named "nightmare competitor exercise," where teams envision a hypothetical competitor that challenges their core business and attracts their customers. This exercise encourages teams to identify this competitor's characteristics and strategize how to outperform or emulate them.

For TSOs, identifying innovations means equipping themselves with new and more effective tools to meet the challenges they face. This way, instead of risking becoming bottlenecks in the energy transition, they can truly become enablers of it. In terms of specific business intelligence tools or practices, firms might conduct "scouting missions" for innovation insights (Amit and Zott, 2020), and use tools like Gartner's Hype Cycle and ThoughtWorks Technology Radar for technology assessment, despite limitations such as broad categorizations and a vendor tech focus (Castelli et al., 2022). Additional insights from consulting firms and institutions like IEEE offer valuable perspectives but might not fully capture technological implications. Tools like the High Impact Technologies Radar and the Innovation Radar broaden the evaluation to digital innovations and startups, aiding in assessing technological impacts and innovative business models (Castelli et al., 2022; Venzin and Konert, 2020). These methodologies encourage tailored

assessments to align with firms' strategic needs and prevent economically unjustified decisions and resource wastage.

Another key business intelligence tool firms can adopt is the benchmarking analysis, used to compare companies to identify gaps and implement best practices, ensuring they stay ahead of the curve. The rest of the section will describe this tool more in details.

3.2.1 Benchmarking analysis

In the realm of business intelligence, benchmarking analysis emerges as a particularly beneficial tool for companies navigating rapidly changing industries (Lane, 2016). It enables, to glean insights from companies or sectors that have adeptly managed uncertainty, allowing them to learn from the responses of others who have faced significant disruptions. This approach helps organizations identify successful strategies and avoid potential pitfalls.

The concept of benchmarking was popularized by Xerox in 1989, which started to use it as key tool for continuous quality improvement (Purmala and Debora, 2021; Dattakuma and Jagadesh, 2014). Over time, it has evolved into a structured methodology, widely adopted across industries, consultancy, and academia for its ability to provide unique insights and drive continuous improvement in diverse areas (GBN, 2013).

Benchmarking approaches vary widely, from internal assessments within an organization to identify best practices to external comparisons with competitors or across industries, aiming to adopt superior practices (Purmala and Debora, 2021). This includes performance benchmarking, which measures a company's effectiveness against others, encompassing both competitive benchmarking with peers and functional benchmarking to identify industry-wide best practices (Bain & Company, 2018; Camp, 2006; Bogan and English, 1994). Performance benchmarking looks at financial, operational, sustainability metrics (WBA, 2023), and innovation metrics such as R&D activities, and the number of projects and initiatives (Biancardi et al., 2021; McKinsey, 2018). Additionally, "method benchmarking" focuses on business processes, while "strategic benchmarking" provides planning insights (Phan, 2023). Amit and Zott (2020) note that benchmarking, requiring minimal investment, is particularly effective in designing new business models. Moreover, in uncertain times, firms often increase benchmarking efforts, leading to a higher imitation likelihood as they engage in social comparisons with others.

When effectively implemented, benchmarking uncovers gaps between an organization and industry leaders, offering ways to bridge these gaps and leading to significant improvements (Stauffer, 2003; Reider, 2000). It can result in cost and time savings, increased efficiency, adaptation to industry changes, competitive advantage, enhanced learning, and improved sustainability (Tasdemir et al., 2019; Lane, 2016; CC, 2014). Another key benefit for companies using benchmarking is that through it, their organizations are exposed to innovative approaches and practices and this may favour the development of a culture of innovation. It also aids in evaluating successes and failures, assisting decision-makers in resource allocation (Boxwell, 1994). However, it's essential for benchmarkers to consider their own organizational culture and circumstances when applying best practices from others, as success factors vary among industries. Without this careful consideration, benchmarking efforts can be counterproductive (ADL, 2023; Stauffer, 2003;).

The methodology for conducting such analysis involves a series of well-defined steps. It begins by selecting a specific dimension for benchmarking, like costs, product quality, efficiency, innovativeness, sustainability, or business models. Next, key performance metrics relevant to the chosen dimension are identified, such as revenue per employee or R&D spending. Following this, appropriate companies or internal areas for benchmarking are chosen. Data collection encompasses performance and practices through methods like desktop research, questionnaires, interviews, roundtables, and workshops (GBN, 2013). Once the data is collected, it is analyzed to identify areas for improvement. The final steps involve adapting and implementing best practices, setting achievable goals, and ensuring company-wide acceptance. Despite this structured approach, benchmarking faces challenges, including data comparability, selecting suitable benchmarking partners, resource constraints, confidentiality, cost-benefit considerations, and the time required to establish and maintain benchmarking processes (Dattakuma and Jagadesh, 2014).

Focusing on innovation, benchmarking is used at global level to compare innovativeness of countries and economies (WIPO, 2023; Schaible and Born, 2023). At company level, instead, many consulting companies have proposed use of benchmarking to compare organizations across different areas and domains (ADL, 2023; BCG, 2023; F&S, 2023; PwC, 2017). For instance, Boston Consulting Group (BCG) offers the 'innovation to impact (i2i)' benchmarking tool, allowing companies to assess their innovation strengths and weaknesses, shaping a

customized innovation strategy. Designed for self-assessment, it measures strengths across ten critical innovation factors, encompassing governance, talent, innovation culture, targets, and ambitions. With access to a benchmark database of nearly 1,200 companies, including industry leaders, BCG's tool provides a comprehensive approach to enhancing innovation capabilities (BCG, 2023).

Similarly, Frost & Sullivan's Frost Radar™ is an advanced analytical tool that evaluates companies in two dimensions: continuous innovation and the ability to translate innovation into sustained growth. It assesses innovation scalability across global markets and industries, examines the effectiveness of research and development strategies, analyzes the revenue contribution from new products, and evaluates alignment with emerging trends, new business models and customer needs. This comprehensive assessment aids companies in enriching their innovation pipeline (F&S, 2023).

Copenhagen Business School (CBS) has introduced an Innovation Benchmark tool tailored for small and medium-sized production companies. This tool assesses innovation levels in production, process efficiency, organizational decision-making, and marketing strategies. Early findings suggest a discrepancy between companies' self-perceived innovation efforts and actual results, highlighting the need for a more accurate assessment of their innovative capabilities (CBS, 2022).

In the electricity transmission industry, benchmarking is a common practice, yet not without its complexities and limitations (Da Silva et al, 2019). Notable initiatives include the Pan-European Cost-Efficiency Electricity and Gas Transmission System Operators Project by the Council of European Energy Regulators (CEER), which assessed 46 TSOs from 16 European countries (CEER, 2023, 2019b). In Germany, the Bundesnetzagentur conducted a study in 2018 for TSOs' efficiency benchmarking as part of its revenue cap determination process for TSOs (Bundesnetzagentur, 2018). Additionally, GT (2023) offers a recent comprehensive analysis of 212 transmission system operators across all continents, including trends in network growth, operational and financial performance, transmission losses, power interruption metrics (i.e. T-SAIFI and T-SAIDI), revenue, profit margins, and capital spending from 2017 to 2021, with projections to 2027.

To date, however, no studies focused on benchmarking innovation across Transmission System Operators (TSOs).

In regulated industries, such as monopoly situations like TSOs, there may be skepticism about the relevance of benchmarking (Fried, 2017). However, when legal and regulatory teams observe peer organizations innovating within the same industry, it often encourages them to follow suit, leading to a "safety in numbers" approach. Sharing peer innovation strategies internally can effectively build a case for innovation, addressing concerns about being industry pioneers in uncharted territories (Fried, 2017).

3.3 Methodology

The benchmarking analysis on how TSOs approach innovation was conducted in two phases. The first phase, conducted in 2020, focused on a select group of European TSOs and a limited number of technologies. This was intended as a scoping study, to demonstrate the feasibility and usefulness of the approach. Six key technologies were selected and analyzed the projects, and initiatives undertaken by each TSO in these areas. Additionally, the regulations in each TSO's country were examined to determine whether national regulatory schemes are favorable, neutral, or unfavorable towards innovation.

The second phase of this study was conducted later in 2023. It expanded the sample to include 61 European and international TSOs, and to analyze eleven additional, particularly innovative, and potentially disruptive technologies. To avoid overlap with the first phase, a choice was made not analyze the regulations or their impact on the innovativeness of TSOs, instead concentrating solely on the analysis of their initiatives.

3.3.1 Benchmarking European TSOs on six key technologies

This study was conducted in three stages. First, 12 TSOs in Europe were identified with the aim of obtaining a representative sample of the diversity across European TSOs, and the geographical and technological challenges that they face. Secondly, the regulations in each TSO's country were analyzed and their reference to innovation and related concepts, to determine whether national regulatory schemes are favourable, neutral or not favourable

towards innovation. Finally, a conceptual framework was created for evaluating the innovativeness of TSOs, based on four steps:

1. select key technologies to analyze;
2. assess the investments and projects undertaken by each TSOs in those technologies;
3. identify different approaches of European TSOs towards business model innovation;
4. assign an innovation score to each TSO in each technological area and rank TSOs by the resulting scores.

Figure 5 provides a graphical summary of the study design.

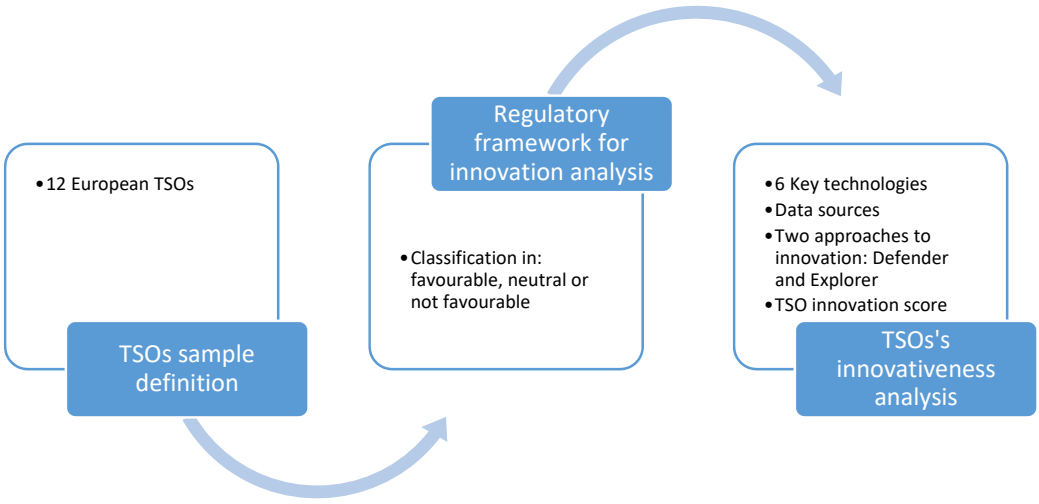


Figure 5 The methodology used and the main steps of the analysis.

3.3.1.1 TSOs sample definition

This study focuses on 12 TSOs which operate 340,000 kilometers of electricity transmission grid across Europe, which are shown in Figure 6. The peer sample was selected based on the size of TSO, the transparency and availability of data, and to maximize the diversity of the countries in which they operate. The latter considered characteristics such as: TSO ownership, regulatory scheme, geography, major sources of energy in the electricity mix (e.g. nuclear or coal), penetration of renewables, penetration of electric vehicles, etc.

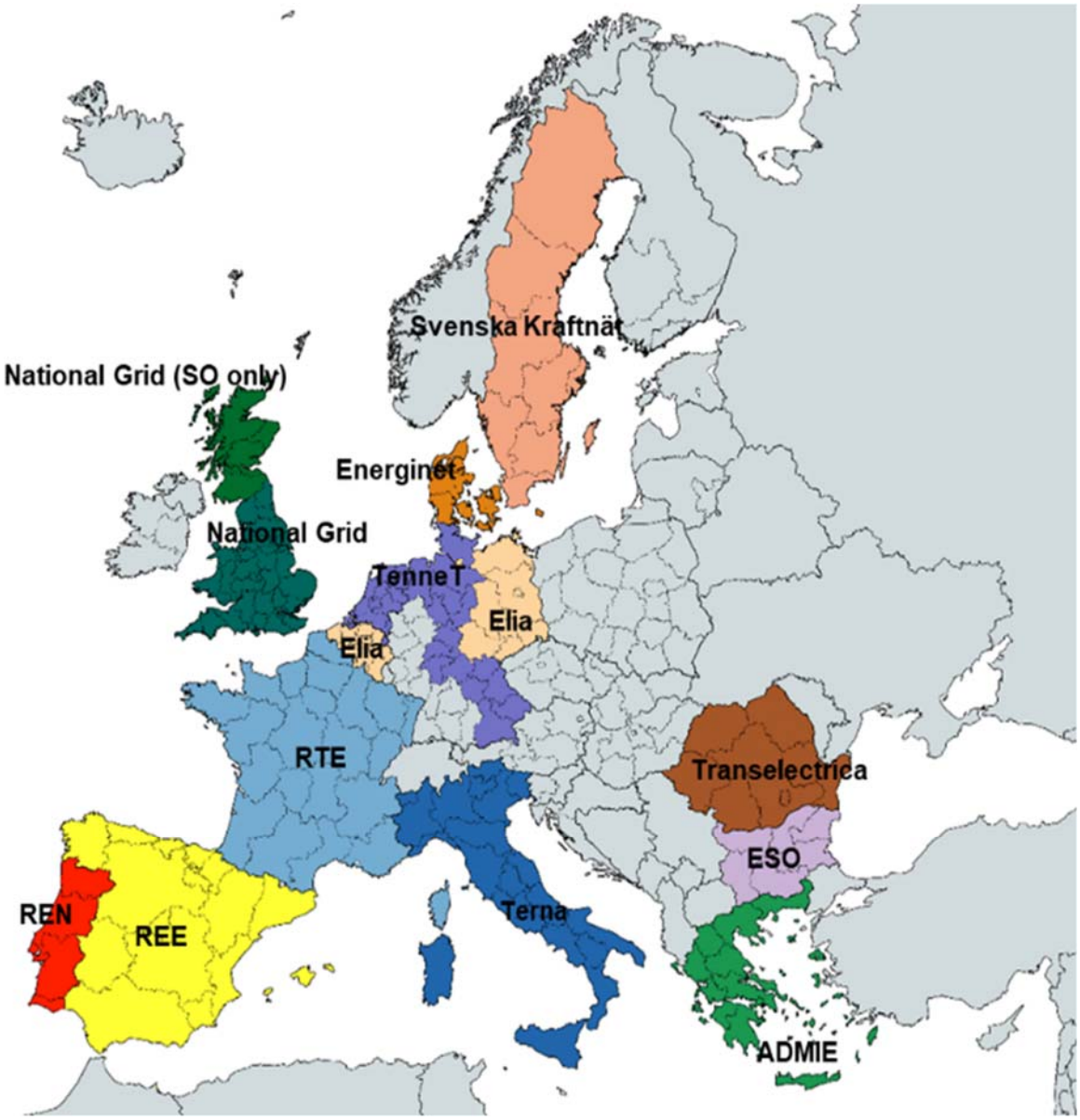


Figure 6 The TSOs covered in the first phase of the study

Table 3 provides general statistics on TSOs' region and scale, share of variable renewables in the electricity mix of their respective country and their annual revenues.

Table 3 The TSOs covered in this study, with general statistics on their region and scale, share of wind and solar in the electricity generation mix and annual revenues

European TSO	Respective country	Transmission grid length (km) in 2018	% of generation from solar and wind in 2015-2019[7]	Firm Total revenues (Million EUR) in 2018	% Revenues from electricity transmission in 2018	Revenues from electricity transmission (EUR/km) in 2018
RTE	France	105,857	6.5%	4,817	98.8%	44,942
Terna	Italy	72,900	14.2%	2,197	90.6%	27,292
Redeia	Spain	44,069	22.1%	1,949	93.0%	41,132
TenneT	Netherlands & Germany	22,862	NL: 10.8% **Mean: 17.0%** DE: 23.2%	4,176	100%	182,617
Elia	Belgium & Germany	18,990	BE: 13.4% **Mean: 18.3%** DE: 23.2%	1,932	99.3%	100,995
Svenska Kraftnät	Sweden	15,000	11.2%	838	99.4%	55,554
ESO	Bulgaria	15,000	6.0%	322	100%	21,433
ADMIE	Greece	11,500	19.7%	249	89.3%	19,363
National Grid	Great Britain	9,490[8]	18.9%	17,472	22.3%	519,641
REN	Portugal	8,907	26.0%	689	63.0%	76,038
Transelectrica	Romania	8,834	13.9%	572	100%	64,793
Energinet	Denmark	6,930	54.7%	1,744	83.9%	245,368

3.3.1.2 Regulatory framework analysis

The regulations in each country were analyzed and their reference to innovation and related concepts, using European Commission (2019a) as the primary source. From this, the relationship between regulation and effective TSO innovativeness was analyzed. The thesis is that regulatory schemes which are more favourable towards innovation will yield TSOs with more active approach to innovation, thus raising the number of innovative activities undertaken by the TSO.

[7] Data taken from International Energy Agency – Country report

[8] This figure includes only the electricity transmission network owned in England and Wales. Indeed, Transmission system operation (the SO) and transmission ownership (the TO) roles are separated in the UK and in particular, there are three Transmission Owners (TOs), in the GB onshore electricity framework: National Grid in England and Wales; ScottishPower Energy Networks in Central Scotland and Scottish Hydro Electricity Transmission in the North of Scotland.

The focus is exclusively on regulatory provisions for innovation of electricity Transmission System Operators. National regulatory frameworks were then classified for innovation between "favourable", "neutral" or "not favourable" based on a qualitative assessment of the legislative provisions in place. The main criteria for deciding a framework's classification were: the explicit reference to innovation in the regulatory framework, the presence of regulatory provisions or incentives for innovative projects and activities, the presence of specific statutory duties/mandate for TSO on innovative activities. For instance, the Belgian regulatory framework which makes explicit reference to innovation has been classified as favourable because it includes premiums on the cost of capital when it relates to innovation. On the contrary, the Portuguese regulatory framework has been classified as not favourable as it does not make any explicit reference to innovation and tend to prioritize cost saving initiatives, thus deterring TSOs so invest in costly and risky innovative activities.

3.3.2 A conceptual framework for analyzing TSOs business model innovation

This chapter proposes a conceptual framework for analyzing European electricity TSOs business model innovation using a four-steps process.

3.3.2.1 Step 1: Technological scope definition

The investments by European TSOs were analyzed for six key technologies, which are characterized by different maturity and are significant interest across Europe. The technologies are: Offshore wind, Power-to-Hydrogen, Interconnectors, Electric Vehicles, Storage batteries and Blockchain. Many other technologies are gaining attention and could also play a role for TSO innovation, not least power-to-heat, dynamic line ratings, flexible alternating current transmission systems, ultra-high voltage current transmission and advanced renewable generation forecasting methods. These were not included as they have yet to make such a significant mark on the industry, and thus less information was available on them.

These technologies are arguably bringing about the greatest opportunities and challenges for network operators either directly or indirectly, and are also a major element of innovation and differentiation among them. Indeed, some of them represent 'grey areas' where regulation has not yet fully clarified what are the prerogatives, if any, of TSOs or where regulatory approach differs from country to country (Meeus and Glachant, 2018). For example, the construction of

electric vehicle charging infrastructure or grid-level battery storage represent a “litigation area” between TSOs, DSOs and private market players. Similarly, the ownership and operation of offshore wind farms connection assets has become a field of regulatory innovation.

Offshore wind has become a key technology for reaching decarbonization goals, especially for Northwest European countries. The connection of large offshore wind farms clearly represents a huge opportunity to expand the Regulated Asset Base (RAB) of TSOs operating in countries with high offshore wind potential unless regulatory frameworks prevent them to own the assets (e.g. in the UK).

Power-to-Hydrogen (P2H) is the process of producing hydrogen from electrolysis, splitting water into hydrogen and oxygen using electricity. Using excess electricity to produce green hydrogen represents a way to manage the variation in power supply from variable renewable generators, avoiding curtailment. Hence, P2H could help accommodate a greater share of intermittent renewables into the electricity generation mix, and provide grid balancing services and long-term storage (Irena, 2019b; Staffell et al., 2019).

Interconnectors are an important source of revenues for TSOs, as the interconnection asset is often part of their RAB (Huang and Van Hertem, 2018). Here the focus is in particular on cross-border interconnectors as the play a central role for the transition towards a smarter, secure and greener European energy system. For instance, increasing the transfer capacity between countries would allow to share variable resources with complementary characteristics (e.g. wind in the North with solar production in the South) by leveraging different weather patterns (Grams et al., 2017). Besides being a source of flexibility to the system, interconnectors strengthen the security of energy supplies by providing system operators the critical tools they need to balance rapid changes in supply and demand. Furthermore, cross-border interconnectors assume a relevant geopolitical relevance as we move towards a more electrified system. For instance, existing proposals for developing regional electricity grids and renewables in the North Sea may play a central role for the UK to engage with the EU after Brexit.

Electric vehicle uptake has increased rapidly, and Bloomberg New Energy Finance (BNEF) has forecasted the share of EV sales in Europe could rise to 67% by 2040 (BNEF, 2017). Increasing demand for electric vehicles (EVs) besides being a potential source of stress for the grid also

create opportunities for system operators to derive value from an increasing number of behind-the-meter batteries. In particular, vehicle to grid (V2G) technology could allow for the smart charging and discharging of the vehicle's battery, by enabling energy stored in electric vehicles to be fed back into the national electricity network at times of peak demand, and withdrawing electricity at time of excess generation, especially from intermittent renewables.

Battery storage costs have fallen significantly (Schmidt et al., 2017), prompted by and further favouring the interest amongst consumers, network operators and policy-makers. Storage will have important roles to play for the power system, improving the utilization of renewables, reducing curtailment, and offering a wide range of services for the grid (from regulating system frequency, to dealing with inter-seasonal balancing) (RMI, 2018). Most storage applications lie at the distribution level or behind the meter (Gardiner et al., 2020); however, some private market players and also some TSOs are increasingly investigating the possibility to use electrochemical storage for grid services.

Blockchain technology is among the issues with the highest potential impact and uncertainty for the energy sector, according to the World Energy Council (2018). The characteristics of Blockchain make it particularly adapted to cope with the increasing decentralization of the electricity system, and may also accelerate this trend. Experts also believe blockchain may have a huge impact on grid management and the role and activities of network operators, in particular by reducing the complexity of network operations and of balancing supply and demand, by using smart contracts to signal to the system when to initiate specific transactions (Irena, 2019c).

3.3.2.2 Step 2: Data sources

Data on TSOs projects and initiatives in the six technological areas were collected from reviewing company reports and public information (i.e. media press, the strategic development plans and other institutional documents). These were supplemented with governmental and industrial reports and other grey literature (where available), to identify technology solutions that are being developed by European TSOs.

The 'snowballing' literature search technique[9] (Davies and Hughes, 2014; Wohlin, 2014) was applied, beginning with ENTSO-E (2019b, 2019c), Irena (2019b), Andoni et al., (2019), EASE (2020), ENTSO-G (2019), European Union (2020) and the 4C Offshore (2020a; 2020b).

More than 190 projects and research initiatives were identified related to the six aforementioned technologies carried out from 2016 to the first months of 2020. Projects and initiatives were only considered if directly carried out by the TSOs or where TSOs have a key operating role or act as main financial sponsors. Specifically, for interconnections, projects were excluded that were already completed and in operation before 2016.

A score from 0 to 3 was attributed to each TSOs and each technological area, based on the number of projects being undertaken and their technological readiness (e.g. pre-pilot). For instance, if a TSOs has already completed at least one demonstration projects on Blockchain it will be scored 3 out of 3 in that technology. Similarly, if there is no reference of investments in Power-to-Hydrogen projects, the TSO will be scored 0 out of 3.

The scoring criteria is outlined in Table 4:

Table 4 Innovation scoring criteria for the six technologies considered in this study

Score	Label	Interconnectors (62 projects)	Offshore Wind (66 projects)	Power-to-hydrogen (16 projects)	Storage batteries (15 projects)	Electric Vehicles (19 projects)	Blockchain (12 projects)
0	**Laggard**	No activity/no information available					
1	**Beginner**	At least one proposal for future collaboration or concrete project or other initiatives					
2	**Expert**	More than one in advanced phase of realization but low interconnection level	At least one connected	Pre-pilot			
3	**Leader**	More than one in advanced phase of realization and high existing interconnection level	At least one connected and other in pipeline	Projects started (e.g. pilot project) or completed			

[9] The snowball method finds literature by using some key documents as a starting point. Additional sources are found through the analysis of the text and citations, the bibliography and/or the appendices, and then finding out other sources analysing these new publications and/or information (Wohlin, 2014).

3.3.2.3 Step 3: TSO categorization

European Transmission System Operators' approach to business model innovation was categorized considering innovation as a way to defend and conserve the status quo or to disrupt and seize new opportunities. Accordingly, two different approaches are identified for European TSOs towards business model innovation: *(i) "Defender" and (ii) "Explorer".* Table 5 summarizes which of the two business model innovation approaches may be evidenced by the technologies investigated in this study.

Table 5: European TSOs business model innovation approaches and specific activities

TSO Defender approach	TSO Explorer approach
(i) focusing on the integration of large renewable power plants (notably offshore wind farms); (ii) investing in power-to-X technologies (notably Power-to-Hydrogen) and strengthen the collaboration with gas TSOs (i.e. sector coupling) (iii) investing in grid assets for increasing cross-border flows of power between EU countries (i.e. expanding interconnections);	(i) investing in electric vehicles (ii) investing in storage batteries (iii) investing in blockchain technology

The first approach is characterized by low impact on the TSO's current way of doing business. Within this approach, companies do not employ any radical change but rather capitalize on their expertise to unlock new advantages, or improve the way existing activities are performed. Actions and activities encompassed by this approach reinforce the centrality of TSOs in the energy system.

The second approach, is instead characterized by a higher impact on TSO's business models. This approach encompasses investments in technologies which present higher potential at distribution level or constitute a potential area of conflict with other market players. While some of these technologies and business solutions are unlikely to substitute for transmission investments needed to access remote renewable resources or to increase transfer capacity

between countries, they are likely to defer, reduce or even eliminate the need for some transmission investments (Jimison and White, 2013). For example, the deployment of electricity storage technologies which allow an increasing amount of generation to be located closer to load, potentially reduce or avoid costly infrastructure upgrades (BNEF, 2021). Indeed, storage batteries represent one of the main non-wire alternatives, referring to those technological solutions that are substitute for upgrades to the transmission infrastructure (e.g. construction of new lines). Should this technology prove to be reliable they will likely play a central role in the coming years since a significant amount of European transmission assets is ageing and has to be replaced and also to reduce transmission congestion costs and renewable curtailments. Intuitively, if the regulatory framework is biased towards CAPEX, network companies might be reluctant to invest in these technologies (European Commission, 2019b; Poudineh et al., 2020), although the economic trade-off between the cost of storage batteries and the cost of building new transmission capacity is yet to be properly assessed.

To some extent, these two approaches also embody two possible views of the electricity system of the future: centralized versus decentralized. On the one hand, long-distance connections of offshore wind farm, cross-border interconnections and power-to-X technologies (e.g. for the production of green hydrogen) would allow distant renewable energy sources to be exploited, and give TSOs a central role to play as the pillars of a single European interconnected energy system. On the other hand, and this is perhaps the most common view nowadays, energy storage, electric vehicles, digital technologies and blockchain could pave the way for a more decentralized electricity system, reducing the need for long distance transmission lines and interconnections across borders.

Finally, one might argue that some of these technologies are characterized by a higher risk as they are still at an early stage of development (e.g. power-to-hydrogen and blockchain) while others are more well established and mature (e.g. interconnectors). This matters as projects at different stage of innovation (e.g. pre-pilot vs mature) are intrinsically characterized by a different level of risk. Despite these aspects, it was chosen not to assess the different risk related to each project/technology and the overall risk of each approach for two reasons. Firstly, this ensured that projects at different stage of implementation and technologies with different technology readiness levels fall under both defender and explorer approaches. For example, defender has both power-to-hydrogen (early stage) and interconnectors (very mature).

Secondly, the two approaches were not intended to measure a different level of risks for the TSO but rather a different impact on the business model which not necessarily implies a higher risk.

3.3.2.4 Step 4: TSO business model innovation scoring

The tendency towards either Defender and Explorer approach was calculated by summing up the scores of each TSOs in each relative technological area.

Table 6 Business model innovation approaches scoring criteria

Defender Approach Score	Explorer Approach Score
Offshore Wind Score + Power-to-Hydrogen Score + Interconnectors Score	Electric Vehicles Score + Storage batteries Score + Blockchain Score

Finally, the scores of each TSOs in each business model innovation approach were summed up and used to rank them from the highest to the lower, by using the following formula:

$$\boldsymbol{TSO\ overall\ innovation\ score} =$$

$$\boldsymbol{Defender\ Approach\ Score} + \boldsymbol{Explorer\ Approach\ Score}$$

3.3.3 Benchmarking International TSOs on additional eleven key technologies

The goal of this second phase is to assess the TSOs performance in terms of innovative projects and initiative being undertaken across eleven key technologies.

3.3.3.1 Geographical scope definition

This study focuses on 61 TSOs across Europe, America and Asia, as shown in Figure 7. The peer sample was selected based on the same criteria listed in section 3.3.1.1

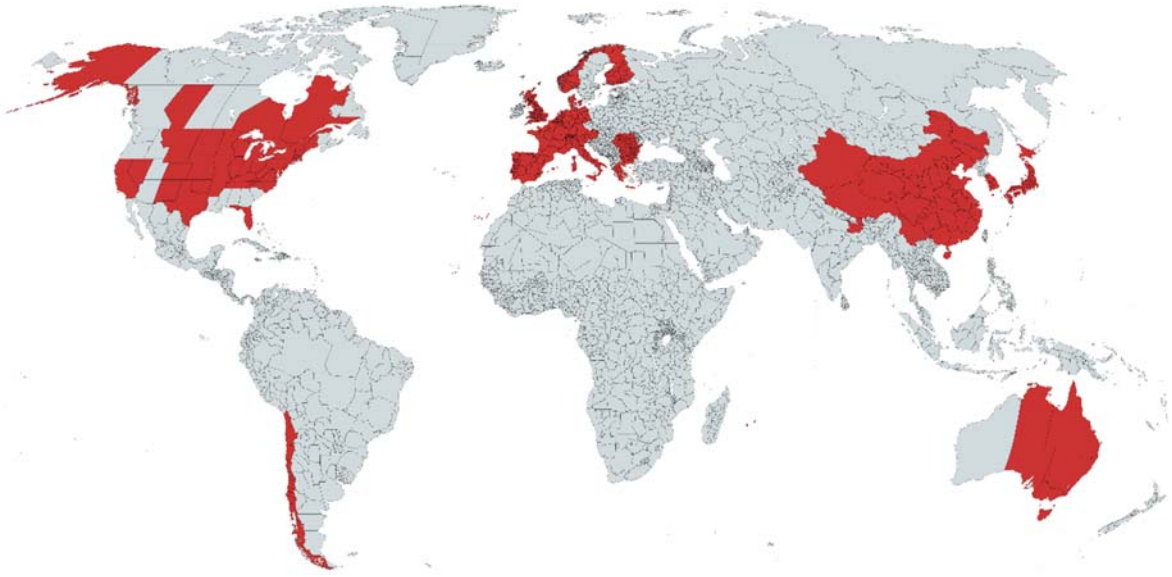


Figure 7 The TSOs' geographical areas covered in the second phase of the study

3.3.3.2 Technology scope definition

The focus was on technologies with lower maturity in TSO business operations but with high potential for disruption. The choice was also driven by the desire to include lesser-known or underrepresented technologies in literature that could be of interest to TSOs. In other words, the aim was to analyze forward-looking technologies to ensure the study's findings remain relevant and valuable for as long as possible into the future.

Table 7 list the technologies and applications selected for the next phases of the radar analysis whereas the rest of the section will briefly describe each of them.

Table 7 The technologies and applications selected for the next phases of the radar analysis

Energy/Grid domain		Digital domain
• SF6 alternatives		• 5G
• HVDC technologies		• Robots
• Vehicle-to-Grid (V2G)	NWA	• Drones
• Dynamic Line Ratings (DLR)	NWA	• Artificial Intelligence (AI)
• Microgrids & energy communities	NWA	• 6G
• Wireless electricity	NWA	

Before exploring each specific technology, it is important to note that in the literature, V2G, DLR, Microgrids & Energy Communities, and Wireless Electricity are often classified as Non-Wire Alternatives (NWAs). These are innovative solutions offering alternatives to traditional electrical grid upgrades.

Energy/Grid - SF6 alternatives:

Sulfur hexafluoride (SF6) is extensively used in the electricity grid as an insulating and arc quenching gas in high-voltage equipment. However, due to its high global warming potential, stricter regulations are driving the search for alternatives, particularly in Europe which aim to phase out fluorinated gases (f-gases) like SF6. Alternatives being explored include vacuum technology and gases like fluoronitriles and fluoroketones, which have a significantly lower environmental impact. These innovations are gaining momentum as they promise similar performance with a reduced environmental footprint.

Energy/Grid - HVDC technology:

High Voltage Direct Current (HVDC) and Ultrahigh-Voltage Direct Current (UHVDC) technologies are key in modern power systems for efficient, long-distance electricity transmission. Ideal for subsea transmission and interconnecting asynchronous grids, HVDC facilitates the creation of "super grids" for wide-scale electricity transmission. Integrating HVDC lines into AC/DC meshed grids enhances power system capacity and stability, improving control over power flows and grid reliability. This technology is crucial for advancing towards a low-carbon future, with applications including converting existing AC lines to DC for increased capacity and implementing DC mini-grids for greater efficiency. HVDC switchgears and circuit breakers are key components in HVDC transmission, with switchgears controlling and protecting equipment, and circuit breakers interrupting HVDC currents, a technically challenging task. Essential for HVDC system stability, these components are evolving with a focus on efficiency and eco-friendliness.

Energy/Grid - Vehicle-to-Grid (V2G):

Vehicle-to-Grid (V2G) technology transforms electric vehicles (EVs) from mere electricity consumers to potential grid suppliers. It allows for bi-directional energy transfer, where EV

batteries store excess grid energy during low demand and supply it back during peak times. V2G contributes to grid stabilization, load balancing, peak smoothing, integration of renewables, and provides emergency backup. It also enables the use of EVs as decentralized storage resources, reducing the need for grid investments and lowering operating costs. Essentially, V2G technology offers flexibility on the electricity demand side and holds potential as a non-wire alternative to constructing new grid infrastructure.

Energy/Grid - Dynamic Line Ratings (DLRs):

DLRs are advanced systems optimizing power line transmission capacity by accounting for real-time weather conditions and environmental factors impacting their thermal limits. Often categorized as grid optimization technologies, DLRs play a dual role.

This technology not only enhances the efficiency of existing power lines but also serve as non-wires alternatives to constructing new electricity infrastructure. This approach is particularly promising as it offers a cost-effective and environmentally friendly solution to meet increasing energy demands without the need for extensive new construction.

Energy/Grid – Microgrids & Energy Communities:

Microgrids and energy communities represent innovative approaches in modern energy systems, offering localized energy generation, distribution, and management. These systems reduce reliance on centralized grids while promoting the use of renewable energy sources. Microgrids, as self-sufficient energy networks, can operate independently or in conjunction with the main grid, while energy communities focus on collaborative energy sharing and management within a locality. Both play a crucial role in advancing sustainable energy practices and fostering community engagement in energy decisions and they can function as non-wires alternatives (NWAs), unlocking flexibility potential at the demand side and enabling the bypass of traditional grid use.

Energy/Grid - Wireless Electricity:

Wireless electricity, tracing back to the era of Hertz and Tesla, has gained renewed traction due to advancements such as wireless charging and 5G. Its potential is catalyzed by emerging sustainability needs and high-power applications (i.e. from watts to kilowatts or megawatts),

promising a realistic implementation in the foreseeable future (Etemadrezaei, 2018). For long-range high-capacity transmission, Emrod and Powerco's project in New Zealand and the Caltech's Space Based Solar Power concept, which uses solar power satellites to wirelessly transmit energy to Earth, are notable examples. Despite current inefficiencies in long-distance transmission, ongoing research and technological improvements show promise for disrupting traditional wired transmission systems. Wireless electricity is perhaps the most extreme example of non-wires alternatives, thus a potential disruptive technology for TSOs.

Digital – 5G

5G is the latest generation of cellular network technology, offering broadband access and succeeding the previous generations: 1G, 2G, 3G, and 4G. Thanks to advancements in technological maturity and improved network infrastructure, including widespread diffusion of standalone and private networks, 5G has evolved significantly over recent years. The integration of 5G technology into the electricity grid marks a significant digital innovation in the energy sector, particularly for the electricity transmission business. 5G's high-speed connectivity and low latency (i.e. the time it takes for data to travel from its source to its destination) are pivotal in enhancing grid management, enabling real-time data transmission and more efficient control of grid operations. Its potential extends to supporting advanced smart grid functionalities, such as remote monitoring, predictive maintenance, and automation of transmission systems. This technology also facilitates the integration of renewable energy sources into the grid, ensuring a more flexible and resilient energy network. As the electricity industry evolves towards a more digitized and interconnected framework, 5G stands as a crucial enabler of this transformation, promising to revolutionize the way electricity is transmitted and managed.

Digital – Robots

Industrial Robots refer to all the applications of robotics in industrial environments that involve intelligent machines capable of performing tasks without constant human intervention. These robots are equipped with advanced sensors, perception systems, and decision-making algorithms that enable them to navigate, interact, and manipulate objects within industrial settings. Robots can be pivotal in the electricity transmission industry, offering advanced

solutions for maintenance and inspection tasks. Their ability to handle complex, repetitive, and hazardous jobs enhances safety and efficiency. Robots can streamline processes like repairing power lines and monitoring grid components, reducing downtime and human error. As the industry evolves, their role in maintaining grid integrity and optimizing operations is becoming more significant.

Digital – Drones

Drones, also known as Unmanned Aerial Vehicles (UAVs), are a type of aircraft that operate without a human pilot onboard. Instead, they are either controlled remotely by a human operator or autonomously by onboard computers. Drones can vary significantly in size and complexity, ranging from small, consumer-grade quadcopters used for photography and recreation to large, military-grade UAVs. This technology may transform the electricity transmission industry by enabling efficient inspection and maintenance of grid infrastructure. For instance, drones aerial capabilities allow for rapid, detailed surveying of power lines and towers, identifying potential issues with precision and safety. This technology reduces the need for manual inspections, leading to significant cost and time savings. As the industry progresses, drones are becoming essential tools for ensuring grid reliability and operational efficiency.

Digital – Artificial Intelligence (AI)

Artificial Intelligence (AI) is a branch of Computer Science that studies intelligent agents, which are computer systems perceiving their environment and taking actions to achieve goals. Currently, this goal is largely pursued through “machine learning” approach, an inductive approach that trains models based on different types on data (e.g., images, natural language, time series). Given the escalating technical maturity, extensive knowledge in the field, accumulated investments, and market momentum, AI is undeniably the digital trend of these years. While challenges in data quality, management, and security pose hurdles to its full implementation, AI's proven effectiveness across various applications is undeniable. Artificial Intelligence may revolutionize the electricity transmission sector with its ability to optimize grid operations, enhance predictive maintenance, and improve energy management. Its rapid analysis of large data sets enables efficient integration of renewables and real-time grid response.

Digital – 6G

6G (sixth-generation wireless) is the next advancement in cellular technology following 5G. 6G networks will operate at higher frequencies than 5G and offer significantly increased capacity and reduced latency. This technology promises to significantly enhance the electricity transmission industry. With faster data speeds and lower latency than its predecessor, 6G will enable more efficient real-time monitoring and management of grid networks. It's expected to support advanced applications like AI-driven analytics and autonomous grid management, paving the way for a more responsive and reliable electricity infrastructure, although its real potential is still not clear.

3.3.3.3 Data sources

Data on TSOs initiatives and projects in the eleven technological areas were collected from reviewing company reports and public information, such: integrated annual reports, eventually including innovation reports and sustainability reports, strategic development plans, media press, official websites, social media and other institutional documents. These were supplemented with governmental and industrial reports and other grey literature (where available), to identify technology solutions that are being developed by TSOs.

More than 2500 projects and initiatives were identified related to the eleven aforementioned technologies carried out from 2016 to the first half of 2023. Projects were excluded across all technologies if already completed and in operation before 2016. Projects and initiatives were only considered if directly carried out by the TSOs or where TSOs have a key operating role or act as main financial sponsors.

The dataset from this second benchmarking analysis differs from the first in scope, due to the analyses being conducted at different times. Ideally, consistent databases would have been used for both analyses, extending the initial technology analysis through to the second half of 2023 and including all TSOs from the second sample. However, this was unfeasible due to time constraints. Priority was therefore given to analyzing recent technological innovations to ensure the findings remain valid and up-to-date. This is also noted in the section on study limitations and future work (see section 6.5.3).

3.3.3.4 Scoring

Scores were assigned ranging from 0 to 3 to each TSO in each technological area based on the criteria outlined in section 3.3.2.2, with a minor modification. Instead of differentiating between pre-pilot and post-pilot phases (which corresponds to the technology readiness level), they distinguished based on the number of projects implemented. This modification was made in order to better capture which organizations are investing the most in these technologies, in terms of the number and scope of their projects and initiatives. The previous methodology might not have adequately reflected this dimension.

For example, if there is no reference of investments or projects in SF6 alternatives, the TSO will be scored 0 out of 3, whereas if it has introduced SF6 reduction goals and explicitly mentioned on its institutional channels that it aims to test SF6 alternatives the TSO will be scored 1 out of 3. If the TSOs has already completed at least one demonstration projects or tested one SF6 alternative technology on its grid, the TSO will be scored 2 out of 3, and if it has already tested or is currently piloting different SF6 alternatives available on the market from different providers, the TSO will be scored 3 out of 3.

Table 8 outlines the scoring criteria:

Table 8 Innovation scoring criteria for the eleven technologies considered in this study

Score	Label	Criterium
0	Laggard	no activity/information available
1	Beginner	first studies, goals, projects and/or initiatives
2	Expert	several studies, projects and/or other initiatives ongoing
3	Leader	currently showing outstanding leadership (e.g. being the pioneer or the first one among TSOs to adopt it, high number of projects concluded and/or ongoing, innovation)

3.4 Results: Transmission System Operators innovativeness

3.4.1 European TSOs innovativeness across six key technologies

Figure 8 shows the results of the analysis conducted on the six technologies selected. The following sub-sections discuss the main findings for each technology.

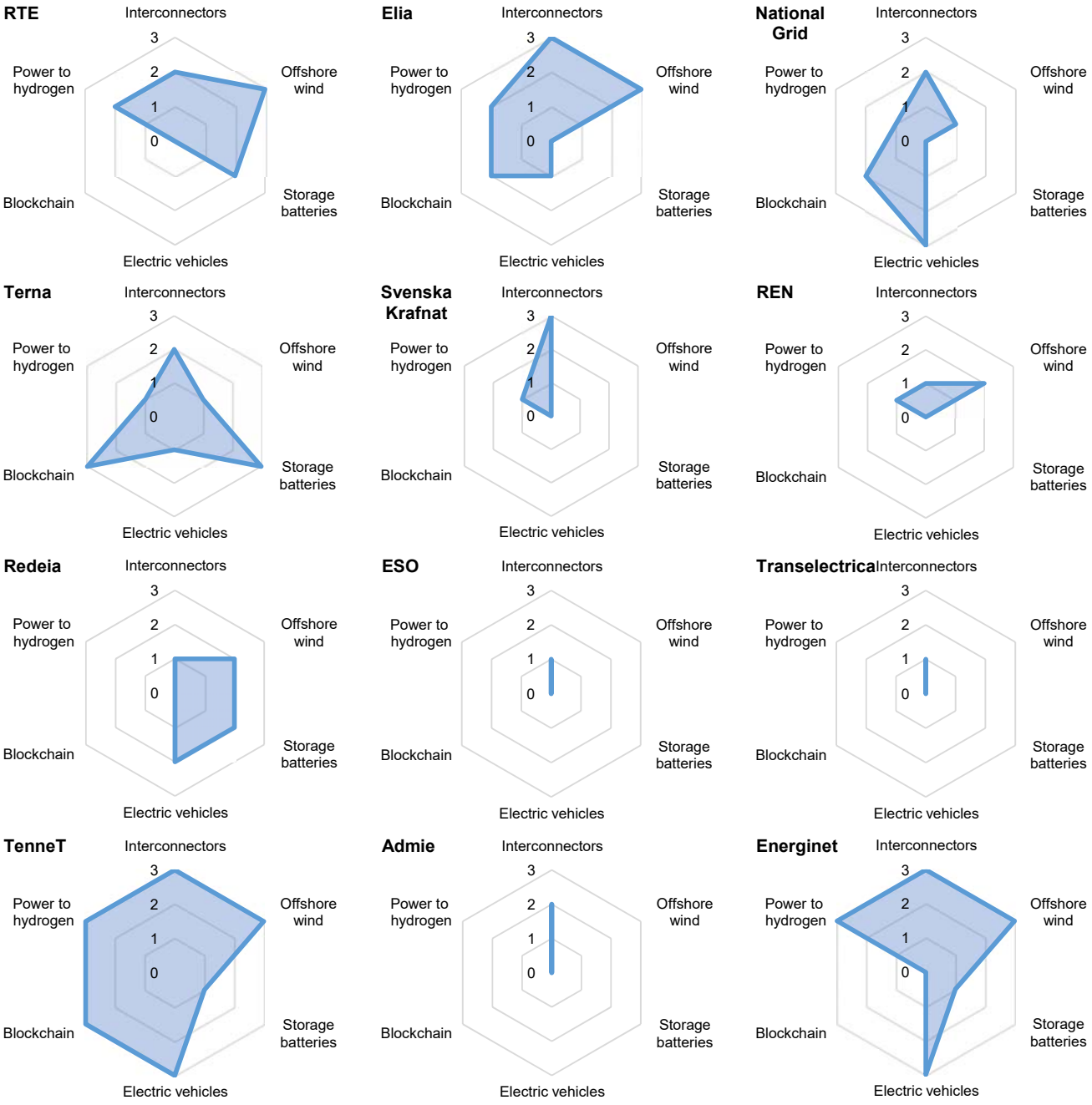


Figure 8 Innovation Map for European TSOs, showing their level of engagement with six key technologies on a scale of 0-3 as defined in Table 4.

3.4.1.1 Offshore wind farms

Although building large amounts of offshore wind will require a coordinated approach towards offshore grid developments, two different models can be identified in Europe at present (Jansen et al., 2020; Navigant, 2019). First is the "TSO Build" model, where TSOs are given the responsibility to develop and operate offshore electricity transmission infrastructure. This model has been adopted by Belgium, Denmark, France, Germany and the Netherlands. In this case the connecting infrastructure becomes part of the RAB, representing a source of revenues for the TSO. The second model is "Developer Build", where commercial parties develop and operate the offshore transmission assets, which is adopted in the UK.

A low score in this category can be the result of different factors. Some TSOs operate in countries with no or very low offshore wind potential (i.e. ESO (Bulgaria), Transelectrica (Romania)). Also, a low score was attributed to the Greek TSO ADMIE, which despite country 's large offshore wind potential, it has not been able so far to develop this business opportunity because most islands lack medium and high voltage grids. This makes it uneconomical to find locations for developing offshore wind farm in a long distance from the mainland. Sweden has only recently started to explore the options to boosting further deployment of offshore wind by relieving offshore wind farms developers of grid-connection costs.

The high scores attributed to TenneT, Elia and Energinet are either the consequence of high offshore wind potential and incentive regulation for offshore wind farm connection. In particular, the high score of Energinet reflects the fact that Denmark was the first mover of the offshore wind industry, thus benefitting from a large portfolio of offshore wind farm interconnections (The Wind Power, 2020). The high score of TenneT and Elia results from a more favourable regulatory framework, especially in Germany. There, electricity TSOs that connect offshore wind farms to the mainland (i.e. TenneT TSO GmbH and 50Hertz Transmission GmbH which is part of Elia Group) have also to submit an offshore network development plan which spans ten to fifteen years. Similarly, the high score of French TSO RTE reflects the legal and regulatory framework aiming to speed up the development of offshore wind projects.

3.4.1.2 Power-to-Hydrogen

Some TSOs are already investigating the opportunities offered by Power-to-Hydrogen technologies. A key example is the "Elemens Eins" project led by TenneT, Gasunie Deutschland and Thyssengas which aims to develop a 100 MW power-to-gas pilot plant in Lower Saxony using electricity produced by offshore wind farms in the North Sea to produce green hydrogen (or methane) that is transported or stored in the gas grids (TenneT, 2018). The Danish TSO, Energinet is also testing how much hydrogen the gas grid is capable of handling, in a pilot with Danish Gas Technology Centre, IRD Fuel Cells. Another example is "Jupiter 1000", a demonstration project to test the production of hydrogen and synthetic methane from the surplus production of renewable electricity, and their injection into the grid, in which the French TSO RTE plays a fundamental role.

3.4.1.3 Interconnectors

In October 2014, the European Council set a target for Member States to achieve an interconnection level of 10% of their installed electricity production by 2020. This target has been extended to 15% by 2030 according with the Clean Energy Package (European Commission, 2019b). In particular, interconnections should be prioritized if any of the following three thresholds are met: *(i) The price differential exceeds an indicative threshold of €2/MWh between countries, regions or bidding zones; (ii) Nominal transmission capacity of interconnectors is < 30% of peak load; (iii) Nominal transmission capacity of interconnectors is < 30% of installed renewable generation capacity.*

Different scores attributed to interconnectors in the study reflect the different interconnection level already achieved in their countries and the current number of projects being developed or proposed to increase such interconnection level. TenneT, Elia, Svenska Krafnat and Energinet received the highest score because they are well above the 2020 interconnection target of 10% and they have other projects under evaluation or development. RTE and Terna were given a score of 2 because they have not reached the 2020 interconnection target at country-level yet, but they have several projects aimed at increasing interconnection capacity (ENTSO-E, 2019b). Redeia, Transelectrica and ESO, instead, were given a score of 1 because they are both struggling to reach their target and have very few projects in pipeline.

3.4.1.4 Electric vehicles and charging infrastructure

Some TSOs have already launched pilot projects or are evaluating initiatives also in this domain. The most advanced TSOs in this regard are TenneT, National Grid and Energinet. For instance, UK National Grid is part of a consortium led by Nissan Motor (GB), which has launched the project "e4Future" project which proposes a large-scale demonstrator of up to 1,000 battery electric vehicles (BEVs) and novel bidirectional chargers (V2G). The V2G is the technology being tested in the demonstration project "REDISPATCH V2G" which aims to prove technical ability to use TenneT's own field service fleet in addressing transmission constraints in Germany.

3.4.1.5 Storage batteries

Terna (Italy) is at the forefront of battery storage technology relative to other TSOs due to its commitment to developing new energy storage solutions that optimize system efficiency and increase system security. Terna has three storage batteries operating as of 2020, totaling 35 MW (Terna, 2020). These batteries can be used to balance variable renewable output with demand, avoiding the need to invest in new transmission capacity. Additionally, they can provide services such as primary and secondary reserves, load balancing and voltage control (NGK, 2019). Another 13 MW battery is in its pilot phase and other pilot projects are envisaged in the next years. It is worth noting that Terna's leading role in this technological area would not be possible without the approval of the National Regulatory Authority. Redeia (Spain) has recently launched the Almacena project, consisting of a battery connected to the transmission grid, and the installation of a prototype inertia flywheel in the Canary Islands (Redeia, 2020). Redeia aim to obtain expertise in building, operation and maintenance of storage technology. Also, RTE (France) launched the "RINGO" pilot project to test the use of batteries on three sites, to obviate the need to reinforce existing local lines.

3.4.1.6 Blockchain

Some European TSOs are testing blockchain technology. For example, the Belgian TSO Elia, is currently learning how to use blockchain technology to target certain processes for demand response, in particular registration, measurement and verification, and financial settlement (Irena, 2019c). Also, National Grid (UK) is working with Electron to look at how grid-edge assets can be integrated into the grid to reduce costs and carbon emissions while increasing reliability (Electron, 2020). The most innovative TSO in this field is TenneT, which has already successfully

completed two pilot projects in Germany and the Netherlands, aiming at using blockchain to procure balancing services from behind-the-meter batteries and from electric vehicle batteries respectively (TenneT, 2019b). Finally, in 2020 three TSOs – Terna (Italy), TenneT (NL) and Swissgrid (Switzerland) – teamed up with ICT company IBM and developed a crowd balancing platform based on blockchain technology which aims to access new sources of flexibility by incorporating small and distributed consumer-based resources (e.g. heat pumps, electric vehicles, water boilers, etc.) into the grid balancing process.

3.4.1.7 Business model innovation approaches and overall innovation scores

The overall score of each TSO was calculated for both "Defender" and "Explorer" approaches and the overall innovation score, both in absolute terms and as a percentage to provide a simple normalization between countries. This accounts for the fact that the offshore wind potential of some countries is very low or inexistent (e.g. if they are landlocked). The maximum attainable Defender score for affected TSOs (ESO (Bulgaria), Transelectrica (Romania)) is reduced from 18 to 15 as they cannot be expected to develop offshore wind. Table 9 illustrates the results.

The results clearly indicate that some TSOs pursue more innovative activities than others. In particular, three clusters of TSOs can be identified. The first cluster contains TSOs with the highest scores and it includes: TenneT, Elia and Energinet and Terna. As illustrated in section 4.1, all of them present a favourable regulatory framework for innovation and they are investing, to different extent, in all the six technological areas of the analysis. The second cluster is composed by TSOs with medium scores and it includes: RTE, Redeia and National Grid while the last cluster identifies the "laggards" and it includes: REN, Svenska Krafnat, ADMIE, ESO and Transelectrica.

The results also indicate that European TSOs tend to prefer the "Defender approach", receiving almost twice the score as the "Explorer approach" summed over all TSOs in absolute terms (56 vs 32). There are variations though, for example TenneT, Terna and National Grid, which show a high propensity to invest in activities which fall under the "explorer approach", in particular in electric vehicles and blockchain.

Table 9 European TSOs innovation scores adjusted based on their effective offshore wind potential and rankings by business model innovation approach

TSO ranking by overall Score	Overall Score	**Overall Score**		TSO ranking by Defender Score	Defender Score	**Defender Score**		TSO ranking by Explorer Score	Explorer Score	**Explorer Score**
TenneT	16 / 18	**89%**		TenneT	9 / 9	**100%**		TenneT	7 / 9	**78%**
Energinet	13 / 18	**72%**		Energinet	9 / 9	**100%**		Terna	7 / 9	**78%**
Elia	11 / 18	**61%**		Elia	8 / 9	**89%**		National Grid	5 / 9	**56%**
Terna	11 / 18	**61%**		RTE	7 / 9	**78%**		Energinet	4 / 9	**44%**
RTE	9 / 18	**50%**		Terna	4 / 9	**44%**		Redeia	4 / 9	**44%**
National Grid	9 / 18	**50%**		National Grid	4 / 9	**44%**		Elia	3 / 9	**33%**
Redeia	7 / 18	**39%**		REN	4 / 9	**44%**		RTE	2 / 9	**22%**
REN	4 / 18	**22%**		Svenska Krafnat	4 / 9	**44%**		REN	0 / 9	**0%**
Svenska Krafnat	4 / 18	**22%**		Redeia	3 / 9	**33%**		Svenska Krafnat	0 / 9	**0%**
ADMIE	2 / 18	**11%**		ADMIE	2 / 9	**22%**		ADMIE	0 / 9	**0%**
ESO	1 / 15	**7%**		ESO	1 / 6	**17%**		ESO	0 / 9	**0%**
Transelectrica	1 / 15	**7%**		Transelectrica	1 / 6	**17%**		Transelectrica	0 / 9	**0%**

3.4.2 The impact of National regulatory frameworks for innovation of TSOs on their innovativeness

Across Europe there are substantial differences between national regulatory frameworks with respect to innovation (European Commission, 2019b). On the one hand, there are countries with few or no evidence of support to innovation, like Portugal, where “there is a great deal of pressure to keep costs down thus the regulator has to be cautious and any investment that is not absolutely required will not be approved” (European Commission, 2019b). On the other hand, there are TSOs that can be granted with specific incentives such as: premiums (i.e. additional WACC) for investments in smart grids (Italy); extra remuneration (in the form of premiums on cost of capital for risky projects) (Belgium); or additional budgets for financing smart grid projects (France). The UK with the RIIO (Revenue = Incentives + Innovation + Outputs) model, introduced by regulator Ofgem, has the most developed regulatory framework for innovation, comprising a price control review scheme that allows network companies to benefit from successful innovations and an innovation stimulus package that provides financial incentive mechanisms (including some competitive funds). These different financial incentives mechanisms partially account for the different level of risk involved at each stage of innovation as suggested in (Poudineh et al., 2020).

Table 10 shows a classification of countries by reference to innovation for Electricity Transmission System Operators, derived from (European Commission, 2019b) and (CEER, 2020).

Appendix 3, instead, offers a breakdown of the regulatory frameworks for innovation across major European countries, based on (European Commission, 2019b) and (CEER, 2020). As acknowledged in the concluding paragraph addressing the study's limitations (see section 6.5.3), future research might extend the analysis to other countries and regions.

Table 10 National regulatory frameworks for innovation of electricity TSOs breakdown, distinguishing between "favourable" and "not favourable" or "neutral" regulatory framework for innovation. Supplementary Material provides more details.

European TSO	**Respective country**	**Regulatory Framework for innovation of electricity TSOs**
RTE	France	Favourable
Terna	Italy	Favourable
Redeia	Spain	Neutral
TenneT	Netherlands & Germany	Favourable
Elia Group	Belgium & Germany	Favourable
Svenska Kraftnät	Sweden	Neutral
ESO	Bulgaria	Neutral
ADMIE	Greece	Neutral
National Grid	UK	Favourable (except for offshore wind)
REN	Portugal	Not favourable
Transelectrica	Romania	Neutral
Energinet	Denmark	Favourable

This analysis identifies two main clusters of countries: the first is characterized by a generally favourable regulatory framework for innovation, and includes France, Italy, Netherlands, Belgium, Germany, UK and Denmark. The second cluster is characterized by a neutral or not favourable framework for innovation, and includes Portugal, Spain, Sweden, Bulgaria, Greece and Romania.

A particular case in point here is the UK, which, as already mentioned, presents several clear elements in support for innovation but prevent the TSO (National Grid) to invest in offshore wind as it decided to allow third-parties (so-called Offshore Transmission Owners (OFTOs)), to

compete for the ownership and operation of offshore transmission assets, thus excluding National Grid from this business opportunity.

The correlation between regulatory frameworks for innovation and overall innovation scores was analyzed. This is aligned with the hypothesis: favourable regulatory frameworks for innovation are associated with significantly higher TSO innovation scores. TSOs with a favourable regulatory framework receive a score of 64±6%, whereas TSOs with neutral or unfavourable regimes receive a score of 18±5%. This difference is significant with a P-value < 0.001. Conversely, the size of the electricity grids has no influence on TSO's propensity to invest. There is no significant correlation between the overall adjusted score and length of transmission grid (P-value > 0.4). The defender and explorer scores (D and E) show sensitivity to the prevailing regulatory framework, with favourable or mixed yielding D = 76±11% and E = 52±9%, versus D = 30±5% and E = 7±7% for neutral or unfavourable. A correlation analysis was conducted with the other factors listed in Table 3 using OLS regression, but this found no statistically significant descriptors with $p < 0.1$.

To summarize, TSOs operating in countries with more favourable regulatory frameworks show higher innovativeness, exploring also new business opportunities, compared to other TSOs operating in countries with neutral or less favourable regulatory frameworks which, instead, tend to be rather "passive".

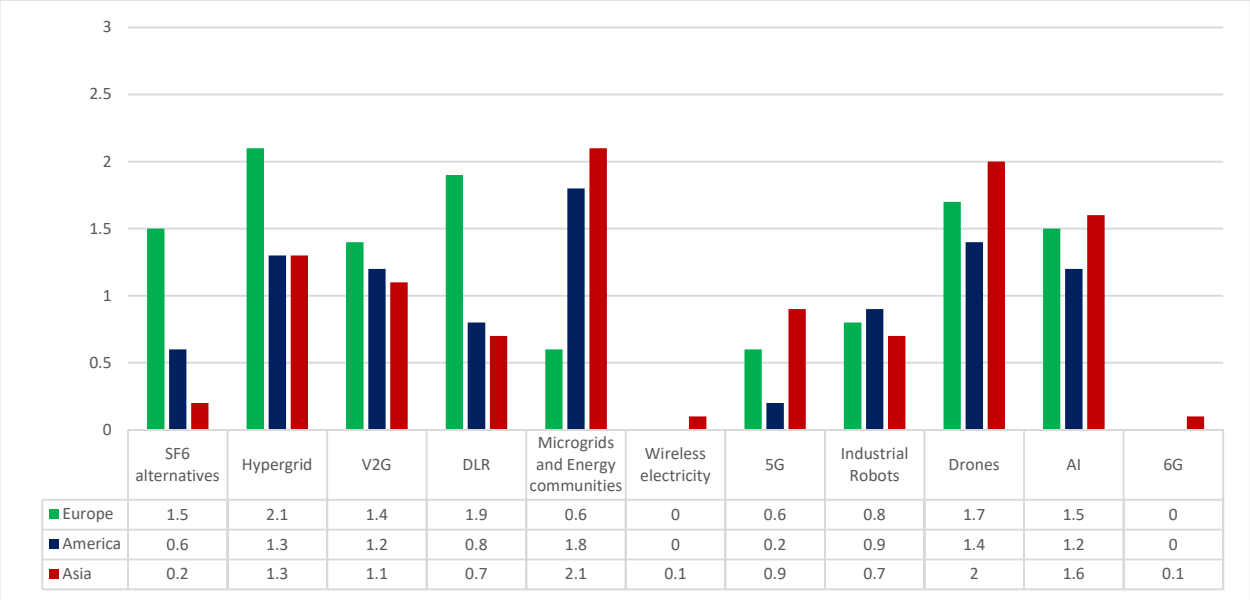
This study was intended as an initial pilot to test the feasibility of the subsequent, larger, study. It is therefore subject to limitations, such as the regression analysis being conducted on a limited sample size, and more broadly, a need to extend and deepen the analysis of the regulatory framework for innovation to include other countries and regions. These are obvious avenues to consider for future research, as discussed further in section 6.5.3 on thesis limitations and future work).

3.4.3 International TSOs innovativeness across eleven additional key technologies

3.4.3.1 Geographical TSO ranking

TSOs were ranked and grouped by geography, calculating their average scores across the eleven technologies, utilizing a scoring scale from 0 to 3 for each technology, as outlined in Table 8 (see Section 3.3.3.4). Average values were also calculated for both the energy and digital domains to highlight which geographies are more active on the digital front or on the energy/grid front. Finally, to avoid any misinterpretation of the results, 'System Operator (SO)-only' players were excluded, which constituted a significant portion of the American TSO sample.

Figure 9 displays the results of this analysis, while Appendix 5 details the scores for each TSO across the eleven technologies, differentiated by geography.



	SF6 alternatives	Hypergrid	V2G	DLR	Microgrids and Energy communities	Wireless electricity	5G	Industrial Robots	Drones	AI	6G
Europe	1.5	2.1	1.4	1.9	0.6	0	0.6	0.8	1.7	1.5	0
America	0.6	1.3	1.2	0.8	1.8	0	0.2	0.9	1.4	1.2	0
Asia	0.2	1.3	1.1	0.7	2.1	0.1	0.9	0.7	2	1.6	0.1

Figure 9 TSOs' average score for each technology on a scale 0-3, grouped by geographical origin of TSO. US excludes System Operator-only.

When comparing results across different geographic areas, European TSOs outperform their American counterparts in both energy/grid and digital domains. However, in comparison with

Asian TSOs, European TSOs perform better in the energy/grid domain technologies (on average 1.3 versus 0.9) but less well in the digital domain (0.9 versus 1.1).

Delving into the specific technology areas, European TSOs show a notably high average score in hypergrid technology (HVDC), closely followed by their use of Dynamic Line Rating. However, their engagement with SF6 alternatives truly distinguishes them, likely spurred by the European policy and regulatory framework towards adopting more eco-friendly alternatives.

European TSOs, instead, significantly lag behind their Asian and American counterparts in the area of microgrids and energy community technology. The prominent position of Asian and American TSOs in this technology area is partly due to their dual responsibility for both transmission and distribution network management. Since microgrids are often installed at the distribution level, TSOs in these regions can more readily engage in experimentation. Furthermore, in countries like the United States and Canada, unlike in Europe, the adoption of Non-Wire Alternatives (NWAs), which encompasses microgrids and energy communities, is encouraged and promoted by regulatory bodies (FERC, 2020; IESO, 2023, 2020; MK, 2020). Therefore, TSOs are motivated to incorporate NWAs into their grid planning and development strategies.

In the digital domain, American TSOs excel in their use and experimentation with robots, achieving the highest scores among the three regions. Meanwhile, Asian TSOs lead in the adoption and advancement of drones, artificial intelligence, and 5G technology.

Finally, all regions display minimal scores in wireless electricity and 6G technologies, suggesting that interest in these areas is still in its early stages.

3.4.3.2 Individual TSO ranking

TSOs were ranked by calculating their average scores across the eleven technologies, utilizing a scoring scale from 0 to 3 for each technology, as shown in Figure 10.

Among the evaluated entities, the State Grid Corporation of China (hereafter referred to as "State Grid"), one of the two Chinese Transmission System Operators (TSOs), stands out from others. China also secures the fourth place with its other TSO, China Southern Power Grid. Among the top European TSOs, Redeia takes the second place, followed by National Grid in the

third. Tied for fifth place with the same average score, there's a long list of TSOs. From Europe, this includes Terna, Statnett, Elia, and RTE. Additionally, there are two Asian TSOs in the mix: Japan's TEPCO and Korea's KEPCO. The highest-ranking American TSOs are Hydro-Québec and Con Edison, which are positioned at fifth place, on par with the previously mentioned European and Asian TSOs.

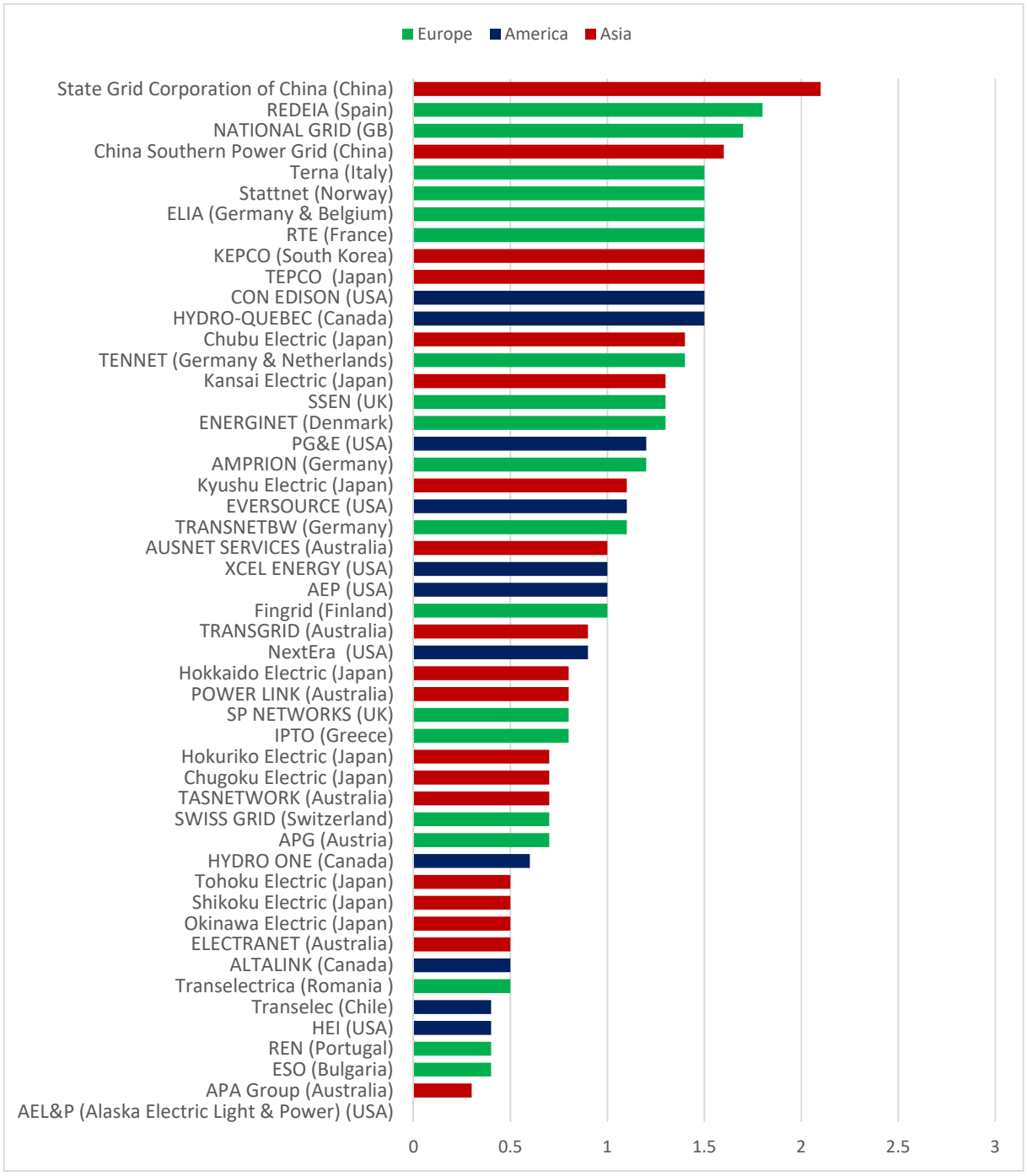


Figure 10 TSO average ranking across key technologies on a scale 0-3

3.4.3.3 Focus on the Best-Performing TSO: China's State Grid

State Grid Corporation of China (hereinafter simply "State Grid") stands out among TSOs, ranking first due to its active engagement across almost every analyzed technology.

For example, regarding the hypergrid cluster, State Grid pioneered numerous large-scale projects and installed some of the world's longest and most powerful HVDC transmission lines. Latest notable HVDC projects include: *the Baihetan-Zhejiang link,* an 8 GW, 800-kV, 2,121 km long ultra-high-voltage direct current (UHVDC) transmission line which from January 2023 transports electricity from the 16 GW Baihetan hydropower plant to Zhejiang province, making it China's second largest hydro plant after the 22.5 GW Three Gorges Dam (Enerdata, 2023); *the Baihetan-Jiangsu link:* an 8 GW, 800-kV, 2,080 km long UHVDC transmission line, operational since July 2022; *the Shanbei-Wuhan link:* an 8 GW, 800-kV, 1,100 km long HVDC transmission line whose construction began in 2019 and became operational in 2022.

State Grid also stands out in V2G technology, operating the world's largest smart charging network. As of November 2020, this network comprised over 1.03 million V2G-equipped charging stations spread across 273 cities and 29 provinces in China (EEOnline, 2021). At the World Congress on Electric Vehicles in 2021, it introduced a "supercharging cluster" system, surpassing Tesla's V3 Supercharger with up to 360 kW charging capacity and bi-directional power flow. Further, in 2022, two subsidiaries, State Grid EV Service and State Grid Hubei Electric Power, collaborated for a load aggregation system for demand response, showcasing effective electricity shortfall management. It is worth noting that State Grid's V2G success is supported by its role in managing distribution networks across China through its subsidiaries (Tycorun, 2022).

State Grid has played a leading role in adopting 5G technology within the energy sector. Notable efforts began in 2017 with a pioneering 5G electric power slicing project in collaboration with China Telecom and Huawei (Huawei, 2017). By 2019, this partnership yielded China's largest 5G smart grid project in Qingdao, featuring over 30 5G base stations to enhance grid functionality and fault detection (5GDNA, 2019). In 2020, State Grid forged strategic partnerships with tech giants like Tencent, Alibaba, Baidu, and Huawei, and developed a 5G-powered differential

protection device for distribution networks, which earned a "Best Innovative Commercial Case in 5G Automation" award (Chen, 2020).

State Grid has distinguished itself in drone and robot technologies through its subsidiary, "State Grid Intelligence Technology Co., Ltd.," which specializes in the manufacture and sale of electric intelligent robots, drones, and other technological products. In 2017, the State Grid Corporation of China, in collaboration with the UTC Training and Testing Center, set a goal to train 10,000 professional UAV power line inspectors within three years, enhancing the standard of power line inspection (UASTC, 2018). By 2018, State Grid had amassed a fleet of 2,000 UAVs, inspecting over 200,000 utility poles in the preceding two years. This expansion into drone technology also included a $3 million purchasing agreement with MMC in November 2018 for additional drones for power line inspections and other partnerships (Suas News, 2019).

In the realm of robotics, 2019 saw the deployment of a new generation of live working robots, including the Chuangxiang-2, -3, and -4 series, by the State Grid Tianjin Electric Power Company in Tianjin municipality (China Daily, 2020). These robots, equipped with AI-driven technologies like 3D environment reconstruction, visual recognition, and motion control, are designed to reduce labor intensity and improve safety. Through high-precision positioning, image and other recognition technologies, in fact, these inspection robots can complete tasks that are difficult to complete manually in various harsh natural environments, and greatly improve operating efficiency through large-scale operations.

State Grid's innovation extends to artificial intelligence (AI), with the company making significant investments in smart grid technologies that incorporate AI and 5G. Their "Ubiquitous Power Internet of Things" initiative aims to integrate the digital world with the electricity network to facilitate the development of smart cities and minimize electricity disruptions (GlobalSpec, 2019). A notable project in Urumqi demonstrated an AI system's ability to restore power within three seconds during outages, showcasing the potential for autonomous, efficient power distribution (Chen, 2022). Furthermore, State Grid's commitment to AI innovation was highlighted by its leading number of AI patent filings within the power industry in Q2 2023, demonstrating its forefront position in implementing and developing AI solutions for the power sector.

According to research conducted by Nikkei in collaboration with the Tokyo-based Cyber Creative Institute, State Grid, alongside other Chinese companies such as Huawei and China Aerospace Science and Technology, ranks among the leaders in 6G patent filings (Watanabe, 2021).

The radar chart below illustrates how State Grid performs across each selected technology on a scale from 0 to 3.

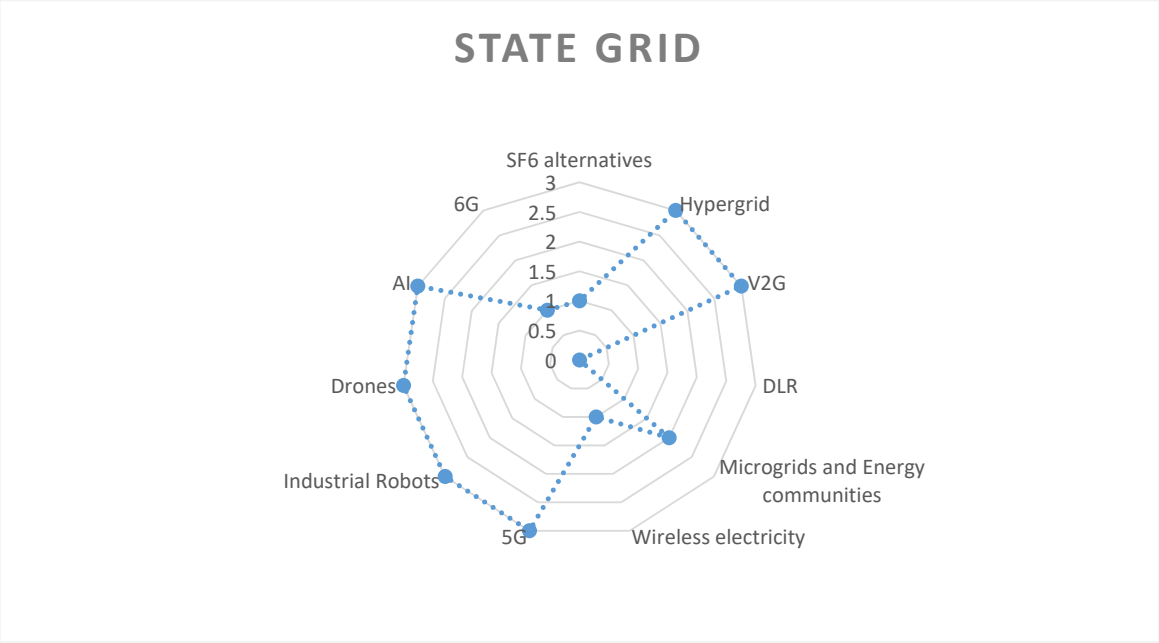


Figure 11 State Grid engagement level across the eleven technologies, on a scale 0-3 as defined in Table 8.

3.4.3.4 Best-in-Class TSOs for each Technology

For each technology, the top performers were identified, specifically the TSOs that achieved the highest score of 3 on a scale from 0 to 3. This allows executives seeking inspiration and best

practices to directly study what these leading TSOs are implementing in various technological domains.

Figure 12 shows the top TSO for each technology whereas the rest of the section provides some key insights on use cases of the technologies among these top performers:



Figure 12 Best-in-class TSOs across each technology. The figure shows only the TSOs with a score of 3, on a scale 0-3, across the eleven technologies.

SF6 alternatives:

RTE and Redeia are the only TSOs assessed that have achieved the highest score in SF6 alternative technologies. They have not only set targets for SF6 consumption reduction and emission but are also actively testing SF6 alternatives from various vendors.

For example, Redeia is targeting zero SF6 waste by 2030 and has implemented a solution that enables the partial recovery of SF6 leaked from GIS installations using absorbent materials. In 2019, it also developed a faster method for repairing SF6 leaks in GIS compartments using flexible sealing systems and clamps, which are adaptable to each leak point without needing to dismantle the GIS compartments or perform final tests. This technique can be applied to equipment from different GIS manufacturers. The company also reported the installation of

graphene-based SF6 sensors and continues to evaluate SF6 alternatives from different suppliers (Redeia, 2022). Similarly, since 2004, RTE has enforced a policy aimed at reducing SF6 gas leaks, intensifying its efforts in 2018 with a comprehensive plan to replace approximately 20 of its oldest and most leak-prone substations containing SF6. This replacement initiative is projected to cost 630 million euros over a span from 2020 to 2035. According to its 2022 annual report, then, RTE has scheduled deployment sites in the first quarter of 2023 for 100 kV circuit breakers that use alternative gases, investigating all the three primary technical solutions available on the market: fluoronitrile (e.g., GE's g3), O_2/CO_2 mixtures (e.g., Hitachi ABB's AirPlus), and vacuum technology (e.g., Siemens). Moreover, their R&D has innovated a new sealing solution, with a patent pending (as of 2022), and is preparing to industrialize its SF6 leak-sealing process, especially for high-emission substations (RTE, 2022).

Hypergrid:

Several TSOs across all the different geographies covered have scored highly in hypergrid technology, indicating widespread experimentation and adoption. Beyond the already noted Chinese TSOs, particularly the State Grid with its world-leading HVDC line installations in both length and project scale, numerous European TSOs excel in this area, driven by the EU's Green Deal goal for climate neutrality by 2050. Achieving these targets, in fact, necessitates substantial transmission network investments to harness and connect Europe's renewable potential. Specifically, direct current (DC) grids are set to be crucial in the future of Europe's grid infrastructure, both offshore and onshore.

V2G:

Among the TSOs excelling in V2G technology, Energinet, the Danish TSO, deserves special mention as one of the pioneers in experimenting with the technology, with the Edison Project in 2010. Energinet has realized several projects to date. For example, in 2016, Enel in partnership with Nuvve installed 10 V2G units at Frederiksberg Forsyning, aiding grid stability by providing capacity services. The Parker project (2016-2018) explored the capacity of EVs to deliver grid services with real fleets. This project's continuation has resulted in the world's first fully commercial V2G hub in Denmark, active since 2016 (V2G-Hub, 2023).

In the V2G domain, another significant player is TransnetBW, one of the four German TSOs, which over the past years launched initiatives and field tests with different players from the automotive industry (e.g. Porsche, BMW) or specialized players like the Dutch smart charging platform operator Jedlix. In 2021 it also initiated a joint venture with Porsche's subsidiary "MHP Management- und IT-Beratung" (IE2S, 2021). This collaboration aims to provide consultancy services leveraging extensive knowledge in automotive and manufacturing, alongside digitization, energy management, and the optimization of large infrastructure projects, including the development of smart charging solutions.

Another player that deserves a special mention in this area is Tokyo Electric Power Company (TEPCO), one of the ten Japanese TSOs and a founding member of the CHAdeMO Association. CHAdeMO, established in 2010 by TEPCO and five major Japanese automakers, is a fast-charging DC technology and the name of the organization that promotes it. Unique for its bidirectional charging capabilities, CHAdeMO is recognized as the sole charging protocol that enables V2G functionality worldwide, with a certification system ensuring compatibility across EVs and V2G devices (Chademo, 2023). It also formed strategic partnerships with entities such as Energy Impact Partners LP (EIP), a firm investing in innovative energy technologies, including AI for V2G and Microgrids (Shepard, 2017) and in 2018, TEPCO led the government-funded V2G Aggregator project to create a V2G system and charging network for electric vehicles across Japan (GCC, 2018).

Dynamic Line Rating (DLR):

Focusing on DLR, a pivotal player is undoubtedly Elia, the TSO for Belgium and part of Germany. Elia embarked on utilizing DLR technology in 2008 through a partnership with Belgian company Ampacimon, showcasing Ampacimon's product suite on its interconnectors to assess transmission lines' thermal rating through direct measurements, thereby enhancing their capacity (RGI, 2018). A landmark field test commenced on Belgium's high-voltage grid in 2008. Substantial DLR deployments occurred in 2014 across a dozen lines to boost cross-border import capabilities and again in 2017, with lines outfitted to facilitate operations. In 2019, Elia incorporated DLR into its regulatory planning, positioning it as a strategic solution for alleviating grid congestions temporarily (CurrENT Europe, 2021).

Another notable entity in the implementation of DLR is the Australian transmission company Transgrid, which began integrating the technology on some of its lines in 2014. As detailed in its latest Transmission Annual Planning Report (TAPR) 2023, Transgrid is now planning to deploy a dynamic line rating system on one of its key lines (94T) to alleviate rating constraints. The operation is budgeted at 0.5 million AUS dollars, with a targeted completion in 2024 (Transgrid, 2023). Another key project is the one being developed together with Australian company Infravision. Specifically, in 2022, the Australian Renewable Energy Agency (ARENA) granted AUS $732,493 to Infravision to pilot its line-monitoring technology on Transgrid's New South Wales (NSW) network (ARENA, 2022). The system, installable by drones, uses sensors to monitor real-time environmental conditions and line sagging, impacting capacity. These data allow a more precise assessment of transmission capacity and safe dispatch of higher electricity volumes under favorable conditions.

Microgrids & Energy Communities:

Among transmission companies active in microgrids and energy communities, Con Edison stands out with its Brooklyn-Queens Demand Management Program (BQDM), initiated in 2014 under New York's Reforming the Energy Vision (REV) initiative. This pioneering non-wires alternative (NWA) project aimed to reduce the need for utility infrastructure upgrades through energy efficiency, distributed energy resources, and demand reduction measures. Notably, the BQDM includes a comprehensive setup at Brooklyn's Marcus Garvey apartments, featuring a microgrid with a 300-kW lithium-ion battery system, 400 kW solar PV, and a 400-kW fuel cell. This approach notably avoided an estimated $1.2 billion cost of traditional utility upgrades (CHP TAP, 2014). Additionally, Brooklyn Army Terminal project, featuring solar PV, behind-the-meter battery storage, microgrid controls, and building management systems, was a finalist for the 2015 Intersolar Project of the Year Award. This project, developed by Con Edison together with NYCEDC, showcases the integration of onsite renewable energy and storage for peak energy reduction. In 2018, Con Edison researchers also received the Electric Power Research Institute's Technology Transfer Award for contributions in solar project management, cybersecurity, and microgrid operations and more recently, in 2023, Con Edison planned to implement a microgrid at the New Rochelle substation, including a 4-megawatt/12-megawatt hour storage system and electric vehicle fast chargers, further cementing its role in promoting innovative energy solutions (Con Edison, 2023).

Australian Transmission Company AusNet Services is another key player at the forefront of developing microgrids and energy communities. In 2017, in collaboration with Deakin University, AusNet and its subsidiary Mondo Power, it launched an AUS $30 million initiative to create an industrial-scale smart microgrid at Deakin's Waurn Ponds campus. This innovative project included a 7.25-megawatt smart microgrid featuring solar generation, 1 megawatt of battery storage, and a new research and visualization center (Deakin, 2017). In 2023, Mondo Power introduced the Ubi™ Energy Management Platform. Originating from a project in Yackandandah (Victoria) aimed at achieving 100% renewable energy, Ubi™ has developed into a comprehensive platform for energy visibility, control, and optimization, aiding communities and businesses in maximizing their energy assets and achieving renewable energy goals (Mondo, 2023). Furthermore, in 2023, Mondo Power embarked on a pioneering trial, commissioning 17 standalone power systems in East Gippsland (Victoria), featuring solar photovoltaic panels, battery storage, and a backup diesel generator (Carroll, 2023).

Wireless electricity:

None of the analyzed TSOs are actively engaged in wireless electricity. However, in 2021, the Chinese SSPS Research Team conducted in-depth research on accurately directing a beam of microwaves towards a target, as part of the State Grid Corporation of China's project on 'Research on Ten-Meter-Level Microwave Radio Wireless Power Transmission Technology' (Rodenbeck et al., 2021; China.org, 2021). Additionally, numerous publications on wireless electricity list authors affiliated with the China Southern Power Grid Corporation's Wireless Power Transmission Joint Laboratory, which is supported by the Opening Foundation Projects. Yet, further details are scarce.

5G:

Redeia is one of the few top performers in advancing 5G technology. In 2020, Elewit, the division of the Group dedicated to innovation and new technological and business solutions, alongside Cellnex and Lenovo, led the investment in Nearby Computing, a Barcelona Supercomputing Center and UPC spin-off specializing in Edge Computing and 5G networks, marking Elewit's first venture into the 5G sector. This investment aims to digitalize and enhance the intelligence of critical infrastructure assets (Cellnex, 2020). In 2021, the Group initiated four pilot projects in

Valencia to explore 5G's utility in electricity grid management as part of Spain's National 5G Plan (REE, 2021). These projects include using 5G for remote management and inspections with robots and drones, establishing satellite redundancy for 5G, remote monitoring of electrical facilities, and applying 5G for digital twins and wide area protection, enhancing system independence and potential decentralization. By 2022, Redeia was industrializing innovative solutions in its “Technology Factory”, including 5G Infrastructure, to leverage transmission grid infrastructure for connectivity (Redeia, 2022). Additionally, Hispasat, the division of the company dedicated to satellites communications services, acquired Axess Networks in 2022 aiming to develop solutions for markets such as 5G via satellite (Redeia, 2022). Furthermore, in 2023 Redeia launched a project to validate its electricity infrastructures as viable hosts for 5G systems, assess environmental impacts, and generate new services and business models around its assets.

Robots:

Hydro-Québec stands out in the field of robotics among TSOs, showcasing several innovative solutions. Introduced in 2010, the LineScout robot inspects live transmission lines with capabilities including high-quality visual and infrared inspections, measuring electrical resistance of splices, and performing minor repairs. It navigates around obstacles, reaching areas difficult for line workers. In 2017, Hydro-Québec's subsidiary, MIR Innovation, unveiled a device capable of placing a sensor on live power lines (Mortimer, 2017). The Linecore sensor, transported by a multirotor, assesses the condition of lines by measuring zinc layer thickness and detecting corrosion, crucial for evaluating the health and remaining service life of aluminum conductor steel reinforced (ACSR) conductors. The company's 2022 Sustainability Report highlights additional technologies, such as the RIAUPEL robotic vehicle for substation inspection or the compact LineROVer, initially designed for de-icing and that it has found broader applications in transmission line inspection and maintenance, even on energized lines. Another breakthrough is the LineRanger robot, developed by Hydro-Québec's research institute (IREQ), specifically for inspecting conductor bundles on high-voltage lines, a challenging task due to their special locomotion requirements.

Drones:

RTE, the French TSO, is a leading player in deploying drone technology for electrical grid maintenance and inspection. As an official aeronautic drone operator since 2016, RTE regularly utilizes drones for a variety of tasks including substation inspections and diagnostics, offering a nimble alternative to traditional helicopter surveys in certain cases (IUS, 2017). The company has successfully operated long-distance drones capable of covering 50 km to inspect 400 kV lines, enhancing the efficiency of maintenance diagnostics under live line conditions. In 2017, RTE, in collaboration with Del-Air Tech, conducted a beyond visual line of sight (BVLOS) drone flight to inspect power lines and model its grid, marking a first in France in this field. By 2018, RTE's investment in drone technology, totaling €4.8 million, included testing long-distance drones for grid inspection and data collection for virtual grid modeling (EnergyWorld, 2018). A significant milestone was achieved in 2020 with the first real-condition flight test of the "Diridrone," an airship drone, designed for high-voltage line inspection, demonstrating the potential for extensive network maintenance and the monitoring of live electrical lines. Additionally, RTE has pioneered in employing drones for vegetation management under power lines, showing that drone and digital data analysis can significantly reduce greenhouse gas emissions by 33% compared to helicopter-only surveys. This is achieved through advanced LiDAR-equipped drones like Delair’s DT26, certified for BVLOS operation by the French Civil Aviation Authority, which allows RTE to detect vegetation encroachment efficiently (Terna, 2021).

Another major player in this field is South Korean TSO KEPCO which since 2016 has been actively involved in drone technology, beginning with an agreement with South Jeolla Province and the Korea Drone Industry Promotion Association to foster new industries for future economic growth. This included developing detective and defensive drone technologies and creating a "drone road" for aerial navigation. By 2015, KEPCO's Technical Diagnosis Department and regional offices were using drones with advanced cameras for inspecting power distribution infrastructure, identifying malfunctions and faults. In 2017, KEPCO's Research Institute introduced a GIS-based autopilot drone system for inspecting power facilities, enhancing the detection of transmission line defects. In 2019, KEPCO partnered with Doosan Mobility Innovation to explore hydrogen fuel cell drone technology, leading to tests of hydrogen fuel cell drones and beyond visual line of sight (BVLOS) operations in 2021 (Lee, 2021). That

same year, KEPCO developed an automatic inspection drone with a deep learning-based auto-tracking camera gimbal for power line defect detection and conducted successful field tests for a comprehensive drone system for power transmission line inspection. These drones, equipped with 3D LiDAR, were utilized for line sag estimation, vegetation encroachment monitoring, and corona discharge inspections, culminating in special flight authorization for UAV operations. In 2023, KEPCO expanded its technological reach by signing a Memorandum of Understanding (MOU) with Terra Defense for cooperation on anti-drone protection systems to counter unauthorized and potentially harmful drones. KEPCO's engagement in drone technology, underscored by its leading position in photovoltaic drone patents (GlobalData, 2022), reflects its commitment to innovating power system maintenance and security.

Artificial Intelligence:

Regarding artificial intelligence, several TSOs stand out for their level of engagement, each adopting a unique approach, strategy, and in some cases, markedly different use cases.

In Europe, one such TSO is undoubtedly Spain's Redeia which, through its technology innovation division Elewit, has launched several notable projects leveraging artificial intelligence. In 2020, SAGA was introduced in collaboration with IBM to enable predictive maintenance based on asset condition and overall network risk. The following year, Elewit and Dutch startup Overstory digitized the vegetation along Spain’s high-voltage power lines, enhancing asset management by automatically identifying 37 vegetation species. In 2021, the ZAPIENS-CIRIS pilot project introduced a virtual health and safety assistant using AI to automatically respond to Redeia staff inquiries. Additionally, the same year, an AI-based partial discharge diagnostic platform was developed to preemptively detect insulation faults in cables. By 2022, Elewit joined Indesia, advocating for data and AI usage among Spanish companies and Small-to-Medium Enterprises (SMEs), and incorporated start-up OKTO GRID into its venture portfolio, focusing on electricity asset digitalization (Elewit, 2022). In 2023, efforts shifted towards using AI for a predictive model in occupational health and safety, developing a probability indicator for risk assessment in maintenance and construction. Furthermore, Newton program, designed for desktop and cloud, facilitates extensive calculations and integrates AI for electricity system planning and operation, showcasing a state-of-the-art approach in power flow and linear calculations.

National Grid, the sole system operator in Great Britain with also activities in the US, is another leader in AI applications within the energy sector. In 2018, National Grid Partners, the venture investment and innovation arm of National Grid, announced a partnership and investment in AutoGrid for AI-driven optimization of grid-edge assets. By 2020, National Grid collaborated with Aperio Systems, using machine learning for real-time sensor data monitoring to protect infrastructure from cyber threats. The same year, it applied AiDash's satellite imagery and AI technology across its Massachusetts network to identify maintenance needs in its distribution lines (National Grid, 2020). In 2022, UK's National Grid Electricity Transmission (NGET) initiated a 12-month trial with Keen AI and sees.ai to automate corrosion assessment using AI and beyond visual line of sight (BVLOS) drone flights. Finally, the company's AI Centre of Excellence, established to expand data science capabilities, focuses on creating a talent pipeline through academia and industry partnerships. This initiative aims to make National Grid an attractive employer for data scientists, working on projects that benefit society and the environment, while supporting the wider energy sector's move towards decarbonization and digitalization.

Another key player in the use of AI in the transmission industry is China Southern Power Grid (CSG). In 2019, CSG, in collaboration with Huawei, deployed its Ascend AI chip technology for smart operations and maintenance (O&M) across Shenzhen. This technology, integrated into drones and transmission towers, automates the detection of potential hazards and structural defects in transmission lines, significantly reducing the need for risky manual inspections. CSG's Shenzhen Power Supply Bureau (SPSB) also established a joint innovation lab with Huawei, which has led to the development of a smart O&M system that leverages edge data processing for real-time analysis of power transmission and infrastructure, enhancing safety and efficiency (Xu and Hua, 2019). In 2021, then, CSG entered a strategic partnership with Baidu to further harness AI for transmission and distribution, utilizing machine vision and natural language processing for data analysis and decision-making. CSG's commitment to AI innovation is also evident in its robust patent filing activity, with a significant number of AI-related patents, highlighting its leadership in smart grid and load forecasting technologies.

Furthermore, Japanese TSO TEPCO has emerged as another leader in AI development within the energy sector. In 2016, the company made a strategic investment in Via Science, Inc., leveraging machine learning and AI for enhancing power system reliability and efficiency. The following year, TEPCO joined Energy Impact Partners LP (EIP), collaborating with companies like

National Grid and Xcel Energy Inc. to explore innovative energy solutions, including AutoGrid's AI-based services for V2G and microgrids (Shepard, 2017). In 2018, TEPCO and NTT DATA Corporation initiated an AI-based project for anomaly detection in distribution substations, aiming to cut inspection times by over 50% (NTT, 2018). A predictive maintenance pilot using AI was launched in 2019, and in 2020, TEPCO partnered with Itochu Corporation on an AI and blockchain-based system for trading power surplus. In 2021, TEPCO Ventures, the corporate venture capital arm of the Group, formed an exclusive alliance with SkySpecs, Inc. for AI-driven wind farm maintenance, showcasing its capability in inspecting over 60,000 wind turbines. Finally, by 2022, TEPCO DX, a subsidiary focused on digital transformation, aimed to reform business practices and enhance customer experiences through data-driven strategies, including AI applications.

6G:

None of the analyzed TSOs are actively engaged in the development of 6G. However, according to a research conducted by Nikkei with Tokyo-based research firm Cyber Creative Institute, China is the leading country in terms of patents (Watanabe, 2021). Furthermore, in 2022, Norwegian TSO Statnett announced its interest in receiving project proposals aimed at developing expertise and solutions for the efficient, stable, and secure utilization of the new 5G and 6G networks for communication and data transmission (Statnett, 2022).

3.5 Discussion

The benchmarking analysis on TSOs has revealed several valuable insights into how TSOs approach innovation and what drives this process. Firstly, the peculiar nature of the TSOs business (i.e. regulated monopolies) means that regulation plays a central role in determining their investment choices and activities. The study indicates that European TSOs tend to be mostly engaged in regulated activities, avoiding investments in innovative activities, especially those with a high potential impact on their business model. Furthermore, TSOs in countries with more favourable regulatory frameworks for innovation seem to engage in a higher number of innovative activities, whereas TSOs in countries with neutral or less favourable regulatory frameworks exhibit a low propensity to innovate. Regulatory tools that might influence innovation among the TSOs include explicit references to innovation and related concepts in

national regulatory frameworks, mandates for TSOs to invest in R&D&I or specific innovative activities (e.g., offshore wind interconnections), and the presence of ad-hoc economic incentives for investments in innovation.

Finding the most suitable regulatory design to adequately incentivize investments in innovation is an ongoing challenge for regulators. National Regulatory Authorities should correct regulations that create disincentives or do not adequately incentivize investments in innovative technologies. This is crucial, as a misaligned political and regulatory framework would hinder the energy transition and prevent society from reaping the benefits of this transition and pursuing broader economic growth opportunities.

Another interesting aspect that emerged from the benchmarking analysis is the significant variance in TSO engagement across the key technologies, both regionally and individually. This variance can be potentially attributed to several factors, including the presence of ambitious environmental goals within a country or region, which significantly impacts the innovativeness of TSOs (i.e. countries or regions with stringent environmental targets often push their TSOs to adopt more innovative technologies and practices to meet these goals) and the existence of industrial policies, strategies or specific goals at national level, for the roll-out of certain technologies. For example, Spain's national 5G strategy is likely linked to Redeia, the Spanish TSO, being a top performer in this technology. Similarly, State Grid's success is bolstered by China's ambition to become the world's leading technological player and provider, supported by substantial investments in cutting-edge technologies in recent years. The EU's Green Deal and push for eco-friendly alternatives have spurred European TSOs to excel in SF6 alternatives (although the total number of TSOs with top performance in this area is very limited) and HVDC technology, essential for the EU's goals. Also, regulatory support significantly enhances the performance of US and Canadian TSOs in microgrids and energy communities, where Non-Wire Alternatives (NWAs) are encouraged. However, it's important to note that the dual role of American transmission companies in both transmission and distribution certainly facilitates greater experimentation with microgrids.

TSOs in regions with national champions or specialized technology firms tend to be more active in those areas, benefiting from geographical proximity that facilitates partnerships. For example, Australian TSO Transgrid excels in Dynamic Line Rating, partly due to its closeness to

Infravision, while Elia's performance in DLR benefits from its relationship with the Belgian company Ampacimon, allowed them to be among the first to experiment with and adopt this technology. This trend underscores the advantage of regional expertise and collaboration in advancing TSO technological engagement. Similar to V2G technology, some of the most active TSOs focus on partnerships with automotive companies within their own countries. For example, TransnetBW has partnered with BMW and Porsche to test V2G applications. Such partnerships are another key factor in explaining the superior performance of some TSOs, especially in areas beyond their traditional business. Numerous examples include RTE boosting its drone activities through a partnership with Delair, Energinet working with Enel and Nuvve on V2G, Redeia collaborating with IBM on artificial intelligence, TEPCO with NTT Data Corporation on AI, and State Grid with tech giants like Tencent, Alibaba, Baidu, and notably Huawei on 5G, to name a few. Collaborations with research centers (and universities), such as Hydro-Quebec's Research Institute (IREQ), have also been crucial, enabling Hydro-Quebec to excel and innovate in robotics. Similarly, the partnership between State Grid and the UTC Training and Testing Center in China has been instrumental in training professional drone operators for power line inspections.

The establishment of dedicated divisions or subsidiaries to manage innovation and advanced technologies emerges as another potential key factor associated with a higher innovativeness score. For example, Hydro-Quebec has created MIR Innovation for robotics, while Redeia manages innovative technologies through a specialized division called Elewit, along with a subsidiary focused on satellite technologies named Hipsat. Similarly, State Grid operates V2G projects through State Grid EV Service and addresses new technologies like drones and robotics via State Grid Intelligence Technology Co. Ltd. Ausnet Services also has a subsidiary, Mondo Power, dedicated to microgrids, showcasing how strategic organizational structures support technological advancement.

Finally, another important aspect is the role of corporate venture capital arms within companies, which invest in innovative and strategic startups. Examples mentioned include National Grid Partners, which recently invested in AI-focused startups like Keen AI, sees.ai, and AutoGrid. TEPCO has made investments related to V2G. Elewit (Redeia Group) has invested in two companies for 5G development: Nearby Computing and Auxess Networks. Additionally, Redeia has invested in OKTO Grid, a company specializing in artificial intelligence.

3.6 Summary

Regulators' terms of reference to innovation and related concepts vary widely across Europe. These regulatory frameworks have a significant influence over how innovative TSOs are. This chapter reviewed TSOs across Europe, finding they have conservative approaches to innovation, meaning they tend to avoid the most potentially disruptive innovations unless adequately incentivized. International benchmarking analysis highlighted significant variance in TSO innovativeness, both regionally and individually. Various factors influence TSOs innovativeness, including: the presence of industrial policies, strategies or specific goals that might influence the adoption of certain technologies, geographical proximity to industry champions or specialized technology firms, collaborations with research centers, the establishment of dedicated divisions within TSOs or subsidiaries to manage innovation and advanced technologies and the presence of corporate venture capital arms within companies that invest in innovative and strategic startups.

4 How European TSOs approach innovation: evidence from interviews

4.1 Introduction

The previous chapter provided evidence on how European TSOs are approaching innovation through two benchmarking analyses. The first analysis focused on a small sample of European TSOs and six key technologies, while the second extended to a much larger sample of international TSOs and an additional eleven innovative technologies.

This chapter complements these desk-based findings with insights gathered directly from interviews conducted with innovation teams at European TSOs. It employs an exploratory approach to TSOs innovation by examining their strategic initiatives, operational practices, and technological innovations, and how such innovations can help future-proof their organizations. The aim is to reveal how TSOs are not just adapting to, but actively shaping, the future of the electricity industry. These objectives are addressed with in-depth interviews with professionals from TSOs' innovation departments. Data was collected through anonymous semi-structured interviews focused on the following specific themes: Technology Trends, Best Practices, Non-Wire Alternatives (NWAs), Challenges, and Future Role Evolution.

This chapter is based upon the paper "How do electricity TSOs embrace innovation to navigate the energy transition?" (Biancardi and Staffell, 2024 – R&R at Energy Strategy Reviews). My role in this paper included the conceptualization – the development of the core idea and research questions – the choice of methodology, the analysis – data collection, elaboration, and visualization – and the writing. My co-author provided support in supervision and writing – review and editing.

4.2 Background on Relevant literature on innovation

Companies are navigating an increasingly complex world where market dynamics, technological advancements, consumer expectations, and regulatory demands are changing rapidly. The COVID-19 pandemic, as noted by Amit and Zott (2020), has intensified these complexities by disrupting global supply chains and highlighting the limitations of focusing solely on efficiency. This has prompted a shift towards prioritizing resilience, adopting new

technologies, and reassessing business models for better future adaptability. Furthermore, disruptive innovations are more frequently emerging from unrelated industries, posing new challenges for companies (Adner, 2023). Mattiello and Taticchi (2023) describe this as a period of significant disruption for businesses: “what we are experiencing is a perfect storm of transformative factors converging at once” (Mattiello and Taticchi, 2023).

Despite being regulated monopolies shielded from direct competition, Transmission System Operators are not immune to disruptive forces, of any kind. To stay ahead of the curve, ensuring they are not blindsided by future disruptions, TSOs must commit to research and innovation, including investing in novel and uncertain initiatives (Fried, 2017). TSOs should also consider innovating their business models by embracing new technologies and diversifying their business activities (Biancardi et al., 2021). This approach, while sometimes overlooked, is vital for companies to maintain their lead and adapt to the evolving industry landscape (ADL, 2023; Foss and Saebi, 2015; Lindgardt and Ayers, 2014).

The following sections will explore the concepts of business model innovation and disruptive innovation in detail, examining their definitions and implications. They review recent contributions from both academic and non-academic sources, shedding light on the evolution and application of these concepts in today’s business landscape. This examination of literature aims to assist TSOs, in refining their innovation strategies and approaches, ensuring they are well-informed and prepared to navigate the uncertainties of the current times.

4.2.1 Business model innovation theory

Broadly speaking, innovation can be seen as any type of change. The term, in fact, derives from the Latin 'novus,' meaning new, and is used to describe any novelty, alteration, or transformation that modifies a political, social, or economic and business context.

One might mistakenly think that innovation typically pertains only to technology, products, services, or processes. However, quite often, innovation encompasses an entire business model (Valtorta, 2017). Despite the lack of a universally accepted definition (Foss and Saebi, 2015; Zott et al., 2011; Teece, 2010), the business model concept, which describes ‘how an organization creates, delivers and captures value’ (Osterwalder and Pigneur, 2010), has gained significant interest over the past years, becoming widely used by both managers, consultant

and scholars, particularly within the domains of strategy, innovation management and entrepreneurship (Sardà and Pogutz, 2019; Baden-Fuller and Haefliger, 2013; Zott and Amit, 2010).

Recent studies emphasized the pivotal role of business model innovation as a primary driver of differentiation, leading to sustained competitive advantage. Moreover, the significance of business model innovation extends beyond mere economic success, aligning closely with the increasing emphasis on corporate sustainability and the imperative to tackle environmental and societal challenges (Sardà and Pogutz, 2019; Markman et al., 2016; Snihur and Markman, 2023). In this regard, a growing body of research show that entrepreneurs and corporations are increasingly steering towards business models that harmonize social, environmental, and economic objectives (Schroedel, 2023; Lüdeke-Freund, 2018; Geissdoerfer et al., 2018; Schaltegger et al., 2016; Bocken et al., 2014; Kiron et al., 2013). By doing so, companies not only enhance their sustainability performance and credentials but also appeal to stakeholders prioritizing environmental stewardship, thereby attracting new customers, preserving their license to operate, enhancing talent acquisition, attracting financial resources, and reducing risks (Sardà and Pogutz, 2019; Lüdeke-Freund et al., 2022; Kiron et al., 2017).

Most importantly, business model innovation is a way to react and adapt to changing in the external environment. It equips firms to better navigate rapidly evolving markets and to continue to drive growth (Lindgardt and Ayers, 2014; Cortimiglia et al., 2016; Demil and Lecocq, 2010). Business model innovation is crucial in responding to "strategic discontinuities and disruptions" that can render existing business models less effective. These disruptions often arise from technological advancements or the entry of new competitors into the market. In such scenarios, the ability to adapt and innovate business models becomes not just a strategy for growth, but a necessity for survival (ADL, 2023; Lyu et al., 2023).

Snihur and Markman (2023) noted that business model innovation serves a dual function: it enables various innovations, including product, process, and technology, and can itself be innovative by introducing new methods of value creation and delivery, potentially disrupting industries or creating new markets, as discussed by Christensen et al., (2015) and Chesbrough (2010). In the latter case, the literature categorizes business model innovation based on its degree of innovativeness (i.e. its degree of novelty or radicalness), distinguishing between

'incremental' and *'radical'* innovation (Tidd and Bessant, 2013; Poole and Van de Ven, 2004) or between innovative business models and those focused on evolution, adaptation, or reconfiguration, which are less innovative and aimed at protecting existing business models (Foss and Saebi, 2015; Massa et al., 2017; Cozzolino et al., 2018).

Regardless of the terminology used, innovating the business model poses a significant challenge, particularly for well-established firms (Chesbrough and Rosenbloom, 2002). Differently from startups that are more flexible finding it easier to undergo transformative changes, in fact, established firms often face internal inertial forces that impede innovation (Cozzolino et al., 2018). Intuitively, this inertia often stems from organizational barriers, established processes, structures, and cultures, which can create resistance to change and impede the adoption of innovative business models (Amit and Zott, 2020; Foss and Saebi, 2015).

Research suggests that innovating a business model often entails redefining the company's scope or boundaries (Leih et al., 2015). This typically involves creating new business units, departments, and internal processes, as well as decentralizing authority and fostering a new organizational culture (Manfredi Latilla et al., 2019). These challenges are generally more pronounced for established firms than for startups, yet every organization can train and develop the necessary capabilities to prepare for and improve their effectiveness in this critical task.

The so called “dynamic capabilities framework” offers valuable insights into the crucial role of human resources and their capabilities in crafting new business models and adapting existing business models (Foss and Saebi, 2015). The dynamic capabilities framework centers on how a company recognizes and leverages its resources to generate new value, a skill referred to as "dynamic capabilities". These capabilities empower a firm to quickly detect, respond to, and foresee upcoming challenges, as well as to capitalize on new opportunities. Particularly, (Teece, 2007) suggests that dynamic capabilities can be broken down into three core processes: 1) Sensing, which involves the identification and assessment of opportunities through exploring technological possibilities, market probing, customer feedback, and environmental scanning; 2) Seizing, which is about mobilizing internal and external resources to capitalize on these opportunities and create value; and 3) Transforming, which requires continuously renewing the organization. This includes phasing out old products, adjusting communication lines, and

modifying business models, methods, and organizational culture as needed. Sometimes, transformation may involve adopting a radically different, potentially unstable structure that revitalizes the organization for a more sustainable and improved design. Mastering dynamic capabilities is key for firms to stay ahead in a fast-paced business world, allowing them to quickly adapt and thrive in the face of new developments and market shifts (Teece, 2007).

4.2.2 Disruptive innovation theory

Innovation theories often use distinct yet related terms to describe two main categories: ordinary innovation, which involves improvements such as technological advances and process optimizations enhancing a company's existing capabilities; and disruptive innovation, which can radically alter markets through new market creation, skill set overhauls, technological paradigm shifts, organizational process revolutions, or complete business model transformations (Valtorta, 2017).

In the literature on innovation, the first reference to this dichotomy was made by Abernathy in 1978, who distinguished between “incremental” from “radical” innovation. Similarly, in 1986, Michael Porter distinguished between “continuous” and “discontinuous” technological changes. Other authors, like (Tushman and Anderson, 1986), have differentiated between incremental innovation and “breakthrough”. The latter demonstrated that technology in any sector evolves through alternating periods of incremental changes and technological breakthroughs, which respectively enhance or disrupt the skill sets held by companies in that sector. Additionally, (Abernathy and Clark, 1985) introduced the distinction between “conservative” and “radical” innovation. However, it's Christensen's concept of “disruptive” innovation, introduced in 1997 and distinct from “sustaining” innovation, that has become particularly influential and significant in the field.

According to Christensen (1997), disruptive innovations often start by serving niche markets with simpler, more affordable solutions. Despite initially lagging in performance, they evolve swiftly, potentially surpassing mainstream products and reshaping entire industries. These innovations have revolutionized various sectors. For example, Personal Computers (PC) democratized computing, Digital Photography rendered film obsolete, Blockchain technology is revolutionizing financial transactions, Virtual Reality is transforming gaming experiences, and Artificial Intelligence is reshaping sectors from healthcare to finance with advanced data

analysis. 3D Printing is another example, revolutionizing manufacturing with more efficient production methods.

However, as Christensen himself updated in 2015, disruptive innovation is not limited to product, services, processes or technological advances; it also encompasses business model innovations (Christensen et al., 2015). Unlike the original theory's focus on gradual disruption from low-end to mainstream markets, disruptive business models can quickly attract mainstream customers as adoption grows (Ansari et al., 2016).

Further elaborating on this, Cozzolino et al. (2018) proposed distinguishing between disruptive technologies' emergence and disruptive business models that exploit these technologies, noting they often occur separately and impact incumbent adaptation differently. Disruptive technologies appear first as opportunities, not immediate threats. The real challenge for existing companies comes with disruptive business models, which may commercialize these technologies innovatively, posing significant threats to incumbents. An example is Apple's iPhone, initially an incremental upgrade over existing phones, which became truly disruptive with the introduction of iTunes and the App Store, turning smartphones into viable substitutes for computers, especially for internet access (Adner, 2023).

To add to the complexity, disruption, once confined to individual industries, now extends across entire ecosystems. Classical disruption typically stems from competitors within the same industry, occurring when a new technology or method supplants another through direct substitution. However, contemporary disruption often originates from ecosystems and does not merely replace existing technology but redefines the entire value proposition. A key example is the advent of autonomous vehicles, which could revolutionize not just the technology in the automotive sector but also the core value proposition, shifting from 'enjoy the road as you drive' to 'forget the road as you are transported' (Adner, 2023). This shift transforms cars into mobility solutions, banks into fintech platforms, pharmacies into health management centers, and production lines into intelligent factories, thereby effectively blurring industry boundaries. In conclusion, in addition to discussing disruptive technology or disruptive business model innovation, 'ecosystem disruption' should also be considered.

4.2.3 The organizational dimension of innovation

Organizational choices play a crucial role in nurturing innovation both in start-ups and in mature firms. Companies can adopt various forms of engagement towards innovations, including potential disruptive ones, but the key initial step is to cultivate a mindset that views disruptive innovation as an opportunity rather than solely a threat (Amit and Zott, 2020). This echoes prospect theory (Kahneman and Tversky, 1979) which also indicates that perceiving innovation as an opportunity spurs creativity and risk-taking. Further supporting this approach, research by Gilbert and Bower (2002) demonstrated that recognizing innovation as both an opportunity and a threat is instrumental for successfully driving innovation within organizations.

The CEO commitment, which involves allocating resources and budgets is also key for the success of innovation strategies, especially in the context of radical innovations (PwC, 2013). ADL (2023) further stresses the importance of an innovation strategy that is seamlessly integrated with the overall business strategy, ensuring a cohesive blend of strategy, innovation, and transformation.

The organizational aspect also encompasses decisions over the size of innovation teams. In this regard, Rogers (2023), notes that significant innovation in both established companies and startups often comes from small, empowered teams practicing rapid, iterative experimentation, as seen in agile, design thinking, lean startup, or product management methodologies. Key traits for success, observed in companies like Amazon, Google, Walmart, and Mastercard, include efficient communication and decision-making through small team sizes, multifunctionality, dedicated focus, decision-making autonomy, clear outcome accountability, and transparent sharing of progress and results.

With regard to the way of organizing innovation programs, then, companies can adopt various models, mainly: a centralized model, featuring a corporate innovation team that often leads to the creation of an innovation excellence center, and a decentralized model, where innovation is managed by individual business units under corporate guidelines (Valtorta, 2017). The latter, while potentially offering a narrower perspective, guarantees closer alignment with customer needs (Valtorta, 2017). Additionally, ADL (2023) underscores the critical need to incorporate business units into the innovation process to prevent cultural conflicts.

In the academic literature, then, a distinction is made between closed and open innovation models (Valtorta, 2017). The closed innovation model represents a traditional approach where companies rely exclusively on their internal resources and capabilities throughout the innovation process, from the research and development (R&D) phase to the commercialization of new products or services. Conversely, the open innovation model encompasses a wide-ranging network of collaboration, involving partners, suppliers, clients, universities, and sometimes even competitors, in cooperative endeavors such as joint ventures and alliances (Chesbrough, 2003). The latter includes inbound (external innovations integrated into the company) and outbound open innovation (company innovations shared externally), with some approaches combining both (Chesbrough, 2006). Open innovation has the advantage of bridging resource and competency gaps and introducing diverse market problem solutions. Companies can engage in open innovation either passively or actively, adapting their approach to suit their strategic goals. However, as Valtorta (2017) and ADL (2023) note, there's no one-size-fits-all organizational model for innovation. Multiple models can coexist within a single company.

Interestingly, research by Lyu et al. (2023) highlights a paradoxical trend: projects spearheaded by in-house R&D teams often demonstrate greater radical innovation, averaging 1.5 points higher in this respect. The advantage of internal innovation lies in the greater control leaders have over strategic technology development decisions, such as application selection, technological platform choices, and the integration of new innovations with existing technologies. However, these insights do not diminish the importance of open innovation (Chesbrough, 2003) which are crucial for filling capability gaps within a company. Rather, they suggest that an overreliance on open innovation, without substantial investment in dedicated exploratory R&D, could hinder the full realization of the innovative potential of new technologies. Therefore, a balanced strategy that synergizes internal R&D initiatives with external sources of innovation is likely the most effective approach.

Regardless of whether a company opts for a centralized or decentralized approach to spearhead innovation, or whether innovation originates from internal efforts or external partnerships, a key challenge for established firms is balancing their innovation portfolios and resource allocation to foster both incremental and disruptive innovations. According to ADL (2023), many companies prefer incremental innovations due to short-term objectives, risk

aversion, and management inefficiencies, often underestimating the value of breakthrough innovations for long-term growth. However, ADL's findings indicate that firms investing in riskier ventures, such as new technologies and new business models, tend to achieve higher overall innovation success. Thus, adopting a balanced approach in managing innovation portfolios, which appreciates both types of innovation, is recommended (ADL, 2023).

Intuitively, one significant challenge in this context is the coexistence challenge presented by radical innovations or innovative business models. These challenges include competition for financial resources among teams or business units, the need to balance between sustaining current operations and developing new ones with uncertain outcomes, differing logics and dynamics, and the risk of making current business models and their resources obsolete. Indeed, the process of embracing radical innovations or developing new business models, akin to creative destruction, leads to the emergence of new capabilities, potentially replacing those of traditional core businesses (Bogers et al., 2015).

A common approach to cope with these challenges, is to foster radical innovation outside their core organizational and process frameworks, by incubating and developing it externally, thus creating dual structures that reconcile potential contradictory logics. This approach can be realized through different organizational variants. The first variant is the one of skunkworks, where a selected group or segment of the organization is isolated to enhance project autonomy before reintegrating the outcomes (Valtorta, 2017). The second is through spin-offs and spin-outs which involve separating a part of the organization to run a business independently. Christensen (1997) and Christensen and Raynor (2003) were among the first studies to recommend creating a separate spin-off organization for disruptive innovation and new market exploration. This entity should function with startup-like agility and independence, even after achieving market success, to avoid stifling its adaptability and disruptive potential upon reintegration into the main organization. Similarly, Gilbert (2006) suggest physical separation to protect new business models from established managers who may view them as threats. Foss and Saebi (2015), instead, highlight the need for mechanisms to exploit synergies between the spin-off and the parent company, balancing integration and separation with ongoing agility and flexibility. This approach echoes Tushman and O'Reilly (1996)'s concept of ambidextrous structures, which segment the organization into distinct units linked solely by top-level governance mechanisms and where each segment is tailored to achieve its unique goals,

enabling the ambidextrous organization to concurrently focus on creativity and innovation, as well as stability and structure.

To stay at the forefront of emerging trends and access cutting-edge solutions without the need for extensive internal development, can also involve investing in disruptors, particularly startups, that specialize in specific innovative technologies. This often takes the form of corporate venture capital, as discussed by Block and Macmillan (1995) and Romans (2016). Corporate venturing is gaining global attention as a strategic tool for established companies to access innovative ideas and opportunities through minority investments (Doll et al., 2022; Masucci et al., 2021; Prats et al., 2019). Sometimes, such investments also aim at rejuvenating corporate culture and attract new talent (Kohler, 2016).

Keil et al. (2008) found that corporate venture capital investments enable "disembodied experimentation," where firms engage in ventures with new, sometimes disruptive technologies and business models. This experimentation aids in understanding and integrating new capabilities from these ventures, facilitating rapid learning in established companies. Corporate venturing can also serve as a risk-reduction tool, helping established companies hedge against unexpected technological changes (Venzin and Konert, 2020). As Reimbasch & Hauschild (2012) and Dushnitsky et al. (2020) point out, in fact, it enables firms to anticipate and potentially influence technological trends early on to their advantage.

Corporate venturing activities can take different forms, including corporate incubators (Becker & Gassmann, 2006) and corporate accelerators (Dempwolf et al., 2014; Hochberg, 2016; Weiblen & Chesbrough, 2015), with the latter two seeing a significant increase in recent years. The key distinction between an incubator and an accelerator lies in the business stage they target. Incubators are geared towards the seed phase, where the focus is on ideation for a product or service without a fully-formed business plan, and the company may not yet be established.

Building on these concepts Venzin and Konert (2020) propose a way to embrace innovation while defending the status quo. They recommend creating a radar to identify and track disruptive firms, investing in those with the potential to disrupt the company. This process involves scanning the entire ecosystem, including players from different sectors, who could

influence industry dynamics directly or indirectly. Regarding investment in these startups, Venzin and Konert (2020) argue that establishing an 'accelerator', as a separate investment unit, is a particularly fitting solution for firms that want to protect their core, for leveraging data on disruptors and introducing adaptability into their investments. This accelerator fund would use a modest portion of the total investment volume to invest in potentially disruptive startups. This serves the dual purpose of protecting core investments and accelerating the growth of startups, creating champions. Investing in startups, as highlighted by Venzin and Konert (2020), enables managers to experience the future before it arrives and prepares the company for potential disruptions.

Corporate venture investing and accelerators, align with the concept of organizational ambidexterity, as discussed by Simsek (2009) and O'Reilly and Tushman (2008, 2004). This concept emphasizes the need to balance exploiting new opportunities with maintaining current operations (Colarelli O'Connor and De Martino, 2006; Gibson and Birkinshaw, 2004; Duncan, 1976). However, this balance is challenging: overemphasis on alignment can limit long-term success, whereas too much adaptability can jeopardize short-term stability.

Last but not least, to ensure the success of these investment forms, as highlighted by Romans (2016), it's essential to evaluate whether startups are open to participating in a corporate accelerator program or forming an alignment with a specific company. This decision can impact their ability to engage with independent accelerators or investment funds not affiliated with a specific corporation. Startups should carefully consider their growth strategy, degree of independence, and the potential constraints and opportunities associated with a corporate partnership. Romans (2016) also underscores the importance of several key steps for the success of these investments. Firstly, companies should identify corporate assets that can enhance the value provided to startups and leverage them effectively. Secondly, they should ensure that venture capital is well-funded and an integral part of the corporate strategy. Building synergistic relationships and networking opportunities between startups, and various business units within the company can promote partnerships and foster growth. Effective management of incentive and compensation schemes for corporate venture capital managers is also crucial. Additionally, companies should not overlook the potential benefits of investing in other funds and consider adopting a fund of funds strategy, viewing it as a profit center to ensure the financial sustainability of the corporate venture capital program.

4.3 Methodology

Data were obtained through semi-structured interviews, guided by specific themes and questions. This approach allowed natural development of themes and patterns based on the unique experiences and interpretations of participants (Saunders et al., 2019). The flexibility of this method, coupled with the anonymity of the interviews, was chosen to foster in-depth and honest discussions, extending beyond the realm of conventional corporate discourse or readily available public data (Guest et al., 2016).

Interviews were conducted with eleven electricity transmission system operators from across Europe, as shown in Figure 13. The sample was selected based on TSO size, and to maximize diversity across the countries in which they operate. The latter considered characteristics such as: TSO ownership, regulatory schemes, geography, electricity generation mix (e.g. nuclear or coal), penetration of renewables, penetration of electric vehicles. The intent was to capture a diverse array of viewpoints while pinpointing shared insights among the participants.

Within each TSOs, interviewees were recruited who served as heads of innovation or a similar job activity. This group was selected for their expertise, as they occupy central roles within their organizations and should possess a deep understanding of the subject matter. Interview participants were recruited using purposive sampling of a homogenous group, by inviting a broad range of individuals who met the criteria (Saunders et al., 2019). Despite the relatively small sample size, it consists of an 'elite' group of stakeholders previously overlooked in research. This makes the sample appropriate for gaining an in-depth of understanding of the experts' views and reasoning (McCracken, 1988).

All interviews were performed in compliance with relevant laws and institutional guidelines, and all data were handled according to the principles of the General Data Protection Regulation (GDPR). All data resulting from interviews were anonymized at source, to allow interviewees to express their views freely without reservation. Informed consent was obtained from all interviewees both at the beginning and end of each interview and via participant information sheets that were sent to each interviewee beforehand. At each of these stages, it was emphasized that participation was purely voluntary, and they retained the right to decline or withdraw from the study at any time without negative consequences. Interview guides (see

Appendix 4) were used to steer the discussions, but the interviews were allowed to flow according to the interviewees' priorities and what they felt was most important to emphasize. The interview guide was periodically evaluated and adapted between interviews to reflect lessons learned. Specifically, the sequence of the questions was altered from its original configuration in order to create a more natural flow to the conversation (see Appendix 4).

Interviews were conducted using Microsoft Teams between November 2023 and February 2024 and lasted between 45 and 60 min (median length 50 min). Interviews were not recorded or transcribed, in part to preserve anonymity; instead, detailed notes were taken during each interview.

One nuanced limitation of this methodology was that the small sample size and exploratory nature of the research might not encompass all perspectives among the interviewees. Additionally, the limited sample size precludes statistical analysis of the entire TSO population, confining the study to qualitative insights. The number of interviewees was quite limited, and the duration of the interviews might be considered insufficient to fully capture the complexity of the numerous topics discussed, as highlighted in section 6.5.3.

Despite these limitations, it is important to note that the interviewees represent an elite group, which is challenging to access, and it is objectively difficult for them to allocate more time for interviews. This presents a unique opportunity to gain valuable insights, offering empirical novelty by providing new qualitative data from an elite group (Sovacool et al., 2018). The study's findings establish a framework of potential responses for further exploration. Moreover, as highlighted in the literature, “qualitative research often concerns developing a depth of understanding rather than a breadth” (Boddy, 2016). It should also be noted that “saturation begins to occur after six in-depth interviews and is definitely evident after 12 interviews” (Guest et al., 2006). Additionally, a small number of subjects (e.g., 6–12) may be “extremely valuable and represent adequate numbers” when studying “hidden or hard-to-access populations” such as elites in the corporate world (Baker and Edwards, 2012).

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



Figure 13 The TSOs' geographical areas covered in this study

4.3.1 Contextualizing the interviewees

Among the TSOs interviewed there is a relevant diversity in the size of innovation departments/units. Sizes range from small groups, as seen with REN (Portugal) and Fingrid (Finland), with only 1–6 people fully dedicated to innovation, to much larger teams such as National Grid ESO (GB) and RTE (France) with teams of 70–100 people, as indicated in Figure 14.

TSO Name (A)	Country (B)	Innovation team size (C)	TSO's total employess (D)	% (out of total) (E)
APG		6-7	~ 850	0.5-1.0%
redeia elewit		18-20	~ 2,400	0.5-1.0%
elia		~ 15	~3130	~0.5%
FINGRID		1-6	~ 514	~1.0%
ipto		~ 25	~ 1600	~1.5%
nationalgrid		~ 68	~3630 (2700 in NGET and 928 in NG ESO)	~2.0%
REN		~ 4	~700	~0.5%
Rte		~100	~ 9,500	~1.0%
swissgrid		~10	~ 694	~1.5%
Terna		~60	5,300-5500	~1.0%
		~9	~ 2,042	<0.5%
	Average	**28**	**2,430**	**~1.5%**

Figure 14 Interviewed European TSOs innovation teams' size. Column E calculates the innovation team size as a percentage of the entire organization workforce. Information were collected from desktop research and interviewees.

It is important to note that, while some innovation departments are larger, the size of the innovation team or department is just one factor and should not lead to misleading conclusions, such as assuming that these TSOs dedicate more effort and attention to innovation.

In fact, interviewed TSOs employ a broad array of tools to support innovation within their organizations. These include traditional internal research and development (R&D). A key example is REN, which collaborates closely with R&D Nester, an affiliated entity that provides substantial innovation support. Therefore, even though the size of the innovation team at REN might appear smaller, it does not account for the significant contributions from R&D Nester.

Interviewed TSOs tools to support innovation also include their participation in EU-funded projects which offer opportunities to collaborate with a diverse network of stakeholders,

including academia, research centers, startups, and other TSOs. Beyond this, TSOs also frequently engage in spontaneous project collaborations with other TSOs. A key example is Equigy, a European crowd balancing platform using blockchain technology to integrate distributed energy resources (such as home batteries, electric vehicles, and solar panels) into the electricity market, founded by a consortium of European TSOs, including Swissgrid, TenneT and Terna.

Additionally, TSOs employ tools like Centres of Excellence (CoEs) or Technology Labs to further promote innovation. Notable examples are: 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 direct current and power electronics.

Other tools include Open Innovation programs designed to attract, grow, and initiate collaborations with their innovation ecosystem network. These initiatives range from specific programs addressing particular topics and challenges to broader schemes that select the best ideas from potential partners for collaboration with TSOs. Examples include Terna's 'Terna Ideas' program, Elewit's 'challenge (m).' program, Elia's Innovation Challenge, Fingrid's Innovation Challenge program, and National Grid's Innovation Event and Open call for Regulator-funded initiatives. Some programs also target the companies' own employees, aiming to nurture innovative ideas from within (i.e. corporate intrapreneurship) and promote an innovation culture throughout the organization. An example is Redeia's Elewit Intrapreneurship Programme, REN's Innovation Leaders program, and Terna Ideas which welcomes innovative ideas from both within the organization and external sources.

Following such initiatives, TSOs typically incubate the selected ideas and startups in incubators or accelerators. Examples among the interviewed TSOs include the Redeia Venture Client Program and Elia Group's Incubation Factory: The Nest. Additionally, some European TSOs use corporate venture capital (CVC) as a tool, involving M&A investments and acquiring stakes in innovative startups. Prominent examples include National Grid Partners, the CVC of National Grid, Redeia's Elewit Venture Capital and Terna's CVC 'Terna Forward'. Recently, Terna invested in Wesii S.r.l., an Italian start-up that uses AI-equipped aircraft and drones for inspection and remote-sensing services for the renewable energy sector.

TSOs also pursue agreements, joint ventures, and partnerships to bridge knowledge gaps and address challenges by leveraging their innovation ecosystem, which includes startups, research centers, universities, and innovative firms. These collaborative efforts complement the specified tools, serving as parallel, supplementary strategies. Figure 15 outlines which TSOs employ selected innovation tools to enhance innovation.

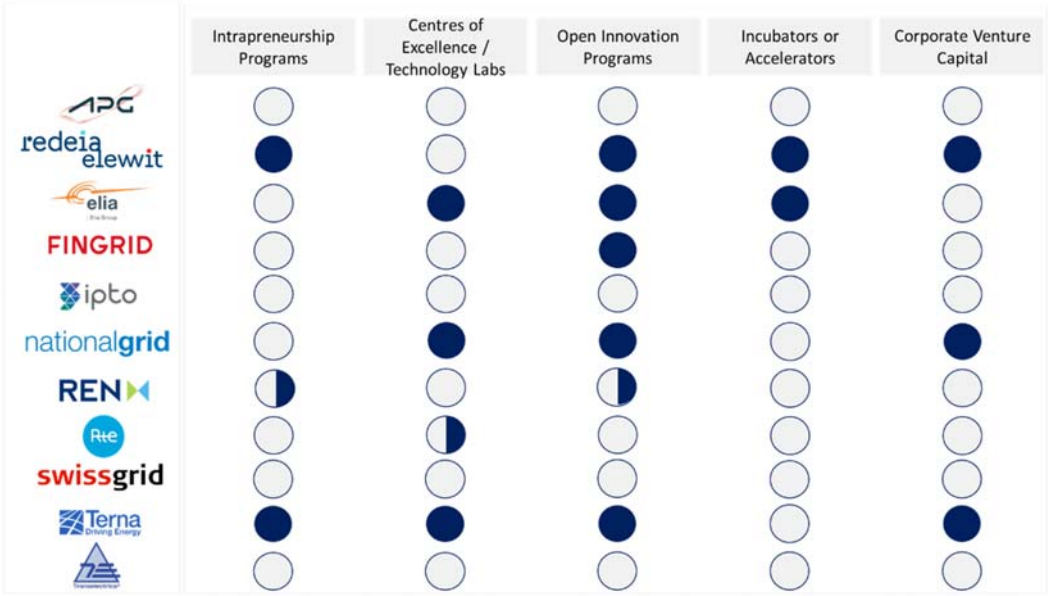


Figure 15 Innovation 'tools' used by Interviewed European TSOs to support innovation within their organizations. R&D, Supranational projects (e.g. EU-Funded projects) and other collaborations are excluded. Full circle indicates initiatives that are fully implemented and in operation. Half-circle indicates 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.

4.4 Results: Insights from some European electricity TSOs

This section first offers an overview of how interviewees approach defining innovation strategies, including the identification of technology trends and specific technologies to focus their innovation efforts. It then outlines the tools TSOs use for benchmarking against peers and their areas of perceived excellence, whether in fostering organizational innovation or in specific technological fields. Following this, interviewees' perspectives are examined on non-wire alternatives (NWAs) and their application in current operations. Lastly, the interviewees' views are explored on the greatest challenges facing TSOs and their insights on the evolving role and

activities of TSOs in the future. Illustrative quotes from the interviews are included in italics. To maintain anonymity, these quotes are not attributed to any specific TSO.

4.4.1 Innovation Approach and Technology Trends

4.4.1.1 Tools and techniques used by TSOs to select innovation focus areas

Among the TSOs interviewed, over half adopt a centralized approach to define their innovation strategy, using a dedicated innovation unit to decide where to focus effort and which projects to undertake. In contrast, 27% of the TSOs employ a hybrid approach, blending centralized planning with decentralized strategies that gather input directly from business units to ensure R&D&I activities align with business needs. A further 18% of TSOs predominantly utilize a decentralized approach.

TSOs have developed a range of methodologies and practices to identify technological trends and select technologies for focus. Over half adopt the radar methodology for innovation processes—corroborated by insights from interactions with other organizations—or have developed other structured methodologies. The remaining TSOs primarily rely on their networks and interactions, or do not adopt any specific methodology. Interviewees from TSOs adopting the radar methodology also highlighted some key pros and cons of it. Table 11 provides details on the TSOs' responses.

Table 11 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 it [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"*

TSOs also shared insights into additional practices they employ to effectively map out emerging technology trends and select specific technologies for their innovation efforts. Figure 16 provides a summary of the TSOs' responses.

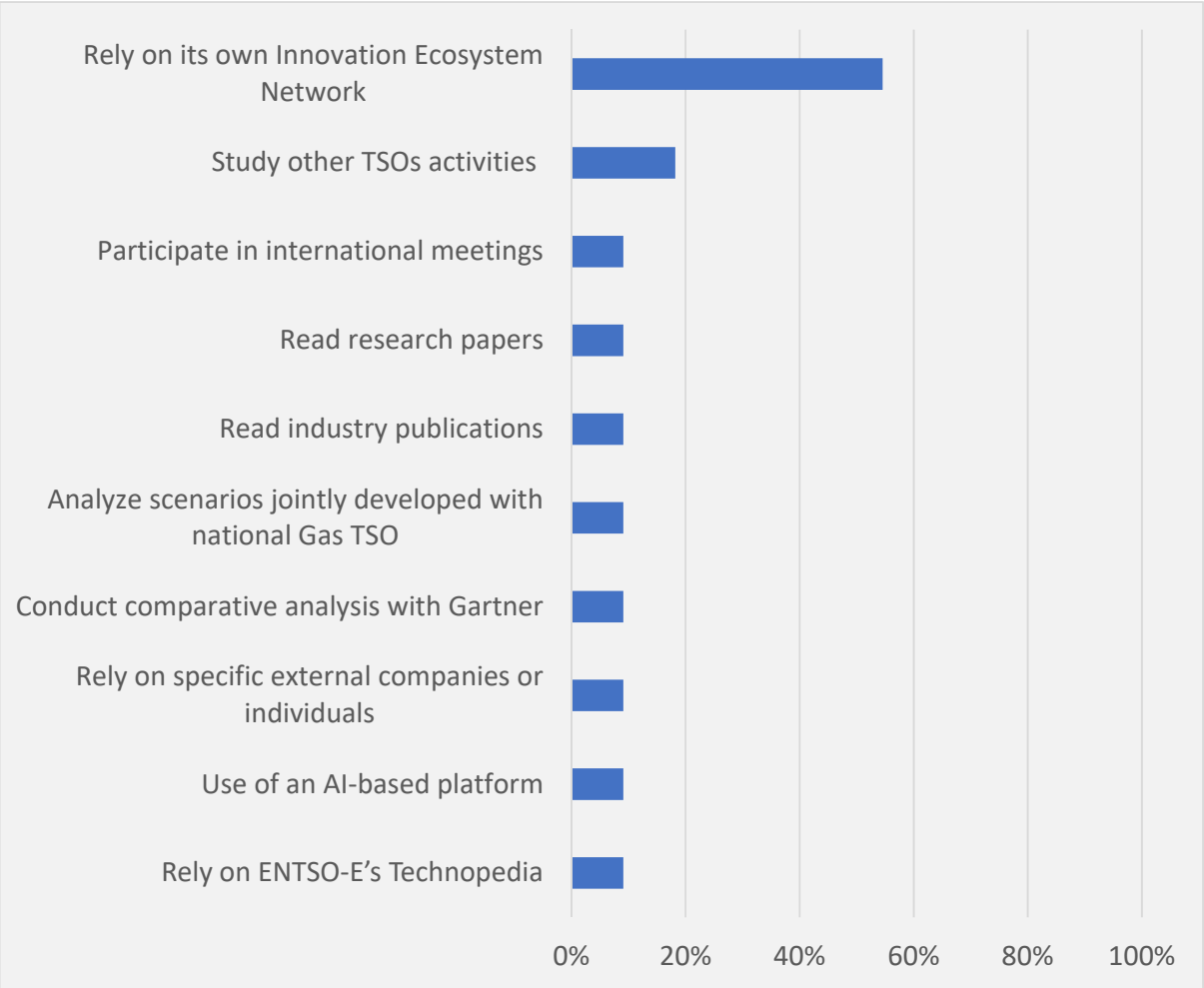


Figure 16 Main methods and practices for identifying technology trends and selecting specific technologies for innovation efforts, other than radar analysis or similar methodology. The given percentage indicates how many of the interviewed TSOs reported using these additional practices out of the total number of TSOs interviewed.

4.4.1.2 Current focus of innovation efforts among European TSOs

Common innovation areas are prioritized by the surveyed European electricity TSOs. Most TSOs reported a focus on 'System Operation', emphasizing operational efficiency and stability. 'Digitalization' is the second-highest priority, highlighting a commitment to 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 role in 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 fewer common themes among the TSOs interviewed. Likewise, few TSOs identified hydrogen as a focus area. The latter is largely due to TSO managing both electricity and gas grids within the same organization, or by 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".* In the words of another interviewee on the same topic: *"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".*

Figure 17 provides a summary of the TSOs' responses.

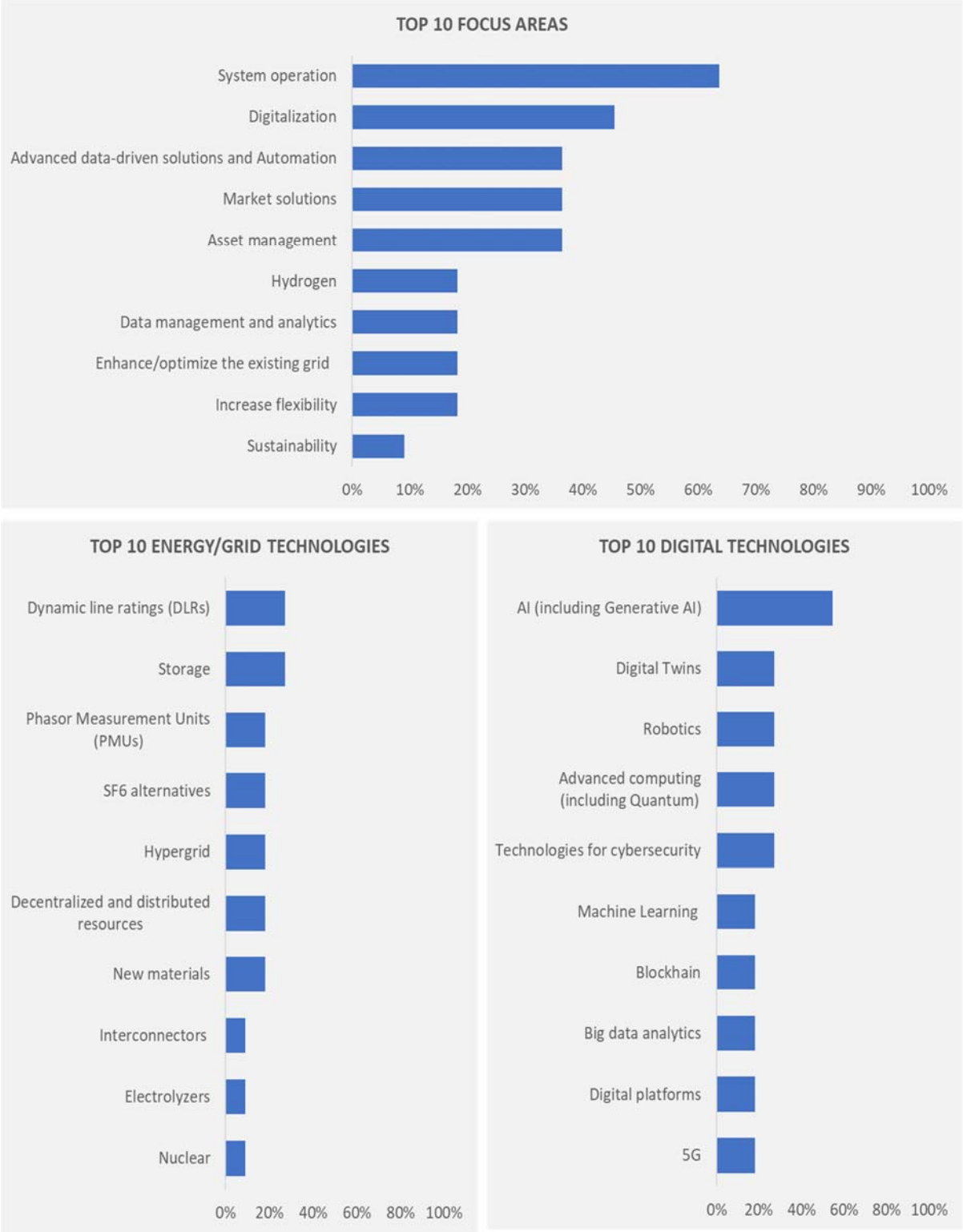


Figure 17 Overview of TSOs' the main areas of focus, and the specific technologies that pertain to the digital domain or to energy/grid systems mentioned during the interviews. The percentage represents the proportion of TSOs mentioning these areas/technologies out of all interviewed.

4.4.2 Best practices

4.4.2.1 Use of Benchmarking techniques among TSOs

Interviews with the sample of TSOs revealed varied approaches to benchmarking, ranging from thorough analysis to informal or implicit information gathering. Three-quarters of TSOs cited participation in sector-specific forums (e.g. ENTSO-E) as their primary benchmarking technique: *"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, yielding insights into how various TSOs approach specific technologies, address certain 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".*

Among the TSOs surveyed, some also conducted formal benchmarking analyses through external partners, including 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 also utilize peer websites for insight: *"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".*

Lastly, one TSO conducts systematic analysis of peer activities, generating internal reports and updates from these reviews. Notably, some TSOs employ benchmarking to either confirm their strategic direction's appropriateness or to pinpoint 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?".*

Figure 18 provides an overview of the surveyed TSOs' most frequent responses.

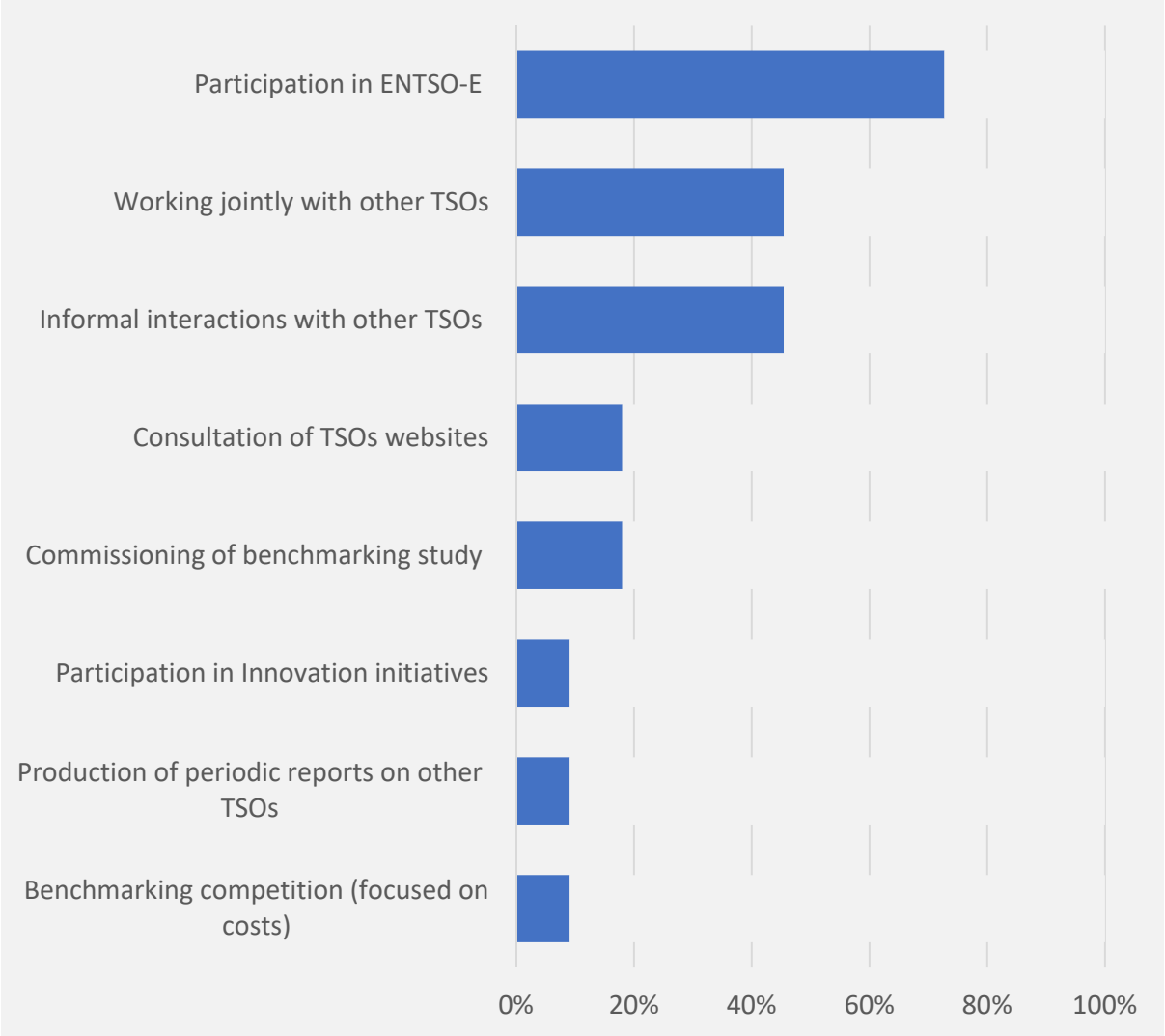


Figure 18 Key Benchmarking Practices Among Interviewed TSOs. The percentage represents the share of TSOs mentioning these practices out of all interviewed.

4.4.2.2 Perceived excellence and best practices

Among the TSOs interviewed, a range of elements emerged as best practices. A significant insight is the adoption of a decentralized innovation strategy, where business units actively define their needs. Some TSOs consider this approach a best practice as it 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".* In the words of another interviewee: *"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 interviewee 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".*

Conversely, one TSO highlighted that its centralized innovation strategy, managed by the same unit responsible for the overarching group strategy, is a success factor. This facilitates the seamless integration of innovation initiatives within the broader strategic framework of the group.

The most common theme, however, with 55% of TSOs considering it best practice, is the collaboration with external specialized companies and other entities and, more broadly, the reliance on their 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. In the words of another interviewee: *"these kinds of collaboration 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 and cooperation especially in areas where the TSO lack of knowledge and expertise*: "in some areas we are not the expert, then we have to take advantage of cooperation".*

Additionally, 27% of TSOs mentioned their ability to rapidly initiate new innovation projects, bypassing complex and lengthy approval processes. Literature on innovation emphasizes the importance of having teams with decision-making autonomy and the ability to experiment rapidly to nurture 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 that TSOs often face challenges in this area due to their regulated nature, which mandates adherence to more complex and lengthy authorization procedures that could potentially stifle innovation. The same proportion of TSOs, then, underscored their attention towards the importance of building an innovation culture across their organizations: *"whereas some TSOs may neglect the importance of cultural aspects, we emphasize it".*

One of them is also attempting to engage the entire workforce in innovation activities. Interestingly, patenting activity as a best practice was only noted by one TSO: "*we have created a structure based on which all the colleagues, potentially all the 5,000 people, are involved in the innovation process".*

Finally, the specific technological innovation areas mentioned by interviewees as best practices vary widely. These include flexibility platforms and market solutions, which 36% of TSOs emphasized, followed by asset management and condition monitoring, and the controllability or management of renewables, each highlighted by 18% of respondents. Other areas mentioned include the capability to handle frequency excursions, defense systems, 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".*

Other areas include: offshore wind technologies, submarine cable technology, electric vehicle infrastructure, power-to-gas solutions, drones, artificial intelligence, robotics, digital substations, Digital Twins, and cybersecurity. This diversity showcases the broad spectrum of innovations TSOs are exploring and adopting as industry best practices. It reflects a complex interplay of factors, ranging from the unique geographical and morphological characteristics of the areas they operate in, which dictate specific technical and infrastructure needs, to the overarching political and national energy strategies that guide their focus and investments. The regulatory frameworks within which TSOs operate are also important, 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".*

4.4.3 Special focus on Non-wires alternatives (NWAs)

Interviews revealed that European TSOs are familiar with NWAs, even if they do not explicitly use this term. They generally view NWAs as opportunities, regarding certain ones as an invaluable tool for addressing the risk of bottlenecks, congestion, and other issues. The network investments required are significant and time-consuming. Therefore, any solution that improves network utilization is 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".*

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".*

Furthermore, some TSOs highlighted potential risks to profitability from the diffusion of 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, with some using them as a tool for grid planning: *"for us, during the recent planning period from 2021 to 2026, 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 reported considering NWAs only in specific contexts, as interim complementary solutions, or merely exploring them.

Regarding specific NWA technologies, 64% of TSOs reported a focus on DLRs. Other technologies mentioned were: battery storage, Flexible Alternating Current Transmission

System (FACTS), Distributed Energy Resources (DERs), hydrogen, electric vehicles and enabling technologies (e.g. V2G), and demand side management.

Finally, wireless electricity, which can be considered the most extreme form of Non-Wires Alternatives, is mostly considered a complex concept 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 possible 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".*

4.4.4 Main challenges perceived by TSOs

The key challenges most frequently mentioned by interviewees concerned digitalization and the integration of new grid technologies. 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 82% of TSOs, are as prevalent as the 'decarbonization of the power sector,' which faces its own set of 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".*

Many TSOs mentioned challenges with talent attraction and retention, recognizing the urgent need to increase the workforce with new personnel to cope with the above challenges: "*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 necessary grid upgrades and risks of rising public opposition if the transition is perceived as inequitable and unjust. TSOs highlighted supply chain risks, exacerbated by increasing geopolitical tensions, the need for greater system integration and coordination, especially between TSOs and DSOs and between electricity TSOs and Gas TSOs, with a focus on grid planning.

4.4.5 Views on the evolution of the TSO

All interviewed TSOs anticipate their role remaining central during the energy transition. Only one predicts a role limited to serving as a backup for the network, due to distributed resources (self-production and energy storage) meaning the TSO will only be needed occasionally to prevent shortages and ensure security. Table 12 provides a summary of the surveyed TSOs' responses.

Most TSOs interviewed foresee their role evolving beyond traditional boundaries, for instance by seeking a stronger voice in sectoral discussions to influence regulations and sector 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".*

Table 12 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."	*"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."*
"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 center 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."	

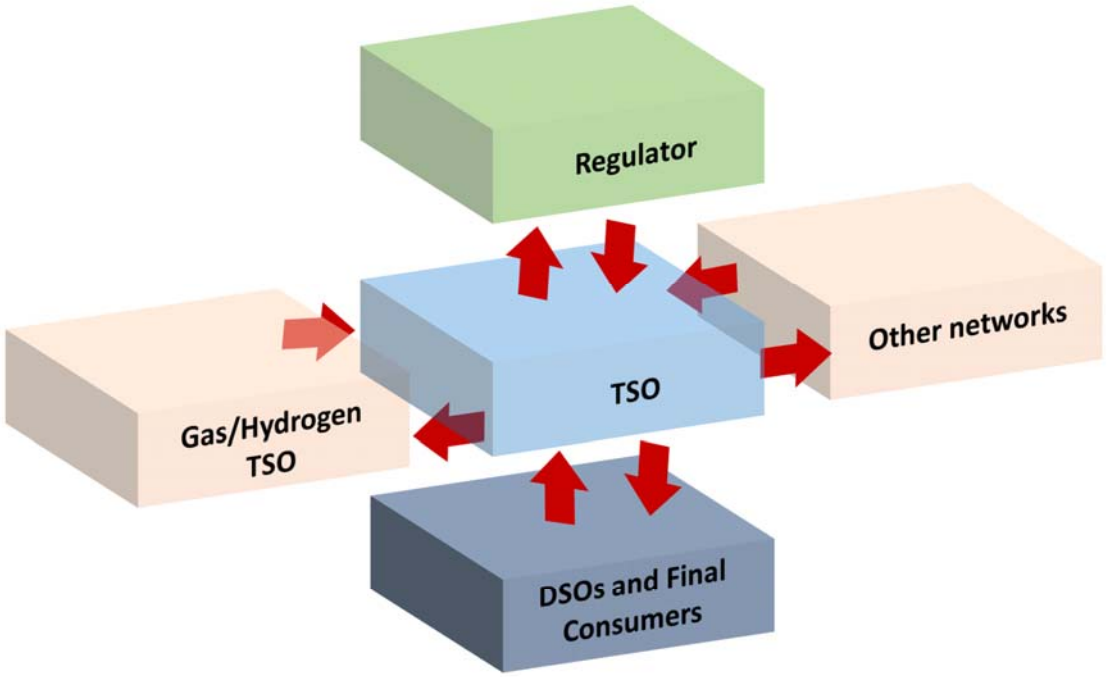
Some TSOs foresee closer, more effective collaboration between TSOs and DSOs, potentially overcoming their traditional separation via unbundling. Intuitively, adapting regulatory frameworks is necessary for TSOs to expand beyond current boundaries: *"the organization that we have nowadays between TSO 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".*

About 40% of TSOs interviewed emphasized the need for a coordinated, strategic approach to all energy infrastructures, playing a key role in sector coupling with gas and facilitating 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".*

Figure 19 illustrates the insights provided by TSOs, differentiating between short-term and long-term evolution across three layers:

- The middle layer of TSO activities is widely expected to transform, enhancing TSOs through greater intelligence and digitalization, incorporating all flexibility solutions, and extending them horizontally through improved coordination with other sectors to optimize network development. This expansion culminates with integration of electrical TSOs with other networks.
- The downstream layer of TSOs (distribution and end consumers), where some TSOs consider operational scope expansion through the flexibility potential of decentralized and distributed resources, and even interacting directly with end consumers. This would require greater coordination with DSOs and other emerging entities such as aggregators or other balance service providers. Some even suggest the idea of acquiring ownership of DSOs.
- The upper layer, related to regulation, which needs to adapt to enable TSOs to successfully tackle future challenges and adjust adequately to the challenges they face.



SHORT-TERM EVOLUTION	LONG-TERM EVOLUTION
• Stronger voice in sectoral discussions; • Revision of the current rules, particularly on permitting.	• Adapting the remuneration formula for TSOs; • Regulatory framework adaptation for NWAs; • Regulatory framework adaptation for Storage; • Reevaluation of unbundling rules between 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 networks, both in terms of planning and ownership.
• Closer collaboration with DSOs; • Harnessing flexibility from distribution.	• Shift towards more decentralized operations; • Embrace new roles and challenges at distribution level; • Engage with final consumers.

Figure 19 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.

4.5 Discussion

This chapter offered insights into how TSOs are approaching innovation, complementing the ones provided by the benchmarking analysis. Furthermore, it identified best practices that other TSOs can adopt, as well as gaps that need to be addressed.

One key best practice consists in adopting a decentralized approach to defining TSOs' innovation strategy and project implementation, potentially complemented by a centralized approach for studying and capturing technological trends. Innovative TSOs also adopt diverse methods to foster innovation, including technology labs, centers of excellence, open innovation programs, incubators, accelerators, corporate venture capital, and mergers & acquisitions. Lagging TSOs should emulate these practices from leading firms. Successful innovation requires CEO commitment, strategic prioritization of innovation, adequate budgeting, and policy review to equip innovation managers with resources for experimentation.

Best practice among innovative TSOs includes swiftly initiating new innovation projects, effectively bypassing the traditionally complex and lengthy approval processes. Agility is critical, as highlighted by the literature, suggesting that granting teams autonomy and the ability to experiment quickly should advance innovation. However, interviews revealed that most TSOs face obstacles due to their highly regulated nature, resulting in intricate and prolonged authorization procedures. TSOs should work collaboratively with regulatory bodies to address this issue. Regulators, in turn, should provide the flexibility and agility for TSOs to innovate and keep pace with technological advancements.

This chapter highlights the importance of collaboration among TSOs, involving partnerships with technology firms, peers, universities, and research bodies to acquire essential knowledge and skills for new technologies and quality service. Such collaborations, especially between TSOs and Distribution System Operators (DSOs), improve data sharing, and embracing a data-driven strategy is vital for client demands, system operations, asset management and for managing distributed resources. Sharing innovation efforts among TSOs can reduce time and costs, supporting a collective approach to common challenges.

Regarding TSOs' perspectives on their future role, the study highlights the conviction held by most TSOs about the relevance and centrality of their role, which is expected to endure,

especially in light of the energy transition. Some TSOs also foresee an expansion of their operational scope, potentially revising current unbundling rules they see as outdated. This could permit TSOs to interact directly with consumers and potentially oversee DSOs, which may lack resources for technological updates, climate adaptation, and renewable integration. Some TSOs also suggest exploring integration with other networks (gas, hydrogen, telecommunications) in both strategic and ownership aspects to support this transition.

The transformative actions previously discussed, however, will not be possible without regulatory adaptation. More broadly, regulatory adaptation can play a key role in driving TSO innovation, with the challenge of designing incentives for investment in riskier, innovative ventures.

4.6 Summary

Interviews with innovation leads at 11 European TSOs have been conducted to explore their approaches to the energy transition, focusing on innovation strategies, technology adoption, and future visions. Some TSOs adopt decentralized innovation strategies, involving business lines in defining innovation needs and exploring digital and grid technologies to improve efficiency and flexibility. However, while TSOs seek to adopt new technologies, they face barriers such as regulatory constraints, excessive bureaucracy, technology immaturity, skills gaps, and organizational cultural inertia. New insights were gained on how European TSOs envision their role evolving in the future. Particularly, this study indicates a consensus on the centrality of their role which is expected to endure but also on the need, highlighted by some TSOs, to broaden their operational scope, potentially interacting directly with consumers, overseeing DSOs, or exploring integration with other networks (gas, hydrogen, telecommunications).

5 The impact of battery electricity storage on TSOs

5.1 Introduction

The previous chapters aimed to gain insights into how European TSOs are approaching innovation, what influences their innovativeness, and how they see their role evolving in the future. This chapter explores how technological innovation might impact TSOs. This allows further conclusions to be drawn about the possible evolution of their future role and how TSOs might future-proof their organizations, and complements the previous qualitative work with some quantitative modelling insights. In particular, this chapter first examines the impact of battery energy storage on congestion rents generated by cross-border interconnectors, particularly relevant for merchant interconnectors. It then assesses the impact of reduced interconnector investment on generation costs and electricity prices, key components of TSOs and regulators' cost-benefit analyses for new transmission infrastructure.

Battery storage can be an invaluable source of flexibility for the grid and thus support TSOs in their daily business, but it also represents a potential shift towards greater decentralization in the energy sector which poses a theoretical threat to TSOs, especially given that the current regulatory framework only allows TSOs to manage these batteries in exceptional cases. In particular, this chapter will evaluate the potential impact of batteries on cross-border interconnectors.

Cross-border interconnectors are crucial to decarbonize power systems and increase energy security. They enable the export of excess renewable energy, reduce curtailment and increase system stability (Joos and Staffell, 2018; Grams et al., 2017). They aid in completing the European Union (EU) internal energy market, addressing the trilemma of energy security, economic competitiveness and environmental sustainability. They also represent a potential source of revenues for TSOs when their construction is included into their Regulatory Asset Base (RAB). However, their development face barriers such as high costs, high construction time, potential public opposition, operational risks, among other challenges (European Commission, 2019a). These infrastructures are also questioned on technical merit, with issues such as energy losses, natural disaster exposure and low utilization rates. Most importantly, the rapid deployment of asset-light innovations like non-wires alternatives (NWAs), particularly

Electricity Battery Storage might reduce the need for costly network upgrades, and lowers costs for consumers (Dyson et al., 2018; Jimison and White, 2013).

This chapter therefore addresses the question of "Will electricity storage threaten the business case for new cross-border interconnectors?". This chapter is based upon the paper "Battery electricity storage as both a complement and substitute for cross-border interconnection" (Biancardi et al., 2024). My role in this paper included the conceptualization – the development of the core idea and research questions – the choice of methodology, the analysis – data collection on storage batteries, development of the scenarios, interpretation of the results and data visualization – and the writing. My co-authors provided support by having previously built the EuroMod model and by running the scenarios I created (as they had access to the necessary GAMS and CPLEX licenses), as well as in supervision and writing – review and editing.

5.2 Background on batteries and interconnectors

5.2.1 Interconnection investment models and income mechanisms

There are two primary investment models for cross-border interconnections in Europe: the regulated and non-regulated or "merchant" model (Gautier, 2020; Poudineh and Rubino, 2017).

The regulated model is most widely used, where electricity transmission system operators (TSOs) finance, construct, and operate interconnectors. Subject to regulatory approval, investment costs are included in the TSO's regulatory asset base (RAB) and recovered through regulated tariffs, ensuring cost recovery and a rate of return. This approach shifts risks and costs onto electricity consumers, protecting TSOs (Joskow and Tirole 2005).

In contrast, the merchant model involves private companies[10], with developers bearing all risks and costs (Rivier et al., 2013). Merchant interconnectors face strict conditions for regulatory approval and have been adopted cautiously (Poudineh and Rubino, 2017; Rubino and Cuomo, 2015).

[10] TSOs may own them indirectly via a legally separate entity

The UK's regulator (Ofgem) introduced a “cap and floor” regime that blends both models by offering a minimum revenue to interconnector owners, limiting their risk. Developers' capital costs are not recovered through network tariffs as in the traditional model.

Most European interconnectors are currently developed by TSOs under the regulated model (ENTSO-E, 2020c).

Another important distinction lies in how merchant interconnectors generate value. Their profitability depends on the opportunity for spatial arbitrage which arises in the presence of transmission congestion between markets. This is influenced by price differentials, energy mix, fuel and carbon prices, and volatility (Kirschen and Strbac, 2018; Gautier, 2020). Congestion rent, the revenue generated from price differentials between interconnected markets when transmission capacity is limited due to constraints on the flow of electricity across borders (Gautier, 2020; Cretì and Fontini, 2019; Kirschen and Strbac, 2018), can thus be considered as a proxy for the commercial value of merchant interconnectors.

Congestion rent is calculated by using the following formula (Meeus, 2020):

$$\boldsymbol{Congestion\ Rent} =$$

$$(\boldsymbol{Price\ in\ high\ priced\ area} - \boldsymbol{Price\ in\ low\ priced\ area}) \times$$

$$\boldsymbol{Amount\ of\ electricity\ transmitted}$$

For example, if the electricity price in Region A (importing) is €60 per megawatt-hour (MWh) and in Region B (exporting) is €50 per MWh, the price difference is €10 per MWh. If the transmission line has a capacity of 50 MW, the congestion rent would be calculated as:

$$\boldsymbol{Congestion\ Rent} = \mathbf{10}€/\boldsymbol{MWh} \times \mathbf{50}\boldsymbol{MW} = \mathbf{500}€$$

Merchant investors have little incentive to invest in large interconnection capacity, which could reduce price differentials between markets and thus lower their revenue from congestion

rents. By underinvesting, they can maintain some level of congestion, keeping price differentials high and maximizing their profits (Cretì and Fontini, 2019).

In contrast, the profitability of most interconnectors in Europe, which are developed by TSOs, is not reliant on congestion rents but depends on the regulatory returns TOs receive on their regulated asset base. Interconnectors developed under the regulated model can also result in underinvestment because investment planning is often driven by national interests, focusing on national welfare rather than a broader, cross-border perspective. National regulators, particularly in low-price zones, may resist increased interconnection due to fears of rising prices from price convergence. De Vries and Hakvoort (2002) identify this issue, while Sagan and Meeus (2014) show that the lack of coordination at the European level significantly reduces interconnection investment compared to centralized planning.

The rationale for investing in regulated interconnectors differs from that for merchant ones, as European TSOs plan grid expansions at cross-border levels to maximize societal value. This involves maximizing total socio-economic welfare which is typically defined as the sum of the economic surpluses of electricity consumers (difference between willingness-to-pay the value of electricity and electricity price for a demand block), producers (difference between locational electricity price and generation cost), and transmission owners (congestion rent) (ENTSO-E, 2024). By enabling cheaper electricity to flow into higher-priced regions, interconnectors benefit consumers with lower prices and producers with access to higher-priced markets, while altering congestion rents for TSOs due to reduced network bottlenecks (ENTSO-E, 2024).

If, as previously mentioned, congestion rent refers to the revenue generated from price differentials between interconnected markets due to limited transmission capacity and constraints on electricity flow across borders (Gautier, 2020; Cretì and Fontini, 2019; Kirschen and Strbac, 2018), interconnection profitability is broader, as it reflects the financial returns for all services that the interconnector provides. It considers revenues from congestion rents as well as capacity markets and ancillary services provided (e.g. enhanced frequency response, reactive power, emergency assistance and cross-border balancing), and factors in the costs associated with maintaining and operating the infrastructure (Gautier, 2020).

The ‘Multi-Criteria and Cost-Benefit Analysis (CBA)’ methodology developed by ENTSO-E, under ACER's supervision, provides a standardized framework for assessing cross-border transmission projects (ENTSO-E, 2024). It is central to the Ten-Year Network Development Plan (TYNDP), identifying priority grid expansion projects across Europe. It enables project evaluation using the most robust indicators, including monetary values where a consistent European-wide unit is available. Unlike standard CBA, which focuses solely on maximizing socio-economic welfare which, in the context of transmission network development, is the sum of the short-run[11] economic surpluses of electricity consumers, producers, and transmission owners (congestion rent), multi-criteria analysis allows to consider multiple objectives that cannot be aggregated using shadow prices or welfare weights such as system safety and environmental impacts, disaster and climate resilience, etc. The evaluation, therefore, incorporates both qualitative and quantitative assessments to ensure a comprehensive representation of costs and benefits, highlighting project characteristics and providing decision-makers with sufficient information. This approach allows for a homogenous assessment of projects, based on monetized costs and benefits while acknowledging the existence of significant non-quantified benefits and facilitating comparisons between projects regardless of their location or the regulatory environment in different countries. Finally, the analysis should be based on scenarios representing future conditions for generation and demand, to assess marginal benefits against a reference network, though in reality, projects alter the reference network, albeit with an often-significant time delay (ENTSO-E, 2024).

With regard to cost allocation at country level for TSO-led cross-border transmission projects, countries typically agreed to pay for assets within their own territories, proceeding if both found the investment justified. If one country had reservations, the project could be delayed or canceled. In such cases, the country more committed to the project had an incentive to offer compensation to its neighbor. As noted by Olmos et al. (2018) and Rivier et al. (2013), since network investments are undertaken based on the benefits they generate, the costs should be allocated to network users in proportion to the benefits they are expected to gain (i.e. "beneficiary-pays" principle).

[11] The method has multi-year horizons. Hence, the short-run surplus is calculated multiple times.

5.2.2 Non-wires alternatives

Traditional grid infrastructure - wires, poles, and substations - is challenged by the rapidly growing deployment of “non-wires alternatives” (NWA). These are low-carbon, cost-effective and easily installed technologies and business solutions that, individually or in combination, provide valuable flexibility services to system operators (Dyson et al., 2018; Navigant, 2017), and help defer and avoid traditional infrastructure upgrades. They can remain resilient to uncertainty of load growth, avoiding stranded costs if load does not increase (IRENA, 2020a, Kirschen and Strbac, 2018).

Integrating NWAs into system planning is common in parts of the United States, particularly at the distribution level where grid operators are incentivized to utilize NWAs. This approach is less widespread in Europe (Power, 2022b), with adoption hindered by regulatory barriers, specifically unbundling rules mandating separation of system operation from electricity supply and generation activities (Steinbacher and Stanton, 2019). This contrasts with the US system, where vertically integrated utilities manage grid assets and have direct oversight of Distributed Energy Resources (DERs). This allows them more flexibility to delay or bypass traditional grid expansion, leading to a more efficient utilization of NWAs. However, utilities in some jurisdictions may not own NWAs and thus may need to contract with NWA providers (Lyons, 2019).

Electricity storage, particularly lithium-ion batteries, are promising NWAs (Menonna and Holden, 2020; EPRI, 2020) and are seeing high growth due to rapidly declining costs and rising investor confidence (Schmidt et al., 2017). Batteries offer flexibility by being easily scalable, relocatable, and quick to construct (Mountain and Carstairs, 2018). Deploying storage requires up to two years less than traditional solutions, realizing savings for consumers (Kumaraswamy et al., 2020).

Electricity storage stabilizes market prices by reducing price volatility and avoiding spikes, threatening interconnector revenue. Utility-scale storage is well-suited for addressing short-lived transmission network constraints by shifting energy supply and consumption, especially during peak demand periods (congestion relief), as demonstrated by Tesla’s batteries in South Australia in 2020 (Mazengarb, 2020). Batteries with a short discharge duration can alleviate

congestion and provide a cost-effective solution for rare network congestion events (Marnell et al., 2019; Del Rosso and Eckroad, 2014).

Battery storage can increase transmission capacity by creating “virtual power lines” (VPLs) with two or more batteries located upstream and downstream of critical transmission bottlenecks (IRENA, 2020b). This offers a cost-effective solution to grid capacity shortages to help avoid curtailment (Sidhu et al., 2018).

The Clean Energy Package limits network operators’ ownership of batteries to promote competition and market openness in the energy sector, ensuring a level playing field for all participants. However, some TSOs have started exploring innovative ways to operate batteries, such as France’s TSO RTE with the “RINGO” pilot project (IRENA, 2020b; Biancardi et al., 2021), AES Gener’s proposal in Chile and Germany’s “Grid Booster”.

5.2.3 Power system modelling

Energy system models aid understanding the future of energy markets, making policy decisions, and guiding investments. With the focus on energy security, affordability, resilience, and environmental sustainability, and new challenges such as flexible demand, electrification, and renewables, there is a renewed focus on improving energy system modelling (Fodstad et al., 2022; Pfenninger et al., 2018).

The discipline of energy system modelling has gained popularity due to the energy transition and technological advancements (Pfenninger et al., 2014). It increasingly intersects with power system models, such as PyPSA, PLEXOS, and ELMOD, which focus on electricity and are used to analyze renewables’ impact on prices and for market design and investment decisions. However, challenges remain, including the need to reassess current methods, integrate innovative approaches, address complexity, comprehend uncertainty, and maintain transparency and reproducibility. For example, improving temporal and spatial resolution to evaluate the feasibility of transitioning to a renewable energy system, which is crucial for informed decision making in the energy modelling community (Pfenninger et al., 2014).

The most common day-ahead markets incorporate techno-economic constraints in price formation, allowing the optimal price to be found that minimizes total system costs. These models estimate hourly wholesale prices assuming that profit-maximizing generators bid at

their marginal cost in a competitive market. The choice between piecewise linear or quadratic cost functions influences dispatch and price curves, with the latter providing better representation, yet this still underestimates price volatility and undervalue storage and transmission as a result (Ward et al., 2019).

Recent models seek to address these flaws. EuroMod, a European electricity market model, improves wholesale price formation by incorporating a quadratic cost function and empirical relationships between price and demand net of renewable generation (Mendes et al., 2024). This results in reduced errors on modelled storage and interconnector revenues.

5.2.4 Literature review

Several studies have focused on the crucial role of batteries and other technologies, such as energy efficiency and demand response, in supporting TSOs in achieving 2030 emissions reduction goals (CurrENT Europe, 2022). These studies assessed the feasibility, cost-effectiveness, and potential impact of these technologies on the transmission system.

Batteries and interconnectors have often been analyzed together as alternatives for integrating large amounts of variable renewables. However, there remains no consensus on which is the better option. For instance, Knezovic et al. (2021), offer a framework for assessing the economic value of integrating transmission, generation, and storage, concluding that interconnection is most cost-effective. Conversely, Mehigan et al. (2022) recognized the ability of well-positioned batteries to manage congestion and defer network investments in a 2030 scenario for Europe.

Hirth et al. (2015) emphasized that variable renewables integration costs depend on their features and the power system's flexibility. Long-term adaptations in operations, market design, and technology will lower these costs compared to short-term adaptations, highlighting the value of storage to the system. Neetzow et al. (2018) explored how storage and transmission interact in renewable energy systems, finding that they can complement each other in minimizing system costs. Applying this to the Italian power system, they find storage and transmission can be both substitutes and complements, guiding infrastructure planning to prevent design errors like misplacement of storage. Additionally, Golombek et al. (2022) highlight the necessity of both storage and transmission for cost-effective European

decarbonization, with the optimal mix depending on factors like renewable source location, grid topology, and technology costs.

Heuberger et al. (2017), found that grid-level energy storage has significantly higher system value compared to other technologies, but that this value declines rapidly as more capacity is deployed. Arteaga et al. (2020) assesses Energy Storage as a Service (ESaaS) for transmission congestion relief, showing that these services can enhance storage value, but its success depends on market competition and potential opportunity costs. Khastieva et al. (2019) explore the joint planning of transmission lines and energy storage in the energy system, finding that their combination significantly boosts social welfare, and recommending that regulators incorporate energy storage into transmission planning.

Focusing on the flexibility needs, Child et al. (2019) suggest that for a fully renewable European energy system, a mix of battery storage, grid expansion, and demand-side flexibility is most cost effective, emphasizing the importance of batteries for short-term flexibility with diverse renewable sources. Rinaldi et al. (2022), compare various flexibility options for integrating renewable energy in Switzerland, including both storage and grid expansion. Resch et al. (2022) provide techno-economic analysis of different flexibility options, including batteries, as alternatives to traditional grid expansion for a specific distribution grid in Germany. Daou Pulido et al. (2022) argue that in Southern Europe, battery storage is a more efficient and versatile solution for grid flexibility than grid expansion, due to its quicker deployment and ability to provide additional services like frequency regulation and peak shaving.

Some research highlights batteries' complementary role with interconnectors (Hormark, 2014; European Commission, 2020). Others consider the role of batteries as substitutes for transmission lines, citing real-world examples of successful non-wires alternatives implementation (IRENA, 2020a; E4TheFuture, 2018), although no study has specifically focused on cross-border interconnectors. For example, IRENA (2020b) evaluated the potential and benefits of Virtual Power Lines in grid management for reducing traditional transmission investments needs, for example in the case of France's TSO RTE with the "RINGO" pilot project.

One study proposed a novel market-based model, the "Contract for Deferral Scheme" (CDS), to evaluate a portfolio of distributed resources as an alternative to grid reinforcement, but with a

focus on distribution grids (Poudineh and Jamasb, 2014). Only one study combines the qualitative evaluation of NWAs with quantitative modelling (Konstantelos and Strbac, 2015). It examined the impact of storage to delay transmission investment and manage planning uncertainty, including its ability to provide grid services and support integration of renewable energy sources. NWAs flexibility was deemed highly valuable since it enables option holders to postpone investment decisions and capitalize on future market conditions. While the study provides valuable insights into the valuation of transmission investment options, it does not account for, nor seek to quantify, the influence of storage on the profitability of interconnectors. This factor is critical for making well-informed investment decisions. For example, if a considerable portion of transmission capacity is determined to be unnecessary as it is substituted by battery storage, it could be a viable option to forgo investment to reduce costs to bill-payers.

Another avenue of research compares the business case of energy storage and interconnection for arbitrage. Studies of storage profitability often focus on a limited number of revenue sources like arbitrage in wholesale markets alone, or in combination with a service such as short-term balancing; and typically conclude that storage is not profitable (Brijs et al., 2019; Wilson et al., 2018). This mirrors developers finding that arbitrage alone is unprofitable, and developing complex, context-specific business cases involving multiple services for increased revenue (Schmidt and Staffell, 2023). This multifaceted approach, varying across countries and influenced by market designs, is not easily captured in continent-scale power system models which encompass many national markets. For instance, despite the current unprofitability of lithium-ion for arbitrage in Great Britain (Schmidt and Staffell, 2023), its capacity is expected to grow to over 12 GW by 2025 (Rystad Energy, 2023).

Summarizing, existing research has focused on modelling non-wires alternatives, exploring the possibility of utilizing storage to delay investments in transmission assets, and on determining the need for integrating storage and interconnectors in system planning. However, to date, no study has specifically addressed the impact of storage batteries on the profitability of interconnectors, particularly with regard to profit from price arbitrage.

5.3 Methodology

The EU power sector was modelled, encompassing both recent history (2017–2020) and several future scenarios (2030). The research aims to investigate the impact of varying storage battery quantity on congestion rents generated by cross-border interconnectors. While congestion rent is only one factor in developing new cross-border transmission at the EU level, and is not the primary objective for most projects—since TSOs typically finance infrastructure through transmission tariffs rather than relying on congestion rents—applying a merchant perspective can help assess the business case for new interconnectors. This approach partially helps identify whether an interconnector could be financially viable and competitive in a market-driven environment, based solely on congestion rents, as other potential revenue streams are not considered, complementing the broader policy and infrastructure goals pursued by TSOs.

Wholesale electricity prices were simulated across European markets, from which the congestion rent across cross-border interconnectors was calculated. To acknowledge the wide uncertainty in future uptake of energy storage, a broad spectrum of scenarios was developed for potential uptake based on diverse methods.

For these scenarios, all other capacities were held constant to assess the short-run equilibrium. The profitability was calculated for storage systems performing temporal arbitrage, to sense-check the economic viability of the capacities being deployed. The congestion rent across cross-border interconnectors was then calculated under this short-run equilibrium, to assess the extent to which storage reduces congestion rents.

Transmission capacity was then adjusted to identify the level that would yield a congestion rent equivalent to the baseline scenario without additional storage (the long-run equilibrium if only transmission investment decisions change). This contextualizes the extent of new cross-border transmission interconnection capacity that could potentially be circumvented.

Finally, the economic effects of reducing grid size are evaluated in terms of the impact on total electricity generation costs (i.e. the cost of fuel and of CO_2) and total expenditure on wholesale electricity. A clear limitation of the study is that it only considers the short-run equilibrium, focusing on operational changes without addressing the long-run equilibrium and potential capacity adjustments. The addition of batteries could also influence other factors, such as the

deployment of additional solar PV. These capacity changes, not accounted for here, would affect both congestion rents and total costs, potentially altering the study's findings.

5.3.1 The EuroMod power market model

The EuroMod model was selected as the most suitable tool for the research, given its capacity to accurately measure congestion rents across cross-border interconnectors, and assess the impact of the proliferation of storage batteries on such rents across Europe (Mendes et al., 2024). This selection was motivated by EuroMod's specific focus on modelling the variability of wholesale prices so that arbitrage for flexibility providers is captured more accurately than with traditional linear programming models.

EuroMod is an electricity model that aims to develop more accurate electricity prices. The model incorporates a zonal European market structure that reflects the market clearing mechanism, taking into consideration both power system and network constraints. EuroMod enhances a classic linear dispatch electricity model by transforming the total system cost function from a step-wise linear form to a quadratic form, and adding a linear post-processing stage. These changes generate more realistic supply and price curves, improving the model's ability to depict daily price variation. These model improvements make it a suitable tool for examining the impact of price volatility on the market, as well as the significance of price spreads on arbitrage earnings and the cannibalization of prices between different technologies.

A comprehensive explanation of the workings of the model can be found in Mendes et al. (2024). In summary, EuroMod is a bottom-up model of the European interconnected power system, covering 27 countries: Austria, Belgium, Bulgaria, Czech Republic, Switzerland, Germany, Denmark, Estonia, Spain, Finland, France, Great Britain, Greece, Hungary, Ireland, Italy, Lithuania, Latvia, Netherlands, Norway, Poland, Portugal, Romania, Sweden, Slovenia, and Slovakia.

It minimizes total system costs with respect to dispatch, storage and interconnectors. For each hour of the year, demand and supply of electricity is matched and a clearing price is determined. Individual generation and storage technologies are explicitly modelled. It features 6 generation and 4 storage technologies (3 types of hydro, plus batteries). Technologies such

wind, solar, run-of-river and other renewables are exogenously included in the model as time-series. Demand fluctuates exogenously and it is perfectly price-inelastic.

The model is subject to a set of technical constraints related to demand and supply balance, combined heat and power, cycling of thermal plants, and operational constraints on hydro. Trading between bidding zones or countries is subject to net transfer capacity, and it takes place until arbitrage possibilities are exploited or capacity constraints become binding. Unit commitment of individual power stations and optimal load flow are not modelled.

Markets are not assumed to be perfectly competitive by proposing two enhancements to the total system cost function:

1. to allow generators to bid or to sell electricity at prices which deviate from their marginal cost, and
2. to apply a linear transformation on the resulting modelled prices so that they better reflect the volatility of prices seen in real power markets.

The resulting market-clearing price resembles the equilibrium price on European wholesale electricity markets. EuroMod is written in GAMS and solved using CPLEX. The dispatch across 27 countries for one year of 8760 hours can be solved on a desktop computer (i.e. with Intel Core i7 - 6850K Processor, 3.6 GHz (6 cores) of speed and 64 GB RAM) in about 10 minutes.

EuroMod extends the analysis of storage technology beyond traditional closed- and open-looped pumped hydro systems to include battery storage technology, adjusting the capacity of the battery storage across various scenarios to assess its impact. EuroMod's approach to dispatching storage aims to minimize the total system cost. This approach effectively mirrors the outcomes of a competitive (rather than monopolistic) market scenario where individual storage operators would seek to maximize their profits through energy arbitrage (Staffell and Rustomji, 2016). This modelling focuses exclusively on the potential of storage to facilitate energy arbitrage, intentionally excluding the exploration of additional revenue streams that could arise from offering ancillary services, a strategy known as "revenue-stacking" that could further enhance the business case for storage technologies (Schmidt and Staffell, 2023).

Specifically, battery storage systems are modelled as 4-h duration lithium-ion, which corresponds to a C-rate of 0.25, with an 86% round-trip efficiency. This duration aligns with the 75th percentile for utility-scale stationary battery systems installed in the US by 2022 (Schmidt and Staffell, 2023), reflecting the shift towards longer-duration battery systems (BNEF, 2024). The round-trip efficiency is reflective of the industry-wide average for stationary systems, further grounding the scenario analysis in realistic technological parameters and industry trends (Schmidt and Staffell, 2023).

5.3.2 Calculating cross-border interconnectors congestion rent

To calculate the congestion rent across cross-border interconnectors, the short-term ability to provide spatial arbitrage was considered, which is calculated as the difference between the value of electricity imported to all countries and the cost of all electricity exported. More precisely, it is computed as the wholesale price in the importing market multiplied by the volume imported, subtracted by the wholesale price in the exporting market multiplied by the volume exported. This calculation accounts for short-term variable costs, including transmission losses, while disregarding fixed operating costs (such as maintenance and insurance) and capital repayment costs.

Next the transmission quantity was modified to determine the volume required to generate a specific congestion rent (€million/GW) equal to that of the base case. This approach obtained an approximation of the possible delay in the need for transmission capacity that may arise as a consequence of the adjustment in storage capacity.

The model treats storage quantity as exogenous, by not re-optimizing the rest of the capacity mix in response to adding more storage. The goal of this study is to test how much storage capacity will affect the value of transmission and the optimal capacity of it, with all else held equal.

One reason for this approach is the reliance on the European Network of Transmission System Operators for Electricity (ENTSO-E) Ten-Year Network Development Plan (TYNDP) scenarios, which are well-established and respected. The three scenarios are: Distributed Energy Generation (DG), National Trend (NT) and Global Ambition (GA). These depict potential futures for the European power sector, based on a range of factors including drivers, challenges, and

opportunities. Specifically, DG aligns with the Paris Agreement's 1.5 ◦C target and envisions a future with increased decentralized power generation, greater utilization of renewable energy sources such as solar panels, and adoption of electric vehicles and vehicle-to-grid technology. In contrast, NT anticipates a gradual increase in renewable energy deployment, while continuing to rely on fossil fuels and nuclear power, and investing in new technologies such as carbon capture and storage. GA also aligns with the Paris Agreement's 1.5 ◦C target and takes a more ambitious approach. It envisages a coordinated and rapid transition to renewables, significant investments in energy efficiency measures, and the eventual phase-out of fossil fuels and nuclear power. Unlike the DG scenario, the GA scenario envisions a future that is led by economic development in centralized generation. The ENTSO-E TYNDP scenarios also incorporate three climatic years (1982, 1984, 2007) used to project electricity demand and supply from weather-driven renewables (wind, hydro and solar).

When considering scenarios with increased battery storage uptake, the capacities of all other technologies were held constant (generation, hydro storage and transmission). Attempting to re-optimize capacity without full access to the assumptions and data underpinning TYNDP would introduce inaccuracies. Furthermore, the pace at which storage capacity is deployed supports this design choice. Storage systems can be developed within a year or less, contrasting with the longer planning and construction timelines of most power station or transmission technologies. Therefore, it is realistic to assume that the power sector's infrastructure may not be able to quickly adapt to new storage investments, and only the operation of existing assets might be able to respond to these changes.

5.3.3 Scenarios for battery storage uptake

Three scenarios for battery storage were developed: Base Case (BC), Robust Growth (RG), and Aggressive Penetration (AP). These scenarios are not forecasts or projections of future storage uptake. Instead, their purpose is fundamentally exploratory, aimed at examining the potential impacts on transmission dynamics in the event these scenarios unfold. This exploration is underpinned by a diverse array of methodologies, each characterized by its distinct perspective and approach: one scenario is derived from ENTSO-E, embodying the perspective of Transmission System Operators; the second is an abstraction across several academic modelling studies, providing a theoretical framework for analysis; and the third originates from

Bloomberg New Energy Finance (BNEF), a commercial consultancy, providing a projection grounded in thorough market analysis. Rather than using modelling to identify the economically optimal capacity of storage for Europe, this approach of using hypothetical scenarios which span a wide range of storage uptake was chosen to reflect the large uncertainty over the technology's future development. Treating storage instead as an endogenous variable, and co-optimizing the investment in storage and transmission is a possible avenue for future work.

In the baseline scenario, the values for battery capacity in 2030 were obtained from the ENTSO-E TYNDP scenarios mentioned in Section 5.3.2. These three scenarios, differ in their levels of storage, with the battery storage capacity across Europe in 2030 totaling 22.6 GW for DG, 16.4 GW for GA and 12.4 GW for NT.

In the second scenario (Robust Growth), higher values for storage were assumed. The values for battery capacity in 2030 were calculated based on the relationship penetration of variable renewables (wind and solar) derived by Schmidt and Staffell (2023). They reviewed thirty academic and industry reports conducted in Europe and the United States and used least-squares regression to produce an exponential relationship between these variables, given in Equation (1):

$$y = 0.02539\, e^{0.02949\, x}$$

Where y is the optimal capacity of storage (relative to peak demand) and x is the share of electricity demand met by non-dispatchable renewable sources. Figure 20 provides a graphic representation of this relationship.

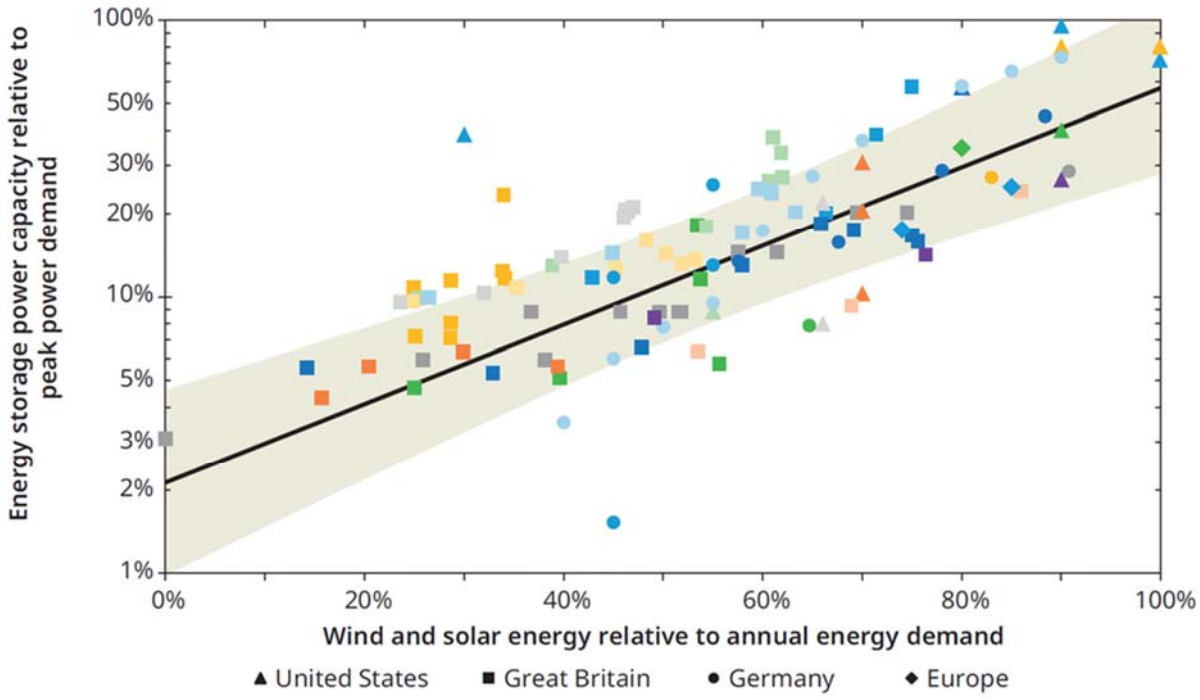


Figure 20: The relationship between the annual energy generated from wind and solar sources and the installed power capacity of storage as a fraction of peak demand. Data points indicate the results from individual studies, with their shape indicating the region covered. The black line signifies Equation (1), the shaded area signifies the prediction interval across all studies. Source: (Schmidt and Staffell, 2023).

All the necessary data required for the computation of the implicit value for battery storage capacity, such as energy demand, wind and solar energy generation, and peak demand capacity were taken from ENTSO-E. The data provided by ENTSO-E across the TYNDP scenarios (DG, GA and NT) was applied to Equation (1) to deduce the implicit absolute value of battery storage capacity. The proportion of annual energy obtained from wind and solar sources was calculated, and the installed power capacity of storage, as a fraction of peak demand, quantified in megawatts (MW). The resulting installed capacity of storage is a factor of 3–5 times higher than in the ENTSO-E baseline scenarios. In the Robust Growth, projected storage capacities vary across the different sub-scenarios, as follows: 66.2 GW for DG, 60.6 GW for GA and 61.5 GW for NT.

Equation (1) provides a high-level empirical approximation for the adequate level of energy storage for power systems with high proportions of variable renewable energy sources. This is based on a regression analysis from various countries, and various studies which employ

different methods and assumptions. It incorporates the share of the electricity mix which is produced by weather-dependent renewables, but ignores other specific aspects of national energy mixes, such as the balance between flexible and must-run power plants (for instance, hydro, nuclear, and gas turbines are not distinguished between). This simplification is a trade-off for breadth of sources considered: the equation was derived from findings across 30 power system modelling studies of diverse geographical regions.

In the third scenario (Aggressive Penetration), data from Bloomberg New Energy Finance was employed for some of the countries for which national projections were given (BNEF, 2022). More precisely, for those countries where BNEF data was available (such as Germany, the United Kingdom, Italy, France, and Spain), the highest estimate between the (BNEF, 2022) data and the values obtained from the preceding scenarios was utilized. In the absence of BNEF data for other countries, the highest estimate derived from the first two scenarios was considered. In the Aggressive Penetration scenario, the projected storage capacity amounts to 95.3 GW, a factor of 4–8 times higher than the ENTSO-E baseline scenarios.

Figure 21 provides a graphic summary of the scenarios developed and used in the study.

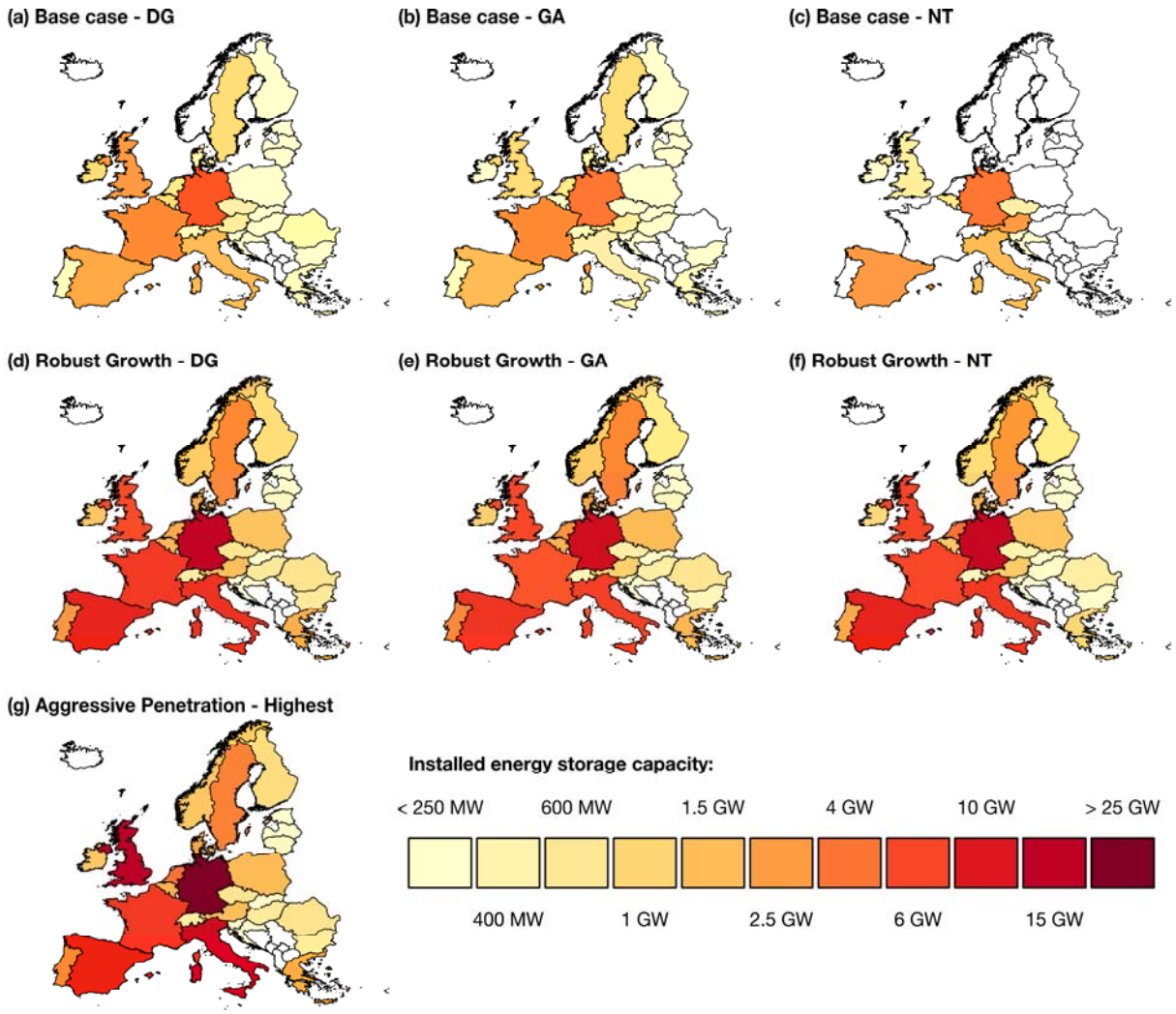


Figure 21 Scenarios on values for battery electricity storage capacity installed in 2030. Light yellow indicates low installed energy storage capacity. Dark red indicates high installed energy storage capacity. Panels (a–c) shows values for Base Case scenario, obtained from the ENTSO-E TYNDP's scenarios (Distributed Energy Generation – DG, Global Ambition – GA, National Trend – NT). Panels (d–f) shows values for the Robust Growth scenario, calculated by utilizing the data from ENTSO-E TYNDP's scenarios (DG, GA, NT) and the correlation identified in the study by Schmidt and Staffell (2023). Panel (g) shows the values for Aggressive Penetration scenario, which considers the highest estimate between the data obtained from the preceding scenarios and data from Bloomberg New Energy Finance – BNEF (2022).

5.3.4 Scenarios with reduced cross-border transmission capacity

Ultimately, the study entails modifying the transmission quantity to determine the requisite volume necessary to generate a congestion rent equivalent to that of the base case. Specifically, simulations were conducted to observe how the total congestion rent across the European

cross-border network changes with reduced transmission grid sizes in contrast to the base case, wherein the grid capacity is 100% as anticipated for 2030 according to TYNDP. It is intuitively expected that the total congestion rent would increase as the grid size decreases, implying that the positive effects of increased price differences would outweigh the negative impacts of decreased transmission volume.

Additionally, an aim was to calculate the total grid size that would enable the achievement of the same anticipated total congestion rent as projected by TYNDP and compare it to the TYNDP plan. This will enable to discern the extent to which new transmission projects intended between 2020 and 2030 in TYNDP could be avoided. It should be noted that this reduction would solely apply to new capacity planned in TYNDP, while existing interconnectors would remain unaffected.

A similar analysis was conducted using specific congestion rent level (€million/GW), which quantifies the amount of congestion rent earned per GW of transmission, to determine the absolute reduction in the grid size required to achieve the same expected specific congestion rent level and estimate the amount of new planned capacity in TYNDP that could be avoided.

Finally, the broader economic impacts of reducing grid size were examined to provide an initial perspective on societal implications. The total cost of electricity production was derived from EuroMod's optimization solution, representing the short-run variable costs of generation, including fuel and CO_2 costs. This was based on the linear programming (LP) version of the model, without the additional quadratic constraints that allow generators to bid wholesale prices that deviate from short-run marginal cost. Additionally, total wholesale electricity expenditure was calculated as the product of electricity demand and its marginal price, aggregated across all hours and countries. The difference between this expenditure and production cost offers a simplified measure of producer surplus, although it excludes fixed operating costs for generation, storage, and transmission assets. Future research could incorporate consumer surplus to assess overall welfare impacts; however, this is currently unfeasible due to EuroMod's assumption of perfectly inelastic demand (below the level of 1000 €/MWh VOLL – value of lost load).

5.3.5 Calculating battery storage profitability

Given that battery storage uptake scenarios are derived from sources external to the primary model scenario (ENTSO-E's TYNDP), their economic viability was evaluated. These scenarios project a substantial increase in storage capacity, which could be economically unsustainable due to the phenomenon of storage cannibalizing its own revenue (Schmidt and Staffell, 2023).

To assess the economic viability of battery storage, the short-run arbitrage profit for storage in each scenario was evaluated. This profit is determined by the revenue from electricity discharge (price multiplied by the volume of discharge summed over all hours) minus the charging costs (price multiplied by the volume of charging summed over all hours), accounting for the assumed 86% round-trip efficiency. This calculation excludes other operating expenses such as maintenance, labour, insurance, etc., making it an indicative measure of a project's profitability, analogous to the spark spread (wholesale electricity price versus the cost of gas needed to produce it) or the crack spread (value of refined hydrocarbons versus the cost of input crude).

5.4 Results: Batteries vs Interconnectors

5.4.1 Validity of modelling cross-border interconnectors congestion rent

To evaluate the model's effectiveness in accurately depicting both transmission flows and market prices in all European countries simultaneously, and consequently the reliability and credibility of interconnector revenue simulation, a retrospective analysis was first carried out by undertaking a comprehensive four-year modelling of the entire European region from 2017 to 2020.

Figure 22 shows the efficacy of EuroMod in representing the pertinent metrics of the study over the period 2017–2020.



Figure 22 EuroMod efficacy in representing the pertinent metrics of the study over the period 2017–2020. Panels (a–c) show the aggregate results across all of Europe over the four years studied, while panel (d) shows the results from individual transmission corridors.

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The numerical data presented in this section show that the average congestion rent (as indicated in panel a) per year between 2017 and 2020 according to ENTSO-E prices and flows was €1.94 bn whereas EuroMod presents a 7% discrepancy, with an average of €1.80 bn per year, except for the year 2020 where there was a 36% shortfall compared to the actual revenue. The discrepancy for 2020 can be attributed to the unprecedented impacts of the COVID-19 pandemic on the electricity market (Mehlig et al., 2021). Indeed, excluding 2020, the average error is only 3%.

Panel b shows the average transmission flows which in EuroMod (324 TWh) were 15% higher than the ENTSO-E figures (282 TWh). This error can be explained by a combination of missing data from the ENTSO-E Transparency Platform, which account for 1–59% of observations (European Commission, 2018), and the structure of EuroMod, which does not employ a DC load-flow approach, and so does not fully represent line congestion which could lead to different dispatch decisions from what happens in reality.

Conversely, the median arbitrage (shown in panel c), representing the price difference between markets weighted by transmission volume, was consistently underestimated in EuroMod by 18% compared to ENTSO prices (€8.52 vs. €10.46), which is expected given the difficulty in replicating extreme price spikes in electricity markets. Models, in fact, even this with better price granularity struggle to replicate the extreme spikes seen in real electricity prices (Ward et al., 2019; Mendes et al., 2024).

EuroMod also reasonably replicates the lines that generate the most congestion rent across Europe (illustrated in panel d), with an R-squared (R^2) of 0.78[12].

However, there are certain deviations in the model's surplus estimation, particularly overestimation on three of Germany's borders and borders with hydro-dominated countries such as DE ⇄ CH, IT ⇄ CH, and SE ⇄ NO. This is understandable, given the structural differences in German prices and the difficulty in modelling hydro prices. Germany, in fact, is highly reliant on lignite but does not have published prices due to the non-market nature of that commodity and the complexity of hydro pricing. A more detailed representation of hydro plants would be needed to explore the different arbitrage opportunities of hydro power plants and get more refined price time series. This detailed information is lost when a more aggregated approach is used, but this is a necessary limitation due to the barriers to obtaining such detail for the 27 European countries used in the model. The intricate nature of the system being simulated precludes the model from achieving complete accuracy across all metrics. Moreover, several factors such as the outages that may arise in individual nuclear reactors or transmission lines, which could have an impact on prices, trade flows, and other aspects of the system, exacerbate

[12] R-squared (R^2) is a statistical measure in a regression model that determines the proportion of variance in the dependent variable that can be explained by the independent variable

the difficulty of attaining total precision. Nonetheless, despite these challenges, the model remains suitable for its intended purpose of evaluating the future profitability of transmission lines. For instance, the large links between GB ⇄ FR and FR ⇄ ES are well modelled, with a negligible error of only 1%.

5.4.2 Impact of battery storage uptake on cross-border interconnectors congestion rent

In relation to the influence of battery capacity on cross-border interconnectors congestion rent, the study examines the landscape of Europe in 2030, specifically focusing on a comprehensive analysis of 27 countries spanning the entire region, using data derived from ENTSO-E TYNDP. Notably, the analysis incorporates distinct scenarios, each comprising combinations of three set of technological factors (DG, GA, NT) and three climatic years (1982, 1984, 2007) as specified by ENTSO-E to capture the variability in electricity demand and supply from wind, solar, and hydro sources due to weather effects (Collins et al., 2018). Furthermore, to assess the impact of battery uptake, these scenarios were evaluated under three separate conditions, considering different scenarios related to the adoption of battery technologies.

Figure 23 compares the historical congestion rent (as shown in the previous figure) with the anticipated congestion rent in the future, under the base case of ENTSO-E TYNDP battery levels, as well as two cases that involve higher battery penetration.

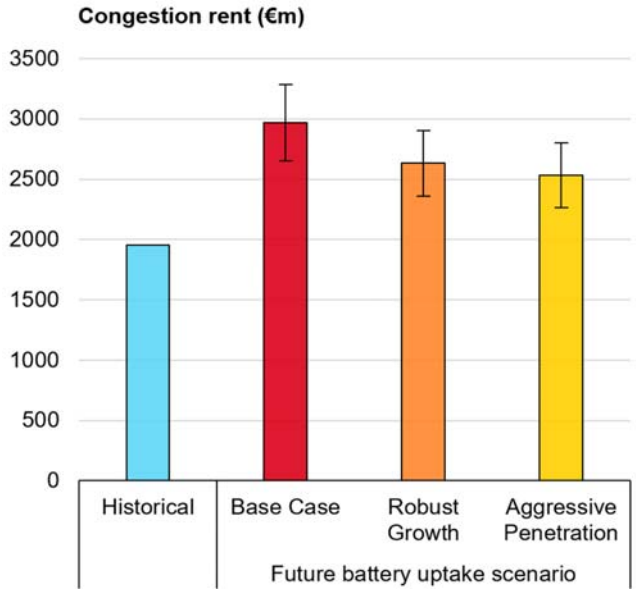


Figure 23 Congestion rent in the three scenarios. It shows the transmission revenue across the 27 European countries modelled, comparing historical congestion rent with future scenarios, which include the base case (ENTSO-E TYNDP battery amount) and two cases with increased battery penetration. The three future bars represent different storage uptake levels (from lowest to highest, left to right). Future charts' error bars indicate variation between scenarios, representing one standard deviation across the nine TYNDP scenarios.

The analysis reveals several key features regarding the impact of battery capacity on congestion rent across cross-border interconnectors in Europe by the end of this decade. Firstly, congestion rent is expected to increase significantly due to greater capacity and higher price volatility caused by variable renewable energy penetration. Secondly, the two battery growth scenarios result in a significant reduction in congestion rent across cross-border interconnectors. Thirdly, there is some variation in the results among the scenarios, with the error bars in the future charts representing one standard deviation across the nine TYNDP scenarios.

The overlap between the battery scenarios is primarily due to the three grid scenarios taken from TYNDP. On average, DG has 15–16% more congestion rent than GA, and GA has 5–6% more than NT. The rationale for this can be attributed to the inherent characteristics of the scenarios, which respectively anticipate a centralized or decentralized development of the energy system, as well as by the different level of electrical demand. Additionally, the three climatic years, which determine renewable productivity, also contribute to the variation in

results. For instance, 1984 yields 7–9% less congestion rent than 1982 and 2007, as it has the lowest wind farm capacity factors of the three years. Despite the variation, there is a consistent and statistically significant decrease in congestion rent when increasing battery storage. Across all the linked sets of scenarios, such as DG 2007 Base Case vs. the other battery scenarios, the average reduction in congestion rent is €337 ± 70 m for Robust Growth and €437 ± 69 m for Aggressive Penetration.

Similar to the reduction in the congestion rent resulting from the deployment of batteries, the expansion of the transmission infrastructure would also cause a decrease in the congestion rent. The ENTSO-E TYNDP plans for 2030 envisage an increase in cross-border interconnection capacity from approximately 81 GW to around 102 GW. However, building less interconnection could enhance market splitting due to congestion, leading to increased revenues from cross-border trade.

5.4.3 Impact of reduced transmission capacity on cross-border interconnectors congestion rent

To investigate the potential impact of reduced grid sizes on the interplay between transmission expansion and storage uptake, the change in total congestion rent across the European network was examined with smaller transmission grids.

Figure 24 displays the changes in congestion rent with decreasing grid capacity, modelling the impact of electricity storage reducing future investment in transmission links. Starting from the right-hand side of the chart, with the full grid capacity, total European cross-border interconnections congestion rent is about €340–440 m lower in the RG and AP scenarios than in the Base Case. This difference is shown in the three future scenarios in Figure 23 earlier.

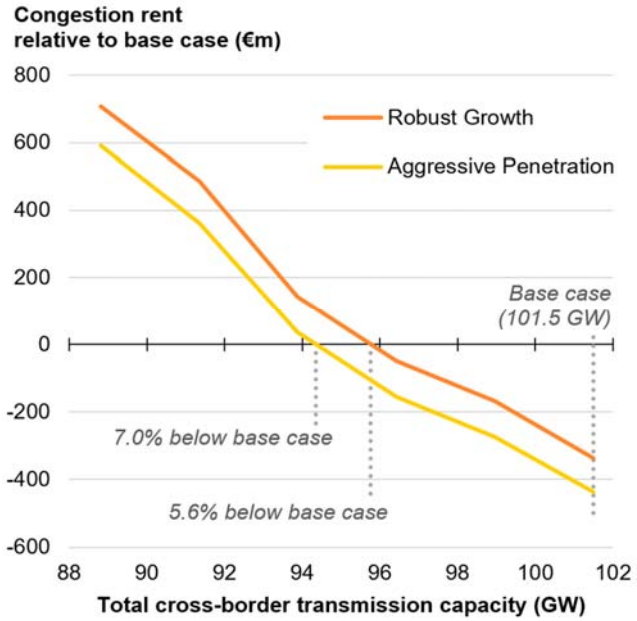


Figure 24 Changes in absolute congestion rent across Europe with decreasing grid capacity. It shows the impact of smaller transmission grids on the total congestion rent within the European network. The decreasing trend observed in the Robust Growth and Aggressive Penetration lines indicates a decline in surplus as grid capacity increases. In the Robust Growth scenario, the total congestion rent remains equivalent to the Base Case scenario (i.e. implicitly expected by ENTSO-E TYNDP) with a 5.6% reduction in grid size. Similarly, in the Aggressive Penetration scenario, the total congestion rent matches that of the Base Case scenario with a 7.0% decrease in grid size.

As the total transmission capacity reduces (moving left along the chart), the total congestion rent increases as line congestion drives greater price differentials between neighboring markets. To achieve the same expected total congestion rent as the base case (€2.97 billion per year) as projected by TYNDP in 2030 under the battery uptake scenarios, the total grid size would have to be reduced by 5.6–7% compared to the TYNDP plan (5.7 GW in the RG scenario, 7.1 GW in the AP scenario). This means that between 26 and 33% of new transmission projects planned in TYNDP between 2020 and 2030 would not be built if a merchant perspective were adopted, while aiming to achieve the same annual congestion rents as in the base case. It is worth noting that this shrinkage only applies to the new capacity planned in TYNDP, as it was assumed that no existing interconnectors would be affected.

However, it is not necessarily required to have the same total congestion rent to support a smaller grid. If less transmission was built under merchant investment model, upfront capital

required would be lower, leading to lower revenue requirements to compensate for the investment.

To further investigate this aspect, the analysis was repeated using specific congestion rent level, which quantifies how much congestion rent is earned per GW of transmission as illustrated in Figure 25.

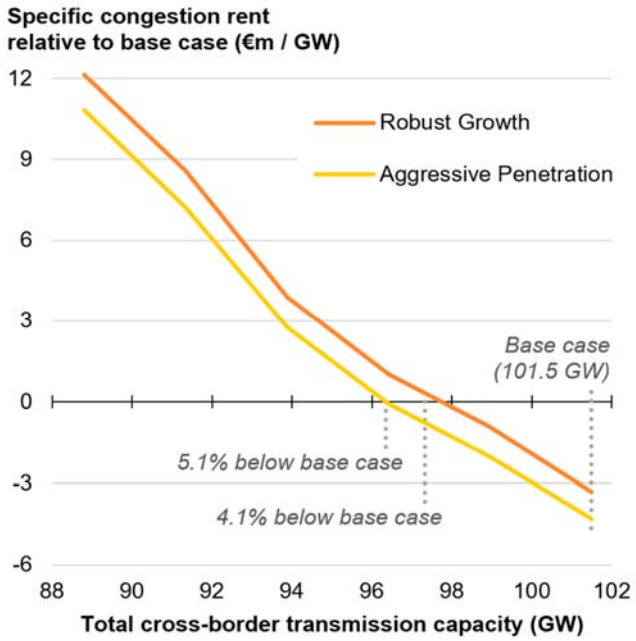


Figure 25 Congestion rent earned per GW of transmission capacity. It shows the impact of smaller transmission grids on the specific congestion rent, measured in (€m/GW) within the European network. The decreasing trend observed in the Robust Growth and Aggressive Penetration lines indicates a decline in specific surplus as grid capacity increases. In the Robust Growth scenario, the specific congestion rent remains equivalent to the Base Case scenario (i.e. implicitly expected by ENTSO-E TYNDP) with a 4.1% reduction in grid size. Similarly, in the Aggressive Penetration scenario, the specific congestion rent matches that of the Base Case scenario with a 7.0% decrease in grid size.

Using specific congestion rent reduces the impact slightly. The absolute reduction in the grid size required to achieve the same expected specific congestion rent is 4.1–5.1% (to 96–97 GW), which corresponds to 19–24% of the new planned capacity in TYNDP between 2020 and 2030.

The findings and following conclusions of this paper are subject to the following caveats. This analysis does not account for line congestion internal to countries, which is a critical issue in many regions. For instance, in Germany, wind farms are predominantly located in the north,

while electricity demand is concentrated in the south. The construction of new transmission lines aims to address such imbalances and reduce energy prices. Consequently, the figures reported here could be lower if these factors were taken into account within a more detailed model.

5.4.4 Impact on electricity generation costs and prices

Since the majority of European interconnectors are developed by TSOs under the regulated model and are evaluated based on societal costs and benefits, this analysis extends to examine the impact of grid size reductions on electricity generation costs and prices. In particular, the goal of this analysis is to determine the impact of smaller grid sizes on electricity costs, which could potentially offset savings from reduced investment in cross-border infrastructure.

Figure 26 compares the anticipated electricity generation cost in the future, under the base case of ENTSO-E TYNDP battery levels, as well as two cases that involve higher battery penetration.

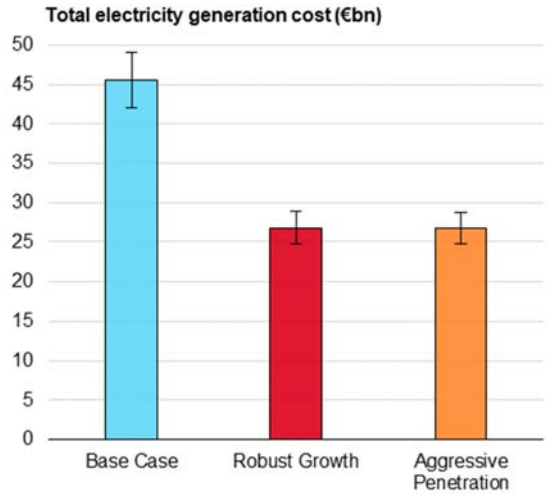


Figure 26 Total electricity generation cost in the three scenarios. It compares electricity generation cost across the 27 European countries modelled, based on different scenarios of battery storage uptake which include the base case (ENTSO-E TYNDP battery amount) and two cases with increased battery penetration (from lowest to highest, left to right). Future charts' error bars indicate variation between scenarios.

This shows a large reduction in the cost of electricity generation due to additional storage. The RG scenario has total electricity generation cost €18.68 billion/year lower than the Base

Case. Moving from RG to AP, instead, sees a reduction in total electricity generation cost of just €0.08 bn/year.

Figure 27 displays the changes in total electricity generation cost in the two scenarios characterized by higher battery penetration, with decreasing grid capacity.

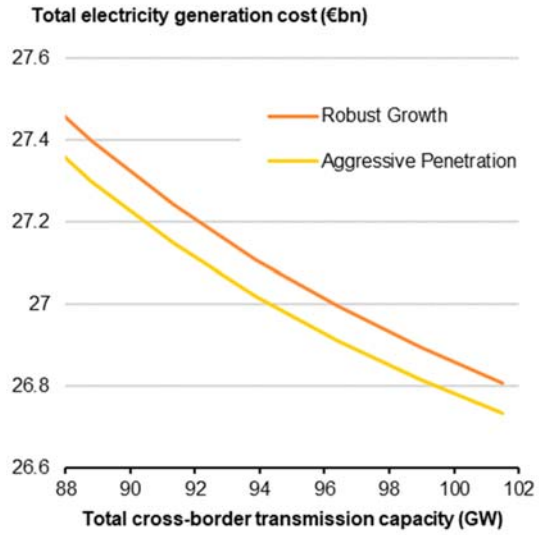


Figure 27 Total electricity generation cost per different levels of cross-border transmission capacity. It shows the impact of smaller transmission grids on total electricity generation costs, measured in (€ Bn) within the European network. The decreasing trend observed in the Robust Growth and Aggressive Penetration lines indicates a decline in total electricity generation cost as grid capacity increases.

The total electricity generation cost averages €26.81 billion under RG and €26.73 under AP with the full grid size. When this is reduced by 4.1% and 5.1% respectively[13], the total electricity generation cost increases by €0.17 and €0.21 billion per year, respectively (to €26.97 and €26.94 billion). These costs equate to around €8/MWh on average, which is notably low because they are based on scenarios with a high renewable share, where an average of 75% of demand is met by clean electricity sources with near-zero marginal costs, including solar, wind, hydro, and nuclear. The annual cost increase represents the additional cost of fuel burnt and carbon emitted (at the assumed carbon prices) due to transmission constraints preventing optimal

[13] These are the reductions which give the same specific congestion rent as the Base Case (see Figure 25)

generators from being used. It also represents the additional expense of electricity generation incurred from not expanding the grid size and should be weighed against the upfront savings from not constructing the projects needed to expand the grid size from 94.9-95.9% to 100% (i.e. about an additional 5.1 GW of interconnector capacity), as well as other non-monetary costs and benefits, such as enhanced security, that the additional interconnectors would have provided.

To provide further context, an analysis has also been conducted on the impact of a 5% reduction in grid size. This reduction was chosen as it aligns with the range suggested in the previous section (model results were generated for grid sizes between 85% and 100% at 2.5% increments). The results were considered across the range of 2030 scenarios considered previously (ENTSO-E scenarios, battery uptake scenarios, and climatic years: 1982, 1984 and 2007). The 5% reduction in grid size increases consumers' total electricity purchase costs by an average of 1.26% (1.07-1.56% range), corresponding to an annual increase of € 1.35 billion (€1.2-1.5 billion range). The total electricity purchase cost in 2030 is projected to be approximately €110 billion, giving a Europe-wide average price of €31.18/MWh in case of reduced grid size compared to €30.79/MWh in case of full grid size.

The results of Section 5.4.3 suggest that if all interconnectors were built solely based on their ability to generate revenue through congestion rents (a pure merchant approach), some should be avoided to maximize profits. However, this section provides additional context on the impact this would have on consumers, marginally increasing electricity prices, and on producers, increasing their costs.

5.4.5 Economic viability of battery uptake scenarios

The profit from storage performing arbitrage was assessed for both the Robust Growth and Aggressive Penetration scenarios across all ENTSO-E TYNDP scenarios (DG, GA, NT) and climatic years (1982, 1984, 2007). Profitability showed substantial variability across countries, ranging from very low in Nordic countries with substantial hydro resources to high in more isolated markets with limited connectivity, such as Italy, Greece, Ireland, and the UK. Figure 28 shows the average profitability across all markets and scenarios of this analysis, and the breakeven capital cost that these profits yield, assuming a 20-year economic lifetime and costs of capital from 5% to 10%.

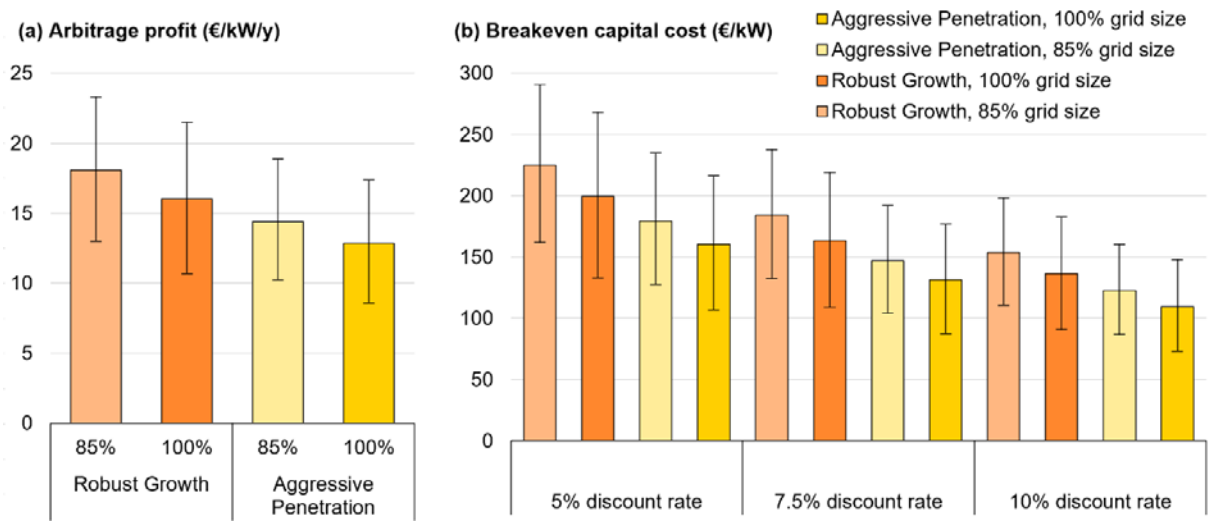


Figure 28 Short-run profit (arbitrage revenue) and maximum breakeven cost that this arbitrage revenue would allow for energy storage across the scenarios. Bars represent the mean across all nine combinations of ENTSO-E scenario and climatic year. Error bars cover the range from minimum to maximum across those combinations. Orange and yellow bars represent the Robust Growth and Aggressive Penetration scenarios for battery uptake (as in previous figures). Bright colours represent the full transmission grid capacity specified in ENTSO-E scenarios. Pale colours represent that grid reduced by 15% (the maximum reduction that was modelled in Figs. 24 and 25).

Panel (a) shows that storage profits are higher in the Robust Growth scenario compared to the Aggressive Penetration scenario, which is due to the volume of storage installed in the former. Similarly, storage profits are higher when the transmission grid size is reduced to 85% of the full TYNDP grid size, which is due to increased congestion, leading to greater price variability. To provide context, in the RG scenario at 100% grid size, a storage system could expect to earn €16/kW, meaning a 100 MW system could anticipate average annual earnings of €1.6 million. The earnings range across the range of TYNDP scenarios from a high of €21.50/kW per year (under DG and 1982 weather conditions) to a low of €10.70/kW per year (under GA and 1984 weather conditions). These profit margins in 2030 are marginally lower than those historically observed in European markets (Schmidt and Staffell, 2023), primarily due to the extensive deployment of storage projected in these 2030 scenarios.

Panel (b) of Figure 28 translates these annual profits into a maximum allowable capital cost for achieving breakeven. This calculation involves determining the upfront investment cost which yielded a net present value (NPV) of zero, across a range of discount rates. For example, in the RG scenario with the full ENTSO-E TYNDP transmission grid capacity, storage systems would

achieve a positive NPV on average in Europe with an initial cost under €200 per kW (€20 million for a 100 MW system) at a 5% discount rate. Across the battery and grid-size scenarios, the capital cost range for breakeven spans €110–154/kW at a 10% discount rate and €161–225/kW at a 5% discount rate. Including variations in ENTSO-E TYNDP scenario and climatic year broadens this range to €73–197/kW at 10% and €107–291/kW at 5% discount rate.

To provide perspective, Bloomberg New Energy Finance reports that the average cost of utility-scale 4-h lithium-ion storage systems was €244/kW in 2023 (BNEF, 2024). With prices decreasing by 24% throughout that year, an additional reduction of just 8% would be required for these systems to reach economic viability at a 5% financing discount rate, or a 37% reduction if the discount rate were 10%. This analysis leads to believe that the scenarios outlined for the uptake of energy storage present a financially viable opportunity for investors and owners in the sector. As the scenarios are based on 2030, it is not infeasible that utility-scale storage costs would fall to the levels found to be required to support the modelled levels of storage uptake.

5.5 Discussion

Cross-border interconnectors are valuable assets for electricity system operation, supporting energy security, market integration, deployment of renewables and the broader energy transition. However, the rapid deployment of electricity storage may threaten the future value of interconnectors, raising questions for policymakers, regulators, merchant interconnector investors and TSO executives.

Traditional network expansion using poles and wires may not be the best or most cost-effective solution, especially in areas with challenging topography or high population density. Building new interconnectors to alleviate grid stress faces public opposition and geographical constraints, leading to delays and increased costs. The planning, permitting, and construction of new grid infrastructure takes up to 15 years, significantly longer than for renewable projects (up to five years) or EV charging infrastructure (under two years) (IEA, 2023a). Conversely, energy storage systems offer a more modular, flexible solution that can be installed rapidly (IEA, 2023a).

This research reveals that greater deployment of storage in Europe could undermine the congestion rent of existing interconnectors and undermine the business case for new cross-

border transmission projects. This challenges the justification for merchant interconnection projects. For TSO-led interconnectors, which represent the majority of cross-border interconnectors currently being developed, the situation differs as they are financed through regulated transmission tariffs, ultimately paid by consumers.

In light of the potential impact of storage deployment, European regulators could explore separating grid planning and ownership. This approach is taken by National Grid in Great Britain, and could facilitate integrated storage planning within the transmission system, promoting cohesive capacity investment across the various flexibility options required by power systems. This strategy may also mitigate the risk of excessive investment in transmission infrastructure arising from uncertainty over private firms' future investments in storage which could devalue transmission assets. Currently, diverse incentive structures and information asymmetries complicate investment decisions in flexibility resources which compete for the same services. A more unified planning approach could streamline current processes, leading to more efficient grid development.

The analysis highlights wide discrepancies in the projected uptake of electricity storage between ENTSO-E's TYNDP and other organizations.

ENTSO-E's current modelling is more conservative, as Bloomberg New Energy Finance anticipate five times more battery capacity installed by 2030 than the average across TNYDP scenarios. This indicates a need for ENTSO-E to re-evaluate and potentially expand its scenarios to incorporate greater storage uptake, aligning with recent industry trends to provide a broader understanding of the future energy landscape. Doing so would enable ENTSO-E to better assess the implications of widespread storage adoption on transmission systems, including economic and operational effects on both merchant and TSO-led interconnectors. Adapting to these evolving dynamics, ENTSO-E could lead in facilitating a resilient and cost-efficient European energy grid, balancing interconnector benefits with the emerging potential of battery storage without imposing undue financial burden on investors and ratepayers.

Linear impacts of storage on cross-border congestion rent were observed across the wide range examined. Decision-makers with specific expectations for the amount of storage that will be installed (e.g. due to policy or government targets), can therefore use the relationships found

in this paper for an initial impact assessment. There is the potential for storage to achieve economic viability across the range of capacities tested, so it is fair to assume that within the wide range of storage capacities tested will lie the amount that will be installed over the coming decade. The study therefore allows readers to form a view on the impact that amount of storage will have on transmission value, without relying on single point assumptions about the equilibrium quantity of storage and transmission (which would become outdated as market dynamics and technology prices change).

The decreasing congestion rent of interconnectors has wider implications for society beyond affecting asset owners and developers. This declining value due to storage uptake raises questions about the need for extensive interconnector expansion, and ultimately the EU's interconnection targets may need to be reevaluated. However, altering the EU's interconnection target in light of energy storage uptake would be contentious, as interconnection targets serve multiple objectives. The implications for EU energy market integration must be balanced against the potential benefit of reduced infrastructure costs for ratepayers. Careful consideration of these competing factors is crucial for ensuring an optimal strategy towards interconnection targets.

The value of interconnectors for energy security may be challenged by the rise of battery energy storage. Cross-border interconnectors hold immense geopolitical significance, as they facilitate energy exchange and serve as vital instruments in fortifying relationships with neighboring countries. Through greater regional cooperation, interconnectors catalyze political integration, becoming conduits of 'electricity diplomacy' (Westphal et al., 2022). They transcend their primary function of electricity transfer, becoming symbols and enablers of mutual reliance and shared prosperity. However, interconnectors require trust between neighbors and are susceptible to political or technical disruptions, whereas batteries enable greater self-reliance and sovereignty as they provide local control and autonomy, allowing countries to manage their own renewable resources 'in-house'. This juxtaposition between the self-sufficiency offered by storage solutions and the interdependence and collaborative solidarity of interconnectors suggests there is vital discussion to be had on choosing paths towards renewable energy adoption: one that emphasizes national independence or one that underscores regional solidarity. Especially after the energy crisis following Russia's war in Ukraine, energy security and sovereignty are high on the political agenda, and so the role of storage batteries as an

alternative to interconnectors warrants further research and analysis to inform decision-making in optimizing energy systems.

The analysis of the economic viability of battery storage systems reveals that short-term arbitrage opportunities could be sufficient to cover their investment costs. This suggests that despite the scenarios used having substantial growth in storage penetration, these levels of uptake could be financially viable. Bloomberg New Energy Finance forecasts that the global deployment of stationary storage will reach 57 GW/136 GWh by 2024, with an annual growth rate of 40% (BNEF, 2024). This projection aligns with the study's implication that significant penetration of battery storage technologies appears to be not only likely, but inevitable.

Finally, the increasing adoption of energy storage, and the potential decrease in interconnector usage and value raise questions about market design and electricity pricing mechanisms. Traditional approaches may no longer be suitable in a landscape with abundant storage. Reevaluating pricing mechanisms and market design becomes crucial to accommodate storage's evolving role. Additionally, a shift toward more self-reliant national markets due to increased storage capacity may have security implications and disrupt market functioning. Balancing self-reliance and the benefits of market coupling, which aims to enhance security and reduce costs, becomes a critical consideration. Rethinking market operations and mechanisms is necessary to ensure a robust and secure energy system while also promoting a resilient, competitive, and cost-effective energy market.

5.6 Summary

Cross-border interconnectors are critically important but their construction faces challenges. This chapter found that battery electricity storage will reduce the congestion rent available to interconnectors. The findings indicate that a reduction in Europe's transmission grid size by 4.1–7% could preserve interconnectors' congestion rent, potentially averting the need for 19–33% of the TYNDP's planned new capacity, if it were assessed on merchant terms. However, most European interconnectors are being developed by TSOs under the regulated model, hence ultimately financed by consumers. A partial consideration of welfare impacts revealed that such a reduction in grid reinforcement would negatively affect both generation costs across Europe and average electricity prices, although the impact is modest at 0.7% and 1.3% respectively.

Assessing the impact of battery storage not only aids in informed policymaking and system planning but also sends a crucial message to TSOs. This suggests TSOs should consider more aggressive battery penetration scenarios than currently projected and evaluate the long-term viability and societal benefit of certain investments. This approach aims to reduce the burden on bill-payers and ensure that infrastructure projects are effectively utilized as intended. TSOs should also strategically assess their next steps: whether to engage in regulatory lobbying to change the rules on the ownership and management of storage or to continue as is, with the risk that increased battery storage could diminish the need for certain transmission investments. This situation could affect the profitability of TSOs, especially when the regulatory framework is CAPEX-biased.

6 Conclusions

Electricity grids form the backbone of our contemporary lifestyle, delivering quality of life and well-being. Transmission networks play a critical role in the transition away from fossil fuels across various sectors, enabling the electrification of industry, transportation, heating, and cooling. As countries rapidly add renewable energy projects to meet their climate targets, the demand for new power lines grows.

TSOs maintain the security and quality of the electricity system, essentially "keeping the lights on", and are pivotal in transitioning away from fossil fuels. Despite being regulated monopolies shielded from direct competition, TSOs, like all other players face substantial challenges and potential disruptions, and therefore must proactively future-proof their organizations. TSOs should invest holistically across innovation, embracing cutting-edge technologies, implementing transformative organizational changes, and innovative business models.

There is little knowledge today on these actors and their organizational arrangements. Little is known about who they are, how innovative they are and what drives their innovation efforts, how they are responding to the current challenges that are reshaping the electricity industry and how they see their role evolving in the future and what is needed to make their organizations more future-proof.

6.1 The TSO Paradox: conservative but eager to expand their scope

The use of benchmarking analysis provides valuable insights into how innovative TSOs are and how they approach innovation. The analysis reveals that European TSOs tend to adopt a "Defender" approach to innovation, aiming to maintain and enhance the status quo, rather than an "Explorer" approach, seeking to seize new opportunities and ways of doing business. In other words, TSOs in Europe tend to pursue innovation conservatively, focusing on projects with minimal impact on their current business models.

Interviews with a sample of European TSOs complement the desk-based benchmarking analysis, providing insights into their perspectives on future roles. Some of the interviewed TSOs highlighted the need to expand their operational scope, recommending the revision of outdated regulations, particularly those related to unbundling. They emphasized that updating

these rules would allow for more direct engagement with consumers and enable oversight of DSOs, who may lack sufficient resources for technological advancements, climate adaptation, and the integration of renewable energy. Additionally, some TSOs propose exploring integration with other networks (gas, hydrogen, telecommunications) in both strategic and ownership aspects to support this transition.

6.2 Batteries vs interconnectors: a tale of two visions

These two approaches mentioned before: Defender vs Explorer reflect different visions of the future electricity system: centralized versus decentralized. Cross-border interconnections are an example of centralized solutions, which can position TSOs as crucial players in a unified European energy system. In contrast, battery electricity storage represents an example of decentralization and a prominent non-wire alternative, offering a substitute for new transmission lines as it allows more generation to be located closer to the load, avoiding costly infrastructure upgrades.

The deep-dive analysis into the trade-off between batteries and cross-border interconnectors reveal that increased deployment of storage in Europe could undermine the congestion rent of existing interconnectors and weaken the business case for new cross-border transmission projects, challenging the justification for merchant interconnection initiatives. These findings may offer insights for regions outside Europe, where similar dynamics between storage solutions and interconnector development could emerge.

In particular, the analysis highlights wide discrepancies in the projected uptake of electricity storage between ENTSO-E's TYNDP and other organizations. ENTSO-E's current modelling is more conservative, as Bloomberg New Energy Finance anticipate five times more battery capacity installed by 2030 than the average across TNYDP scenarios. This indicates a need for ENTSO-E to re-evaluate and potentially expand its scenarios to incorporate greater storage uptake, aligning with recent industry trends to provide a broader understanding of the future energy landscape. Doing so would enable ENTSO-E to better assess the implications of widespread storage adoption on transmission systems, including economic and operational effects on both merchant and TSO-led interconnectors. Adapting to these evolving dynamics, ENTSO-E could lead in facilitating a resilient and cost-efficient European energy grid, balancing

interconnector benefits with the emerging potential of battery storage without imposing undue financial burden on investors and ratepayers.

Most importantly, the uptake of storage batteries should induce TSOs to reevaluate the cost-benefit analysis of existing and proposed interconnector projects in light of the changing energy landscape influenced by storage technologies. This assessment will involve critically examining the value and economic viability of interconnectors considering the potential impact of storage in the specific markets they serve. By optimizing capital expenditure and aligning infrastructure plans with the evolving market dynamics, TSOs can make informed decisions that prioritize investments providing value that is robust to potential storage uptake. This assessment should extend to proposed interconnector initiatives, taking into account the disruptive effects of storage technologies.

Additionally, TSOs must address the potential impact on the value of their regulatory asset base (RAB) as storage technologies gain prominence. A reduced need for extensive interconnector installations may shrink the RAB, affecting TSOs' revenue and profitability. TSOs face strategic choices in response to this changing landscape. One option is to accept a decline in their traditional responsibilities and allow greater involvement of private enterprises in storage ownership and operation. Another approach is to advocate for regulatory framework adaptations to enable TSOs' participation in the storage market. Balancing private enterprise participation and maintaining a fair regulatory framework is essential for ensuring long-term viability and energy security.

The findings also suggest that European regulators should consider adopting non-wires alternatives (NWAs) such as electricity storage in system planning, similar to the well-established support in the United States. Current limitations imposed on TSOs regarding the ownership and management of storage batteries, except in special circumstances, in fact, hinder the incentive for TSOs to experiment with these alternative solutions to the construction of traditional infrastructure.

6.3 How to future-proof TSOs

There are several strategies and actions TSOs can adopt to support innovation and make their organizations more future-proof. TSOs should operate on two fronts both internally, and

externally with other entities and stakeholders. Often, for an action to succeed, an internal initiative must be complemented by an external one. These actions are also categorized temporally: some are short-term focused, while others take a longer-term perspective, as illustrated in Figure 29.

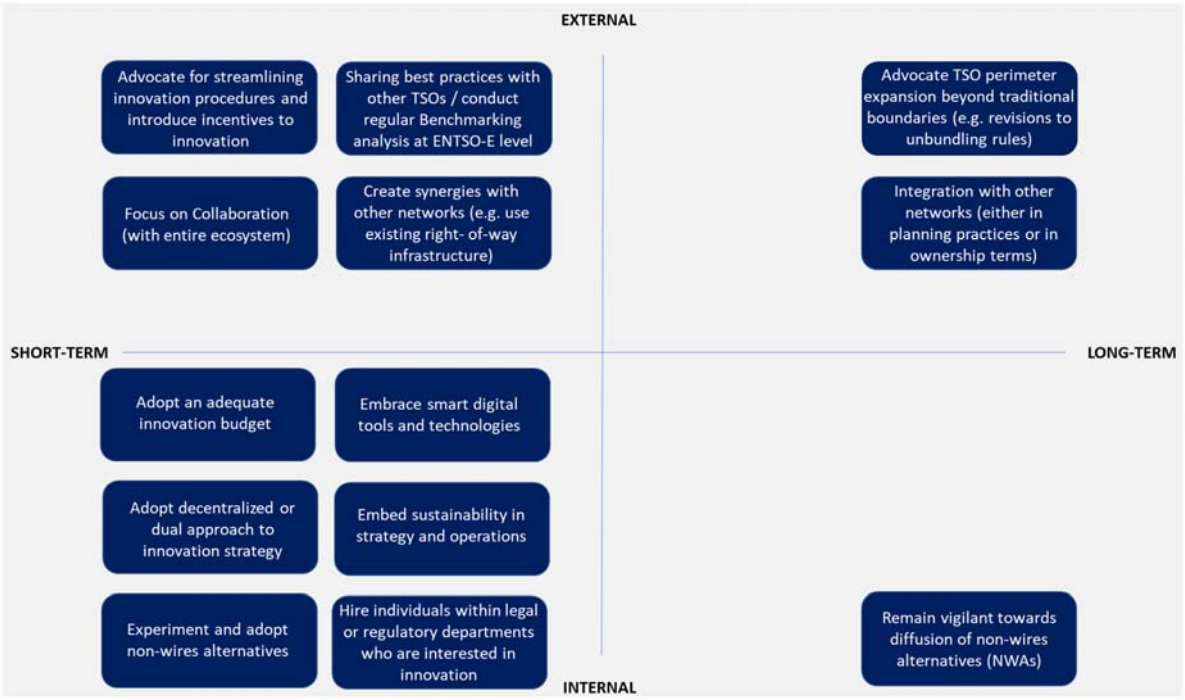


Figure 29 The main solutions identified to future-proof TSOs, based on interviews

Focusing on internal actions, a key best practice consists in adopting a decentralized approach to defining TSOs' innovation strategy and project implementation, potentially complemented by a centralized approach for studying and capturing technological trends. Innovative TSOs also adopt diverse methods to foster innovation, including technology labs, centers of excellence, open innovation programs, incubators, accelerators, corporate venture capital, and mergers & acquisitions. Lagging TSOs should emulate these practices from leading firms. Successful innovation requires CEO commitment, strategic prioritization of innovation, adequate budgeting, and policy review to equip innovation managers with resources for experimentation.

A best practice identified among most innovative European TSOs includes swiftly initiating new innovation projects, effectively bypassing the traditionally complex and lengthy approval

processes. Agility is critical, as highlighted by the literature, suggesting that granting teams autonomy and the ability to experiment quickly should advance innovation. However, interviews revealed that most TSOs face obstacles due to their highly regulated nature, resulting in intricate and prolonged authorization procedures. TSOs should work collaboratively with regulatory bodies to address this issue. Regulators, in turn, should provide the flexibility and agility for TSOs to innovate and keep pace with technological advancements.

TSOs must embrace digital innovations to future-proof their organizations and modernize operations, with digitalization enhancing decision-making, resource optimization, renewable integration, and load management. Innovations like real-time monitoring, predictive maintenance, and satellite technology improve infrastructure management and environmental consideration. Digital tools also promote project transparency and social acceptance. However, TSOs face challenges in adopting these technologies, including cultural adaptation and skilled talent recruitment, alongside increased cybersecurity risks. To address rising infrastructure costs and congestion, TSOs should focus on grid-enhancing technologies and Non-Wire Alternatives (NWAs), such as Dynamic Line Ratings (DLRs), for cost-efficient transmission expansion. Despite the benefits, regulatory frameworks often favour capital-intensive projects over quicker, cheaper NWA solutions, a mismatch that could redefine TSOs' roles amid shifting towards decentralized energy systems. Faced with this evolving landscape, TSOs have the option to cede certain responsibilities to private NWAs operators or seek regulatory adjustments to participate in these markets.

Given their pivotal role in the energy transition, TSOs should mitigate their environmental impact by embedding sustainability in planning and delivering new infrastructure, e.g. by assessing and monitoring biodiversity and local community impacts. This approach improves social acceptance and reduces the risk of project delays, thus safeguards the TSOs' license to operate. Emphasizing sustainability may also attract and retain people preferring to work for organizations committed to environmental and societal challenges.

This study highlights the importance of collaboration among TSOs, involving partnerships with technology firms, peers, universities, and research bodies to acquire essential knowledge and skills for new technologies and quality service. Such collaborations, especially between TSOs and Distribution System Operators (DSOs), improve data sharing, and embracing a data-driven

strategy is vital for client demands, system operations, asset management and for managing distributed resources. Sharing innovation efforts among TSOs can reduce time and costs, supporting a collective approach to common challenges.

Cooperation with other network operators, including Gas/Hydrogen TSOs or water and highways infrastructure operators, enables coordinated planning and development, optimizing resources and preventing bottlenecks. An example is the UK, where the regulator has initiated the formation of the “National Energy System Operator”. This positions the System Operator as a public, government-owned yet independent entity, facilitating cooperation with different networks to plan the development of all national energy infrastructure. Even without such far-reaching changes, TSOs can identify efficient solutions, such as installing new lines alongside existing highways and railways to create synergies. The $2.5 billion SOO Green HVDC Link project in the US serves as a case study using existing transportation corridors for 2 GW of underground transmission to mitigate siting and permitting challenges (John, 2021).

More related to information sharing than to collaboration, benchmarking analysis helps TSOs to avoid overlooking critical aspects, identify improvement areas, and adopt best practices. It offers insights into how peers tackle challenges like cybersecurity in an increasingly digital landscape. A practical method for TSOs to share and learn from each other's experiences could be through ENTSO-E facilitating a platform for continuous benchmarking and technology monitoring. Although ENTSO-E already produces R&D&I Monitoring reports, expanding its scope to include a broader range of technologies and innovative practices could enhance information sharing. This approach helps disseminate successful strategies and avoid repeated mistakes, streamlining processes and saving resources.

6.4 No future-proof TSOs without a fit for the future Regulation

Different factors might explain different levels of innovativeness among TSOs. For instance, the presence of ambitious environmental goals in the country (or region of operation) or the existence of an industrial policy aimed at creating national champions in the country of operation, hence the existence of industrial players which might become partners of the TSOs in research and innovation projects all potentially influence their innovativeness. But certainly, one of the key factors potentially driving higher TSOs’ innovativeness is regulation.

Regulatory frameworks must therefore be revised when they hinder innovation. National Regulatory Authorities should urgently correct regulations that disincentivize or inadequately encourage investments in innovative technologies. Misaligned political and regulatory frameworks can impede the energy transition and limit economic growth opportunities. For TSOs, advocating for regulatory changes is crucial to future-proofing their organizations. By pushing for regulatory reforms, TSOs can foster an environment that supports innovation and aligns with the evolving needs of the energy sector.

Regulatory support is also essential for TSOs to implement the transformative actions needed to future-proof their organizations. TSOs must engage with regulatory bodies to highlight the benefits of regulatory adaptations. More broadly, regulators play a key role in designing incentives for investment in riskier, innovative ventures. TSOs should advocate for regulatory revisions to eliminate barriers and promote investment in new technologies. Misaligned regulations could hinder the energy transition and block broader economic benefits. This can be achieved effectively through their existing association, ENTSO-E, to maximize the chances of success (Meeus, 2021). It is also advantageous to have individuals within legal or regulatory departments who are interested in innovation, as they can advocate for regulatory changes. As noted by Fried (2017), legal and regulatory professionals may be reluctant to embrace innovation and push regulators in that direction. Expanding on the benchmarking analysis performed here could be extremely beneficial. Observing how industry peers innovate and influence regulations, and how regulators respond, can reassure these professionals, promoting a "safety in numbers" approach (Fried, 2017).

6.5 Main takeaways of the thesis

6.5.1 What is new? – Summary of Contributions

This thesis sheds light on a fundamental topic that has, until now, received little attention in the literature: how electricity transmission system operators (TSOs)—crucial actors for the success of the energy transition—approach innovation. It explores what drives their innovation efforts, how they are responding to industry-transforming challenges, how they envision their evolving roles, and what actions they can employ to future-proof their organizations.

The study employs multiple methodologies to achieve these insights:

- Benchmarking Analysis: this thesis creates a dataset that allows for a comparative assessment of TSOs' innovativeness and their approach to innovation.
- Interviews with Industry Professionals: Conversations with an elite group of professionals heading innovation departments across various TSOs provide in-depth perspectives on current practices and future directions.
- Quantitative Modelling: Using an existing electricity market model and integrating it for this specific goal, the study quantifies the juxtaposition between two different technological innovations—one that defends the status quo and another that has the potential to disrupt it.

The contributions are categorized along the initial objectives of the PhD thesis in more detail below.

Objective A: Evaluate the innovative efforts of TSOs across Europe and conduct a comparative analysis of their approaches.

This thesis creates a comprehensive dataset of projects and initiatives undertaken by transmission system operators (TSOs) across key technologies. This dataset, in turn, serves multiple purposes. Firstly, it provides an overview of how various TSOs are engaging with and integrating these technologies into their business models. This helps to identify whether TSOs are ignoring or merely considering these technologies or actively incorporating them. Second, by distinguishing between the potential disruptive impacts of these technologies, the dataset allows to understand whether TSOs are primarily focused on defending their current business models through incremental innovations or are willing to radically innovate and seize new opportunities (i.e. in the "Defender vs. Explorer" dichotomy).

The dataset enables comparisons between TSOs, identifying the most innovative ones and those lagging behind. Including international TSOs operating in different geographies and contexts enable evaluations beyond intra-European comparisons. It allows for an understanding of how European TSOs perform relative to their global peers, providing valuable insights into their innovativeness on an international scale. Most importantly, this analysis enables the identification of best practices that TSOs, especially those lagging behind, could adopt to close the gap. By examining higher-scoring TSOs, others can learn from their

approaches and draw valuable lessons. More generally, it helps to understand how some TSOs have tackled challenges in adopting innovative technologies and how they have utilized these technologies to enhance and modernize their operations and activities.

This understanding can shed light on the factors that potentially drive or hinder innovation within these organizations.

Objective B: Examine how European TSOs are perceiving the challenges that are occurring in the electricity industry, how they envision their role and business model evolving in the future.

This thesis provides unique insights directly from professionals working as heads of innovation departments at European TSOs. Such individuals are those who make crucial decisions regarding innovation strategies within TSOs, including where to invest, which technologies to prioritize, and the rationale behind these choices.

The insights gained from in-depth interviews complement those gathered through desk-based research, offering a deeper understanding and capturing subtleties that a benchmarking analysis alone cannot reveal. These interviews provide a window into how TSOs envision the evolution of their roles and business models. In particular, TSOs foresee a future in which they continue to play a central role, especially in light of the energy transition. Some of them also convey on the need to expand their activities beyond their current business perimeter, for instance by engaging directly with end customers connected at distribution level or even take-over the control of distribution grid. Clearly, such changes will not be possible without the adaptation of the regulatory framework.

Objective C: Evaluate the potential impact of disruptive innovations on TSOs' traditional business.

This study conducts an economic analysis of the potential impact of disruptive innovation on TSOs' traditional business models. Specifically, it selects battery electricity storage as an example of technology innovation and cross-border interconnectors as a representative of the traditional approach. Using the electricity model, EuroMod, which simulates the functioning of the European electricity market while considering the integration of storage technologies, it

assesses the potential impact of the widespread adoption of lithium-ion batteries on the congestion rent generated across cross-border interconnectors. In particular, the research revealed that increased deployment of storage in Europe could undermine the congestion rent of existing interconnectors and weaken the business case for new cross-border transmission projects, challenging the justification for merchant interconnection initiatives and prompting TSO to re-evaluate their cost-benefit analysis of such projects. This analysis allows to reveal critical insights into how emerging technologies like battery storage could disrupt conventional transmission investments, providing a comprehensive understanding of the economic implications for TSOs.

Objective D. Identify actions that can make TSOs organizations more future-proof.

This thesis identifies several strategies and actions TSOs can adopt to support innovation and make their organizations more future-proof. TSOs should operate on two fronts both internally, and externally with other entities and stakeholders. Often, for an action to succeed, an internal initiative must be complemented by an external one. These actions are also categorized temporally: some are short-term focused, while others take a longer-term perspective.

6.5.2 Why does it matter? – Key recommendations for TSOs and regulators

These are the key conclusions and recommendations of the thesis for TSOs and regulators, which will help future-proof these organizations and meet the aim of my thesis. They are listed with reference to the thesis objectives.

A.1 The analysis of the projects and initiatives undertaken over the past years across a range of key technologies, reveal that European TSOs tend to pursue innovation conservatively, focusing on projects with minimal impact on their current business models.

A conservative approach aims to maintain and enhance the status quo and is opposite to an approach which seeks to seize new opportunities. These two approaches also reflect different visions of the future electricity system: centralized versus decentralized. Cross-border interconnections are an example of centralized solutions, which can position TSOs as crucial

players in a unified European energy system. In contrast, battery electricity storage represents an example of decentralization and a prominent non-wire alternative, offering a substitute for new transmission lines, as it allows more generation to be located closer to the load, avoiding costly infrastructure upgrades. TSOs should acknowledge these two different approaches and consider the necessity of maintaining a balance between them. Alternatively, they might temporarily adopt a more exploratory approach, experimenting with potentially disruptive new technologies to gain knowledge and increase their resilience

A.2 Differences in regulation partially explain the different levels of innovativeness among TSOs.

The analysis conducted on a sample of 12 European countries, shows a positive correlation between the presence of innovation stimuli tools (e.g. premium on cost of capital) in the country of operation and TSOs innovativeness. There are challenges to designing incentives for investing in riskier technologies, but there may be best practices that can be translated from the regulatory environments of the most innovative TSOs. At a more basic level, National Regulatory Authorities should correct regulations that create disincentives or fail to adequately encourage investments in innovative technologies. A misaligned political and regulatory framework would hinder the energy transition, preventing society from reaping its benefits and pursuing broader economic growth opportunities.

A.3 Other factors seem to explain different levels of innovativeness among TSOs.

The benchmarking analysis of international TSOs, supplemented by in-depth interviews with heads of innovation departments at various European TSOs, highlights several factors that potentially influence TSOs' innovativeness. These include the presence of ambitious environmental goals in the country or region of operation and the existence of an industrial policy aimed at creating national champions. Such policies foster industrial players who can potentially become partners with TSOs in research and innovation projects. Regulators and policymakers, particularly those who have yet to establish such goals, should recognize and assess the potential implementation of these regulations or policies. This approach can, in turn, promote innovation and yield broader societal benefits.

B.1 This study indicates that TSOs commonly perceive their central role in the energy sector as enduring, especially given their crucial part in enabling the energy transition. However, some TSOs foresee broader operational scope, including closer and more effective collaboration between TSOs and DSOs, potentially overcoming their traditional separation via unbundling, which they view as outdated.

This could permit TSOs to interact directly with consumers and potentially oversee DSOs, which may lack resources for technological updates, climate adaptation, and renewable integration. Some TSOs also suggest exploring integration with other networks (gas, hydrogen, telecommunications) in both strategic and ownership aspects to support this transition.

C.1 The deep-dive analysis into the trade-off between batteries and cross-border interconnectors revealed that increased deployment of storage in Europe could undermine the congestion rent of existing interconnectors, weakening the business case for developing merchant cross-border transmission projects, and potentially affecting the societal cost-benefit analysis of regulated projects.

The analysis highlights wide discrepancies in the projected uptake of electricity storage between ENTSO-E's TYNDP and other organizations. ENTSO-E's current modelling is more conservative, as Bloomberg New Energy Finance anticipate five times more battery capacity installed by 2030 than the average across TNYDP scenarios. This indicates a need for ENTSO-E to re-evaluate and potentially expand its scenarios to incorporate greater storage uptake, aligning with recent industry trends to provide a broader understanding of the future energy landscape. Doing so would enable ENTSO-E to better assess the implications of widespread storage adoption on transmission systems, including economic and operational effects on both merchant and TSO-led interconnectors. By adapting to these evolving dynamics, ENTSO-E could lead in facilitating a resilient and cost-efficient European energy grid, balancing interconnector benefits with the emerging potential of battery storage without imposing undue financial burden on investors and bill-payers.

C.2 TSOs should evaluate the cost-benefit analysis of existing and proposed interconnector projects in light of the evolving energy landscape influenced by storage technologies.

As storage capacity might increase much faster than previously anticipated, the value of interconnectors to society and their economic viability could be impacted. By optimizing capital expenditure and aligning infrastructure plans with the evolving market dynamics, TSOs can make informed decisions that prioritize investments offering robust value against potential storage uptake. This evaluation should also extend to proposed interconnector initiatives, considering the disruptive effects of storage technologies.

C.3 TSOs face strategic choices in response to this changing landscape, in particular with regard to battery electricity storage.

One option is to accept a decline in their traditional responsibilities, allowing greater involvement of private enterprises in storage ownership and operation. Another approach is to advocate for regulatory framework adaptations that enable TSOs' participation in the storage market. Balancing private enterprise participation and maintaining a fair regulatory framework is essential for ensuring long-term viability and energy security.

C.4 Current regulatory limitations imposed on TSOs regarding the ownership and management of storage batteries, except in special circumstances, hinder the incentive for TSOs to experiment with non-wires alternatives (NWAs) to the construction of traditional infrastructure.

European regulators should therefore consider adopting NWAs such as battery electricity storage in system planning.

D.1 Innovative TSOs exhibit common approaches to innovation that can be considered best practices.

One key best practice consists in adopting a decentralized approach to defining TSOs' innovation strategy and project implementation, potentially complemented by a centralized approach for studying and capturing technological trends. Other methods encompass technology labs, centers of excellence, open innovation programs, incubators, accelerators, corporate venture capital, and mergers & acquisitions. Lagging TSOs should emulate these

practices from leading firms. Successful innovation also requires CEO commitment, strategic prioritization of innovation, adequate budgeting, and policy review to equip innovation managers with resources for experimentation.

D.2. A best practice identified among most innovative European TSOs includes swiftly initiating new innovation projects, accelerating the traditionally complex and lengthy approval processes.

Agility is critical, as highlighted by the literature, suggesting that granting teams autonomy and the ability to experiment quickly should advance innovation. However, interviews revealed that most TSOs face obstacles due to their highly regulated nature, resulting in intricate and prolonged authorization procedures. TSOs should work collaboratively with regulatory bodies to address this issue. Regulators, in turn, should provide the flexibility and agility for TSOs to innovate and keep pace with technological advancements.

D.3. TSOs must embrace digital innovations to future-proof their organizations.

More broadly, digitalization will modernize operations by enhancing decision-making, resource optimization, renewable integration, and load management. Innovations like real-time monitoring, predictive maintenance, and satellite technology improve infrastructure management and environmental consideration. Digital tools also promote project transparency and social acceptance. However, TSOs face challenges in adopting these technologies, including cultural adaptation and skilled talent recruitment, alongside increased cybersecurity risks.

D.4 Given their pivotal role in the energy transition, TSOs should mitigate their environmental impact by embedding sustainability in planning and delivering new infrastructure, e.g. by assessing and monitoring biodiversity and local community impacts.

This approach improves social acceptance and reduces the risk of project delays, thus safeguards the TSOs' license to operate. Emphasizing sustainability may also attract and retain

people preferring to work for organizations committed to environmental and societal challenges.

D.5 This study highlights the importance of collaboration among TSOs, involving partnerships with technology firms, peers, universities, and research bodies to acquire essential knowledge and skills for new technologies and quality service.

Such collaborations, especially between TSOs and Distribution System Operators (DSOs), improve data sharing, and embracing a data-driven strategy is vital for client demands, system operations, asset management and for managing distributed resources. Sharing innovation efforts among TSOs can reduce time and costs, supporting a collective approach to common challenges.

D.6 Integration with other network operators, including Gas/Hydrogen TSOs or water and highways infrastructure operators, could enable coordinated planning and development, optimizing resources and preventing bottlenecks.

An example is the UK, where the regulator has initiated the formation of the “National Energy System Operator”. This positions the System Operator as a public, government-owned yet independent entity, facilitating cooperation with different networks to plan the development of all national energy infrastructure. Even without such far-reaching changes, TSOs can identify efficient solutions, such as installing new lines alongside existing highways and railways to create synergies. The $2.5 billion SOO Green HVDC Link project in the US serves as a case study using existing transportation corridors for 2 GW of underground transmission to mitigate siting and permitting challenges (John, 2021).

D.7 More related to information sharing than to collaboration, benchmarking analysis helps TSOs to avoid overlooking critical aspects, identify improvement areas, and adopt best practices. It offers insights into how peers tackle challenges like cybersecurity in an increasingly digital landscape.

A practical method for TSOs to share and learn from each other's experiences could be through ENTSO-E facilitating a platform for continuous benchmarking and technology monitoring. Although ENTSO-E already produces R&D&I Monitoring reports, expanding its scope to include a broader range of technologies and innovative practices could enhance information sharing. This approach helps disseminate successful strategies and avoid repeated mistakes, streamlining processes and saving resources.

D.8 To address rising infrastructure costs and congestions, Non-Wire Alternatives (NWAs), could be an invaluable tool. However, regulatory framework, at least in Europe, hinders the adoption of these solutions.

Despite the benefits, regulatory frameworks often favour capital-intensive projects over quicker and cheaper NWA solutions, a mismatch that could redefine TSOs' roles amid shifting towards decentralized energy systems. Faced with this evolving landscape, TSOs have the option to cede certain responsibilities to private NWAs operators or seek regulatory adjustments to participate in these markets.

D.9 TSOs should engage with regulatory bodies to highlight the benefits of regulatory adaptations.

Regulatory support is necessary for TSOs to implement the transformative actions previously discussed. More broadly, regulation is key to driving TSO innovation, with the challenge of designing incentives for investment in riskier, innovative ventures. TSOs should advocate for regulatory revisions to eliminate barriers and promote investment in new technologies. Misaligned regulations could hinder the energy transition and block broader economic benefits. It is also advantageous to have individuals within legal or regulatory departments who are interested in innovation, as they can advocate for regulatory changes. As noted by Fried (2017), legal and regulatory professionals may be reluctant to embrace innovation and push regulators in that direction. Conducting benchmarking analysis, expanding on the one performed in this study, can be extremely beneficial. Observing how industry peers innovate and influence regulations, and how regulators respond, can reassure these professionals, promoting a "safety in numbers" approach.

D.10 The regulatory framework could evolve to not only permit TSOs to experiment with grid-enhancing technologies and non-wire alternatives but also to generally adapt for the benefit of the entire system.

The goal should be to find the best solutions to manage system costs effectively while achieving the energy transition in a timely manner. This involves revising current system planning processes and exploring new approaches. Regulatory changes should focus on fostering innovation, ensuring cost efficiency, and supporting the timely realization of the energy transition. For instance, adopting more flexible and adaptive regulatory mechanisms could enable more efficient integration of renewable energy sources and advanced technologies into the grid, ultimately benefiting the overall stability and sustainability of the energy system.

6.5.3 What is missing? – Limitations and Future Work

There are limitations to this PhD thesis that must be acknowledged and can be overcome in future work.

First and foremost, a broad limitation of this study must be acknowledged: it discusses innovation for TSOs but does not incorporate the full scope of the EU-level R&D innovation cycle that might shape and drive innovation for TSOs. To a certain extent, this omission prevents the presentation of a complete and accurate picture. Future research could enrich the overall understanding by incorporating key elements such as the EU strategy on innovation, including the Strategic Energy Technology (SET) Plan, and the role of TSOs in initiatives like the European Technology and Innovation Platform Smart Networks for Energy Transition (ETIP SNET), where EU-level innovation priorities are highlighted. Furthermore, several other critical initiatives that drive TSO innovation are not covered, including the Digitalisation of Energy Action Plan, the Energy Market Design (EMD) Reform, the Data Act, and the Network Code on Demand Side Flexibility. Future research should integrate these elements to provide a comprehensive view of the innovation landscape for TSOs within the EU framework. This would offer deeper insights into how EU-level strategies and policies shape the innovation pathways for TSOs, thereby enhancing the relevance and applicability of the study's findings.

Some of the solutions identified to future-proof TSO organizations will require an in-depth policy debate and regulatory approval or adaptation, aspects not covered in this thesis. Therefore, future studies should explore these areas in greater detail, focusing on improving system planning procedures and other regulatory aspects to minimize system costs and facilitate a smooth and timely energy transition.

A comprehensive analysis of regulatory frameworks for innovation across different countries and regions could yield valuable insights into varying levels of innovativeness. This would facilitate a more robust regression analysis to understand the impact of regulation on innovation. Additionally, while this thesis highlights the regulatory framework as a key factor influencing TSOs' varying levels of innovativeness, it does not explore the optimal regulatory frameworks for incentivizing innovation, such as diverse approaches and specific tools and provisions for innovation, which future research could address.

Another limitation of this thesis is the challenge in determining which strategies/actions correlate most strongly with higher performance indicators. The diverse strategies and proactive approaches observed suggest that top-performing TSOs dynamically leverage every available tool to bridge the resource, skill, and knowledge gaps associated with innovative technologies. This is perhaps the most crucial insight from the benchmarking analysis, offering a starting point for lower-performing TSOs to reflect upon and bridge the performance gap. Future research could analyze this aspect in greater detail.

The very concept and definition of innovativeness presents another challenge. In this study, innovativeness was measured through the analysis of projects and initiatives. Incorporating a risk factor for these activities could enhance the analysis, as some technologies and activities are more inherently risky and disruptive. Future studies could investigate this aspect further. Additionally, other indicators, such as R&D budgets, the size of innovation teams, and the number of open innovation initiatives, could provide a more robust measure of TSOs' innovativeness. In particular, this thesis overlooks the R&D efforts of TSOs. It does not analyze in detail their various R&D structures and departments, budgets, investments, or related patents. This type of analysis could be undertaken in future studies.

Another limitation of the thesis is its lack of contribution to the scholarly discourse on quantifying the benefits of innovation. This is inherently complex because the full benefits of any solution are only evident several years after large-scale deployment. Even then, the monetization of benefits and the link between incentives and measurable outcomes are not straightforward. Furthermore, some benefits cannot be monetized, such as increased safety, environmental impact reductions, and the growth of the innovative ecosystem. Future studies however could try to address these challenges.

Among the conclusions, the installation of new lines alongside existing highways and railways, leveraging existing rights-of-way was highlighted as an efficient solution that TSOs can adopt to facilitate the energy transition and address barriers faced by traditional infrastructure projects, such as lengthy permitting processes. This approach, exemplified by the SOO Green HVDC Link project in the US, creates synergies and minimizes the need for new land acquisitions. This field holds significant potential for further research and could bring substantial benefits, warranting deeper investigation.

Future research could examine the insights and lessons that can be derived from TSOs that concurrently manage electricity distribution networks and/or gas networks. Similarly, future research could be extended to examine which TSOs around the world also manage other infrastructure networks such as water, telecommunications, highways, railways, etc. The focus would be to determine if such integration leads to better results and synergies or merely adds complexity. It could be useful to investigate whether privately-owned companies perform better than state-owned enterprises, particularly when financial actors are the primary shareholders. Additionally, future studies might delve deeper into the ownership structures of these companies, utilizing network analysis to illuminate the intricate connections. For instance, such analyses could shed light on the network of participations by entities like China's State Grid or specific investment funds in other transmission companies worldwide.

Another potential element of future analysis is represented by the dataset size used for the benchmarking analysis, which in this study covers only a sample of TSOs and not all the TSOs worldwide. Expanding this dataset to include other TSOs from all over the world and additional technologies would provide a more comprehensive view. Additionally, the data should be regularly updated to reflect the latest information on TSO innovativeness.

Most importantly, with regard to the dataset, one area for improvement in the thesis is the execution of two separate benchmarking analyses, hence the creation of two different dataset. The first analysis focuses on a specific sample of TSOs, some key technologies, over a time period from 2016 to the first half of 2020. The second analysis, instead, examines a different sample of TSOs, different technologies, and spans from 2016 to the first half of 2023. This discrepancy arises because the analyses were conducted at significantly different times. Ideally, it would have been beneficial to have consistent databases for both analyses. This would involve updating the analysis of the initial technologies to extend through the second half of 2023 and including all the TSOs from the second sample in the first benchmarking analysis.

Future research could explore the relationship between Transmission System Operators (TSOs) and Distribution System Operators (DSOs) in greater detail. Innovation in system operation, particularly, requires close collaboration between TSOs and DSOs to effectively tap into decentralized flexibility resources and leverage them for congestion management. However, the topic of flexibility markets was only marginally covered in this thesis. In general, it must be acknowledged that this study presents a 'TSO-centric' perspective, which does not fully represent the balanced collaboration between them. Future research could focus on the role of DSOs and examining how their involvement impacts TSO innovation.

Another relevant limitation is represented by the fact that the sample of TSOs interviewed in this study was very limited (only 11), which may not be representative of the entire TSO category and precludes statistical analysis, confining the study to qualitative insights. Furthermore, the duration of the interviews might be considered insufficient to fully capture the complexity of the numerous topics discussed. Moreover, the interviews were conducted with professionals working as heads of innovation teams, potentially introducing a bias. Despite the challenge of interviewing busy professionals with limited time, future research could benefit from including a broader and more diverse sample of interviewees to provide a more balanced perspective. Additionally, other data collection tools, such as questionnaires, could be employed to gather more comprehensive insights.

The quantitative analysis focused exclusively on battery storage as a non-wires alternative. Future studies should examine other non-wires alternatives and grid enhancing technologies. Future research could also further investigate the profitability of cross-border interconnectors

to assess whether there is significant difference when they are developed by private investors (merchants) rather than by TSOs, identifying eventual best practices, especially in the permitting and development phase.

Regarding the quantitative analysis of the impact of storage technologies diffusion on traditional business models, future studies could extend the analysis to long-duration energy storage (LDES), such as 8-hour lithium-ion batteries, to gain a deeper understanding of their effects. Another area of research could focus more specifically on the detailed analysis of the cost of constructing new lines versus non-wires alternatives (across the world). This would necessitate the collection of comprehensive cost data, which was beyond the scope of this study.

Another important limitation of the study lies in its focus on short-run equilibrium, considering only operational changes and not long-run capacity adjustments. A long-run equilibrium analysis, accounting for impacts like increased solar PV deployment, could affect congestion rents and total costs. Conducting such an analysis would be a valuable direction for future research. Since EuroMod is not designed to optimize capacity, and the capital costs of constructing interconnectors vary significantly, it is not appropriate to estimate total costs, including capital repayments. However, incorporating such estimates would provide a more comprehensive assessment of the welfare effects of reducing interconnector capacity in response to increased battery adoption and other developments, which is suggested for future research.

Finally, future research could evaluate the possibility of Transmission System Operators to either establishing a pan-European TSO or merging specific TSOs. This approach would allow financially constrained TSOs to benefit from joining larger organizations, which could catalyze innovation across their operational areas and reduce the current fragmentation in innovation practices within the industry. This strategy could significantly improve efficiency and innovation in the European electricity transmission industry, creating ‘supranational champions’.

In conclusion, while this thesis provides valuable insights on crucial aspects of TSO innovation strategies, addressing these limitations in future research could lead to a more comprehensive understanding of TSOs' approaches to innovation and the factors influencing their success.

Thank you for reading my PhD thesis! I hope you found it insightful and worthwhile.

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Appendices

Appendix 1 Global Overview of TSOs

The following tables provide a nearly complete list of transmission grid companies by region and country. The tables were compiled through a manual web search for the TSO in each country or region, supplemented by consultations of each TSO's official website to gather the necessary information.

Across all tables, the following acronyms are used: VIU: vertically integrated utility; LTSO: Legally Unbundled Transmission System Operator; ITSO: Independent Transmission System Operator; ISO: Independent System Operator; TO: Transmission Owner; Int. International.

Europe:

Country	TSO	VIU	LTSO	ITSO	ISO	TO	Ultimate ownership	Origin of Ultimate Owner
Albania	OST			X			State	Domestic
Austria	APG		X				State	Domestic
Austria	VUEN					X	State	Domestic
Belarus	BelEnergo	X					State	Domestic
Belgium	Elia			X			State	Domestic
Bosnia Herz.	NOS BiH				X		State	Domestic
Bosnia Herz.	TransCo					X	State	Domestic
Bulgaria	ESO		X				State	Domestic
Croatia	HOPS			X			State	Domestic
Cyprus	CTSO			X			State	Domestic
Czechia	ČEPS			X			State	Domestic
Denmark	ENERGINET			X			State	Domestic
Estonia	Elering			X			State	Domestic
Finland	Fingrid			X			State	Domestic
France	RTE		X				State	Domestic
Georgia	GSE			X			State	Domestic
Germany	50Hertz			X			State	Foreign
Germany	AMPRION			X			Private	Domestic
Germany	TRANSNETBW		X				Mostly State	Domestic
Germany	TenneT Germany			X			State	Foreign
Great Britain	NGET					X	Private	Int.
Great Britain	National Grid ESO				X		Private	Int.
Great Britain	SP Energy Networks					X	Private	Int.
Great Britain	SSEN					X	Private	Int.
Greece	Ipto			X			State	Domestic

(continued)

Country	TSO	VIU	LTSO	ITSO	ISO	TO	Ultimate ownership	Origin of Ultimate Owner
Hungary	MAVIR		X				State	Domestic
Iceland	Landsnet			X			State	Domestic
Ireland	EirGrid				X		State	Domestic
Ireland	ESB Networks					X	State	Domestic
Italy	Terna			X			State	Domestic
Kosovo	KOSTT			X			State	Domestic
Latvia	AST			X			State	Domestic
Lithuania	Litgrid			X			State	Domestic
Luxemburg	CREOS		X				State	Domestic
Malta	Enemalta	X					State	Domestic
Moldova	Moldelectrica			X			State	Domestic
Montenegro	CGES			X			State	Domestic
Netherlands	TenneT TSO B.V.			X			State	Domestic
North Macedonia	MEPSO			X			State	Domestic
Northern Ireland	SONI				X		State	Foreign
Northern Ireland	NIE Networks					X	State	Foreign
Norway	Stattnet			X			State	Domestic
Poland	PSE			X			State	Domestic
Portugal	REN			X			State	Foreign
Romania	Transelectrica			X			State	Domestic
Russia	PJSC FGC-Rosseti					X	State	Domestic
Russia	JSC SO UES				X		State	Domestic
Serbia	EMS			X			State	Domestic
Slovenia	ELES, d.o.o..			X			State	Domestic
Slovak Republic	SEPS			X			State	Domestic
Spain	Redeia			X			State	Domestic
Sweden	Svenska Kraftnät			X			State	Domestic
Switzerland	SWISS GRID			X			State	Domestic
Turkey	TEiAŞ			X			State	Domestic
Ukraine	Ukrenergo			X			State	Domestic

Middle East & North Africa:

Country	TSO	VIU	LTSO	ITSO	ISO	TO	Ultimate ownership	Origin of Ultimate Owner
Algeria	GTRE	X					State	Domestic
Bahrain	EWA	X					State	Domestic
Egypt	EETC		X				State	Domestic
Iran	Tavanir	X					State	Domestic
Iraq	MoE	X					State	Domestic
Israel	IEC	X					State	Domestic
Jordan	NEPCO	X					State	Domestic
Kuwait	MEW	X					State	Domestic
Lebanon	EDL	X					State	Domestic
Libya	GECOL	X					State	Domestic
Morocco	ONEE	X					State	Domestic
Oman	OETC			X			State	Domestic
Qatar	KAHRAMAA	X					State	Domestic
Saudi Arabia	National Grid SA (Saudi Electricity Company)	X					State	Domestic
Syria	MoE	X					State	Domestic
Tunisia	STEG	X					State	Domestic
UAE	DEWA	X					State	Domestic
UAE	TRANSCO			X			State	Domestic
Yemen	GEC	X					State	Domestic

Africa:

Country	TSO	VIU	LTSO	ITSO	ISO	TO	Ultimate ownership	Origin of Ultimate Owner
Angola	RNT			X			State	Domestic
Botswana	BPC	X					State	Domestic
Ethiopia	EEPCo	X					State	Domestic
Ghana	GRIDCo			X			State	Domestic
Ivory Coast	CIE	X					Private	Domestic
Kenya	KETRACO			X			State	Domestic
Madagascar	Jirama	X					State	Domestic
Mozambique	EDM	X					State	Domestic
Namibia	NamPower	X					State	Domestic
Nigeria	TCN			X			State	Domestic
Rwanda	REG	X					State	Domestic
South Africa	NTCSA (Eskom)	X					State	Domestic
Tanzania	TANESCO	X					State	Domestic
Uganda	UETCL			X			State	Domestic
Zambia	ZESCO	X					State	Domestic

Asia:

Country	TSO	VIU	LTSO	ITSO	ISO	TO	Ultimate ownership	Origin of Ultimate Owner
Armenia	CJSC High-Voltage Electric Networks			X			State	Domestic
Australia	AEMO				X		State	Domestic
Australia	AEO					X	Private	Int.
Australia	APA Group					X	Private	Int.
Australia	AusNet Services					X	Private	Int.
Australia	ElectraNet					X	Private	Int.
Australia	Horizon Power					X	State	Domestic
Australia	Pilbara ISOCo				X		Private	Domestic
Australia	Powerlink Queensland					X	State	Domestic
Australia	Rio Tinto					X	Private	Int.
Australia	TasNetworks					X	State	Domestic
Australia	TransGrid					X	State	Domestic
Australia	Western Power					X	State	Domestic
Azerbaijan	Azerenerji			X			State	Domestic
Bangladesh	PGCB			X			State	Domestic
Cambodia	EDC	X					State	Domestic
China	CSG			X			State	Domestic
China	State Grid			X			State	Domestic
India	Adani					X	Private	Domestic
India	APTransco			X			State	Domestic
India	BSPTCL			X			State	Domestic
India	GETCO		X				State	Domestic
India	HVPNL			X			State	Domestic
India	KPTCL			X			State	Domestic
India	MPPTCL			X			State	Domestic
India	MSETCL (or Mahatransco)			X			State	Domestic
India	OPTCL			X			State	Domestic
India	POSOCO				X		State	Domestic
India	PowerGrid					X	State	Domestic
India	PSTCL			X			State	Domestic
India	RVPN			X			State	Domestic
India	SPTL					X	Private	Int.
India	TANTRANSCO			X			State	Domestic
India	Tata Power Transmission					X	Private	Domestic
India	TSTRANSCO			X			State	Domestic
India	UPPTCL			X			State	Domestic
India	WBSETCL			X			State	Domestic
Indonesia	PLN	X					State	Domestic
Japan	Chuden	X					Private	Domestic
Japan	Chugoku Electric	X					Private	Domestic
Japan	HEPCO	X					Private	Domestic
Japan	J-POWER					X	Private	Domestic

(continued)

Country	TSO	VIU	LTSO	ITSO	ISO	TO	Ultimate ownership	Origin of Ultimate Owner
Japan	KEPCO	X					Private	Domestic
Japan	Kyushu Electric Power Co., Inc.	X					Private	Domestic
Japan	Okiden	X					Private	Domestic
Japan	Rikuden	X					Private	Domestic
Japan	Shikoku Electric	X					Private	Domestic
Japan	TEPCO	X					Private	Domestic
Japan	Tohoku Electric	X					Private	Domestic
Kazakhstan	KEGOC			X			State	Domestic
Kyrgyzstan	NESK			X			State	Domestic
Laos	EDL-T			X			State	Foreign
Malaysia	SESB	X					State	Domestic
Malaysia	SESCO	X					State	Domestic
Malaysia	TNB	X					State	Domestic
Nepal	NEA	X					State	Domestic
New Zealand	Transpower			X			State	Domestic
Pakistan	K-Electric	X					Private	Int.
Pakistan	NTDC			X			State	Domestic
Philippines	NGCP			X			Private	Domestic
Singapore	SP		X				State	Domestic
South Korea	KEPCO					X	State	Domestic
South Korea	KPX				X		State	Domestic
Thailand	EGAT			X			State	Domestic
Uzbekistan	NEGU			X			State	Domestic
Vietnam	EVN NPT	X					State	Domestic

Central & South America:

Country	TSO	VIU	LTSO	ITSO	ISO	TO	Ultimate ownership	Origin of Ultimate Owner
Argentina	Cammesa				X		Mostly State	Domestic
Argentina	Distrocuyo					X	Private	Domestic
Argentina	Litsa					X	Private	Domestic
Argentina	Transba					X	Private	Domestic
Argentina	Transener					X	Private	Domestic
Argentina	Transnoa					X	Private	Foreign
Argentina	Transpa					X	Private	Domestic
Bolivia	CNDC				X		State	Domestic
Bolivia	ENDE					X	State	Domestic
Bolivia	ISA Bolivia					X	State	Foreign
Brazil	Argo Energía					X	Private	Foreign
Brazil	CEEE GT					X	State	Domestic
Brazil	Cemig					X	State	Domestic
Brazil	Chesf					X	State	Domestic
Brazil	Copel					X	State	Domestic
Brazil	CTEEP					X	State	Foreign
Brazil	Eletronorte					X	State	Domestic
Brazil	Eletrosul					X	State	Domestic
Brazil	Furnas					X	State	Domestic
Brazil	ONS				X		Independent	Domestic
Brazil	TAESA					X	State	Domestic
Brazil, Peru, Uruguay	CDPQ					X	Private	Foreign
Chile	Alfa Desarrollo					X	Private	Foreign
Chile	CEN				X		Independent	Domestic
Chile	CTNG					X	Private	Int.
Chile	ENGIE Energía Chile S.A.					X	Private	Foreign
Chile	ISA Chile					X	State	Foreign
Chile	STA					X	Private	Foreign
Chile	STM					X	Private	Foreign
Chile	TEN					X	Private	Foreign
Chile	Transelec					X	Private	Foreign
Colombia	ISA			X			State	Domestic
Costa Rica	ICE	X					State	Domestic
Ecuador	TRANSELECTRIC S.A		X				State	Domestic
Guatemala	AMM				X		Independent	Domestic
Guatemala	ETCEE					X	State	Domestic

(continued)

Country	TSO	VIU	LTSO	ITSO	ISO	TO	Ultimate ownership	Origin of Ultimate Owner
Guatemala	TRECSA					X	Private	Int.
Guatemala	TRELEC					X	Private	Int.
Mexico	CENACE				X		State	Domestic
Mexico	CFE					X	State	Domestic
Panama	ETESA			X			State	Domestic
Paraguay	ANDE	X					State	Domestic
Peru	COES SINAC				X		Independent	Domestic
Peru	CONENHUA					X	Private	Domestic
Peru	CTM					X	Private	Foreign
Peru	REP SA					X	State	Foreign
Peru	Redesur					X	State	Foreign
Uruguay	UTE	X					State	Domestic

North America:

Country	TSO	VIU	LTSO	ITSO	ISO	TO	Ultimate ownership	Origin of Ultimate Owner
Canada	AESO				X		Independent	Domestic
Canada	Altalink					X	Private	Foreign
Canada	ATCO					X	Private	Domestic
Canada	BC Hydro	X					State	Domestic
Canada	ENMAX Power Corporation					X	State	Domestic
Canada	EPCOR					X	State	Domestic
Canada	Hydro One					X	State	Domestic
Canada	Hydro-Quebec	X					State	Domestic
Canada	IESO				X		State	Domestic
Canada	Manitoba Hydro					X	State	Domestic
Canada	NB Power	X					State	Domestic
Canada	Newfoundland and Labrador Hydro	X					State	Domestic
Canada	Nova Scotia Power (Emera Incorporated)	X					Private	Int.
Canada	SaskPower	X					State	Domestic
USA	1803 Electric Cooperative, Inc.					X	Cooperative	Domestic
USA	AEL&P (Alaska Electric Light & Power)					X	Private	Domestic
USA	AEP					X	Private	Int.
USA	Alaska Electric and Energy Cooperative, Inc.					X	Cooperative	Domestic
USA	Allegheny Electric Cooperative, Inc.					X	Cooperative	Domestic
USA	ALLETE, Inc.					X	Private	Foreign

(continued)

Country	TSO	VIU	LTSO	ITSO	ISO	TO	Ultimate ownership	Origin of Ultimate Owner
USA	Ameren Corporation					X	Private	Int.
USA	Arizona Electric Power Co-op, Inc.					X	Cooperative	Domestic
USA	Arkansas Electric Cooperative Corporation					X	Cooperative	Domestic
USA	ASCC				X		Private	Domestic
USA	Associated Electric Co-op, Inc.					X	Cooperative	Domestic
USA	ATC					X	Private	Domestic
USA	Avangrid					X	Private	Foreign
USA	Basin Electric Power Cooperative					X	Cooperative	Domestic
USA	BGE					X	Private	Int.
USA	BHE US Transmission					X	Private	Int.
USA	Big Rivers Electric Corporation					X	Cooperative	Domestic
USA	Bonneville Power Administration					X	State	Domestic
USA	Brazos Electric Power Cooperative, Inc.					X	Cooperative	Domestic
USA	Buckeye Power, Inc.					X	Cooperative	Domestic
USA	CAISO				X		Independent	Domestic
USA	Central Electric Power Co-op, Inc.					X	Cooperative	Domestic
USA	Central Electric Power Cooperative					X	Cooperative	Domestic
USA	Central Iowa Power Cooperative					X	Cooperative	Domestic
USA	Central Montana Elec. Power Co-op					X	Cooperative	Domestic
USA	Central Nebraska Public Power Irrigation Dist					X	Cooperative	Domestic
USA	Central Power Electric Cooperative, Inc.					X	Cooperative	Domestic
USA	CentrePoint Energy					X	Private	Int.
USA	Chugach Electric Association, Inc.					X	Cooperative	Domestic
USA	ComED					X	Private	Int.
USA	Con Edison (or ConEd)					X	Private	Int.
USA	Continental Cooperative Services, Inc.					X	Cooperative	Domestic
USA	Cooperative Energy					X	Cooperative	Domestic
USA	Corn Belt Power Cooperative					X	Cooperative	Domestic
USA	Dairyland Power Cooperative					X	Cooperative	Domestic
USA	Deseret G&T					X	Cooperative	Domestic
USA	Dominion Resource					X	Private	Int.
USA	Duke Energy					X	Private	Int.
USA	East Kentucky Power Cooperative					X	Cooperative	Domestic
USA	East River Electric Power Cooperative, Inc.					X	Cooperative	Domestic
USA	East Texas Electric Co-op					X	Cooperative	Domestic

(continued)

Country	TSO	VIU	LTSO	ITSO	ISO	TO	Ultimate ownership	Origin of Ultimate Owner
USA	Electric Transmission Texas					X	Private	Domestic
USA	Entergy					X	Private	Int.
USA	ERCOT				X		Independent	Domestic
USA	Evergy Inc.					X	Private	Int.
USA	Eversource					X	Private	Int.
USA	FirstEnergy Corporation					X	Private	Int.
USA	Georgia Energy Cooperative					X	Cooperative	Domestic
USA	Georgia Transmission Corporation					X	Cooperative	Domestic
USA	Golden Spread Electric Cooperative, Inc.					X	Cooperative	Domestic
USA	Great River Energy					X	Cooperative	Domestic
USA	Heartland Consumers Power District					X	Cooperative	Domestic
USA	HEI	X					Private	Int.
USA	Hoosier Energy REC, Inc.					X	Cooperative	Domestic
USA	ISO-NE				X		Independent	Domestic
USA	ITC Holdings					X	Private	Int.
USA	KAMO Power					X	Cooperative	Domestic
USA	Kansas Electric Power Co-op					X	Cooperative	Domestic
USA	L & O Power Cooperative					X	Cooperative	Domestic
USA	M & A Electric Power Co-operative					X	Cooperative	Domestic
USA	Members 1st Power Cooperative					X	Cooperative	Domestic
USA	MidAmerican Energy Company					X	Private	Domestic
USA	Minnkota Power Cooperative, Inc.					X	Cooperative	Domestic
USA (and Canada)	MISO				X		Independent	Domestic
USA	National Grid USA					X	Private	Int.
USA	Nebraska Electric G&T Co-op, Inc.					X	Cooperative	Domestic
USA	New Horizon Electric Cooperative, Inc.					X	Cooperative	Domestic
USA	New York Power Authority					X	State	Domestic
USA	NextEra					X	Private	Int.
USA	North Carolina EMC					X	Cooperative	Domestic
USA	Northeast Missouri Elec. Power Co-op					X	Cooperative	Domestic
USA	Northeast Texas Elec. Co-op					X	Cooperative	Domestic
USA	Northwest Iowa Power Cooperative					X	Cooperative	Domestic
USA	NorthWestern Energy					X	Private	Int.
USA	NV Energy					X	Private	Domestic
USA	NW Electric Power Cooperative, Inc.					X	Cooperative	Domestic
USA	NYISO				X		Independent	Domestic

(continued)

Country	TSO	VIU	LTSO	ITSO	ISO	TO	Ultimate ownership	Origin of Ultimate Owner
USA	OG&E					X	Private	Int.
USA	Oglethorpe Power Corporation					X	Cooperative	Domestic
USA	Old Dominion Electric Co-op					X	Cooperative	Domestic
USA	Oncor Energy					X	Private	Int.
USA	PacifiCorp					X	Private	Int.
USA	PECO					X	Private	Int.
USA	PG&E					X	Private	Int.
USA	PJM				X		Independent	Domestic
USA	PNGC Power					X	Cooperative	Domestic
USA	PNM Resources					X	Private	Int.
USA	PowerSouth Energy Cooperative					X	Cooperative	Domestic
USA	PPL Corporation					X	Private	Int.
USA	Prairie Power, Inc.					X	Cooperative	Domestic
USA	PSE&G					X	Private	Int.
USA	Rayburn Electric Cooperative					X	Cooperative	Domestic
USA	Rushmore Electric Power Cooperative, Inc.					X	Cooperative	Domestic
USA	San Miguel Electric Cooperative, Inc.					X	Cooperative	Domestic
USA	SDG&E					X	Private	Int.
USA	Seminole Electric Co-op, Inc.					X	Cooperative	Domestic
USA	Sho-Me Power Electric Cooperative					X	Cooperative	Domestic
USA	South Texas Electric Cooperative, Inc.					X	Cooperative	Domestic
USA	Southern California Edison					X	Private	Int.
USA	Southern California Edison					X	Private	Int.
USA	Southern Company					X	Private	Int.
USA	Southern Illinois Power Cooperative					X	Cooperative	Domestic
USA	SPP				X		Independent	Domestic
USA	Square Butte Electric Cooperative					X	Cooperative	Domestic
USA	Sunflower Electric Power Corp.					X	Cooperative	Domestic
USA	Tennessee Valley Authority					X	State	Domestic
USA	Tri-State G&T Assn., Inc.					X	Cooperative	Domestic
USA	Upper Missouri Power Cooperative					X	Cooperative	Domestic
USA	Wabash Valley Power Assn., Inc. dba Wabash Valley Power Alliance					X	Cooperative	Domestic
USA	Western Farmers Electric Co-op					X	Cooperative	Domestic
USA	Western Montana Electric G&T Co-op					X	Cooperative	Domestic
USA	Wolverine Power Supply Co-op, Inc.					X	Cooperative	Domestic
USA	XCEL Energy					X	Private	Int.

Appendix 2 European TSOs revenue breakdown

The table overleaf provides a breakdown of the revenues generated by European TSOs as of 2018, distinguishing between:

a) the revenues generated by regulated activities related with the transmission of electricity carried out within national boundaries;
b) the revenues generated by activities carried out within the national boundaries, both regulated (e.g. transmission of gas, distribution of electricity or gas) and non-regulated (e.g. telecommunications business)
c) the revenues generated by both regulated and non regulated activities abroad.

Revenues are calculated by using last available financial information (e.g. financial statement, annual report, etc.).

National Grid (UK) represent a particular case in point because most of its revenues are generated abroad (i.e. in the US). In particular, the high rate of internazionalisation of National Grid dates back to the beginning of 2000s when it started to pursue mergers and acquisitions becoming a key player in the US. As of 2018, National Grid owns and operates electricity transmission facilities, electricity and gas distribution networks across the northeastern US.

With regard to Revenues from other domestic activities (both regulated and non-regulated), instead, the relatively high percentage of Portuguese TSO REN, UK National Grid and Danish TSO Energinet, instead, depends primarily on the fact that these TSOs also manage gas transmission infrastructure[14].

[14] Danish TSO Energinet has also some electricity distribution infrastructure.

Selected European TSOs revenues breakdown in 2018

European TSO	Revenues from domestic regulated activities related with transmission of electricity (%)	Revenues from other domestic activities (both regulated and non-regulated) (%)	Revenues from International activites (both regulated and non-regulated) (%)
RTE	98.8%	1.1%	0.2%
Terna	90.6%	8.9%	0.6%
REE	93.0%	4.5%	2.5%
TenneT [15]	100.0%	0.0%	0.0%
Elia Group	99.3%	0.2%	0.5%
Svenska Kraftnät[16]	99.4%	0.6%	0.0%
ESO	100.0%	0.0%	0.0%
ADMIE	89.3%	10.7%	0.0%
National Grid	22.3%	11.5%	66.2%
REN[17]	63.0%	37.0%	0.0%
Transelectrica	100.0%	0.0%	0.0%
Energinet	83.9%	16.1%	0.0%
Average	86.6%	7.5%	5.8%

[15] TenneT is also involved in certain limited non-regulated activities, some of which are directly or indirectly relevant for the transmission network development. However with the information at disposal it was not possible to distinguish their amount from the rest of the revenues and calculate their share accordingly.

[16] Data are referred to 2017, the last year with public information available

[17] In February of 2017, REN acquired a 42.5% stake in Electrogas, a Chilean company that owns a gas pipeline of great relevance in central Chile. On the 1st of October of 2019, REN acquired the entire share capital of Transemel. Predominantly located in northern Chile, Transemel operates 92 km of power transmission lines and five substations, with approximately 93% of its revenue coming from regulated activities. However, with the information at disposal it was not possible to distinguish the amount of revenues generated by international activities and calculate their share accordingly.

Appendix 3 European regulatory frameworks for innovation of TSOs

The following tables give a full breakdown of regulatory framework for innovation of selected European TSOs. The tables were compiled using the European Commission (2019a) and CEER (2020) as the primary sources.

TSO:	Country:	Regulatory mechanism:	Regulatory period length:	National regulatory framework:
RTE	France	Incentive-based revenue cap with pass through elements	4 years	Explicit reference to innovation or related concepts

Regulatory provisions and/or financial incentives for innovative projects:

Specific incentives for innovative projects:

- Research and development, and innovative projects are covered by system charges
- The NRA allows a budget to RTE in order to promote research and development and/or innovation.
- The operator can also obtain additional budgets during the tariff period for financing smart grid projects, subject to confirmation of its socio-economic value based on a cost-benefit analysis.

National Regulatory Authority connotation and interpretation of "innovation":

- Primarily understood as technical innovation which could be technological or digital change.
- Technological change amounts to offering new technical development solutions by fostering the emergence of new components which take advantage of nanotechnology development, power electronics and superconductivity. Digital change involves developing a methodology to facilitate infrastructure maintenance and optimisation and contributing to the development of smart grids.

TSO:	Country:	Regulatory mechanism:	Regulatory period length:	National regulatory framework:
Terna	Italy	Hybrid (Combined model of Price Cap for OPEX and Rate-of-Return for CAPEX) Transition to TOTEX regulation regime envisaged.	6 years	Explicit reference to innovation or related concepts

Regulatory provisions and/or financial incentives for innovative projects:

Specific incentives for innovative projects:

- Specific premiums are available for investments, which relate to innovation, particularly in the area of smart grids.
- The NRA started the transition to a new regulatory framework with same treatment of CAPEX and OPEX (i.e. TOTEX). This will incentivise low-CAPEX innovative solutions.

National Regulatory Authority connotation and interpretation of "innovation":

- n.a.

	Country:	Regulatory mechanism:	Regulatory period length:	National regulatory framework:

TSO:

Redeia	Spain	Other (A system of reference unit values)	6 years	No explicit reference to innovation or related concepts

Regulatory provisions and/or financial incentives for innovative projects:

Implicit/partial incentives for innovative projects:

- Reference unit values of investment and of O+M are used.
- Innovation projects are in practice often remunerated. For specific projects, the TSO can obtain approval and funding on a case-by-case basis if they are not on the list with reference unit values (acquiring the status of "special investments").

National Regulatory Authority connotation and interpretation of "innovation":

- n.a.

TSO:	Country:	Regulatory mechanism:	Regulatory period length:	National regulatory framework:
TenneT	NLD & Germany	Incentive-based Revenue Cap (Netherlands) / Incentive-based Revenue Cap (Germany).	3-5 years (Netherlands) / 5 years (Germany)	No explicit reference (Netherlands or Germany)

Regulatory provisions and/or financial incentives for innovative projects:

Specific incentives for innovative projects (Netherlands):

- TenneT may receive a direct subsidy for the offshore electricity grid and possibility to obtain an exemption from regulatory control of tariffs or tariff methodologies for all or part of new interconnectors, if strict conditions are met.
- In addition to that, there are subsidy schemes designed to incentivise investment in innovation but typically, the cost of investments is at first incurred by the TSO, who can include it to the RAB only after an ex-post assessment by the regulator on the efficiency of execution

Specific incentives for innovative projects (Germany):

- Incentive mechanism for R&D costs in the form of adjustment to the revenue cap, equals 50% of the total costs not covered by public funding.
- Exemptions of some projects from efficiency targets: the actual costs of TSOs are decoupled from admissible network tariffs within the five year regulatory period

National Regulatory Authority connotation and interpretation of "innovation":

- the ability of a network operator to act adequately and cost-efficiently to new developments in the production and consumption of electricity in the short and long term (Netherlands)
- R&D is also an element of innovation (Germany)

TSO:	Country:	Regulatory mechanism:	Regulatory period length:	National regulatory framework:
Elia Group	Belgium & Germany	Cost-based (Belgium) / incentive-based Revenue cap (Germany).	4 years (Belgium) / 5 years (Germany)	Explicit reference to innovation or related concepts (Belgium) / No explicit reference (Germany)

Regulatory provisions and/or financial incentives for innovative projects:

Specific incentives for innovative projects (Belgium):

- Extra remuneration (in the form of premiums on cost of capital) for risky projects, which, so far, has only been used for modular offshore wind project.
- R&D projects which are not part of these subsidies are incentivised starting from 2020 through a 4 year R&D plan which must be developed by the TSO sent for approval to the NRA
- At the completion of previously approved projects the TSO is granted with an extra remuneration.

Specific incentives for innovative projects (Germany):

- Incentive mechanism for R&D costs in the form of adjustment to the revenue cap, equals 50% of the total costs not covered by public funding.
- Exemptions of some projects from efficiency targets: the actual costs of TSOs are decoupled from admissible network tariffs within the five year regulatory period

National Regulatory Authority connotation and interpretation of "innovation":

- Should include R&D and based on specific criteria, such as innovativeness of new technologies or processes from the point of view of each TSO in its specific context. Other criteria linked to welfare gain and uncertainty, for instance, do not directly relate to innovation itself but are criteria for the support of innovation that could be awarded through the regulatory framework.
- "Developing and/or applying new technologies to increase efficiency and reduce costs. As an example, this could include optimising the use of existing assets through improved forecasting methods, stochastic-based risk management and decision making, application of Dynamic Line Rating, optimisation of non-costly remedial actions, etc" (Belgium)

TSO:	Country:	Regulatory mechanism:	Regulatory period length:	National regulatory framework:
Svenska Kraftnät	Sweden	Incentive-based Revenue Cap	4 years	Explicit reference to innovation or related concepts

Regulatory provisions and/or financial incentives for innovative projects:

Implicit/partial incentives for innovative projects:

- Unnecessary assets not to be included in price control but exclusion of such assets is subject to reasonableness test.
- May provide opportunity to include costs of innovative/pilot investments i.e. if it would be unreasonable to exclude them.
- The revenue cap financing mechanisms present the inherent drawback of favouring CAPEX intensive projects over OPEX focused ones.

National Regulatory Authority connotation and interpretation of "innovation":

- A product that has passed research and development and is established on the market. Since this product is still considered innovative there are expectations on continued technical development affecting not only sustainability but also the price of the product.

TSO:	Country:	Regulatory mechanism:	Regulatory period length:	National regulatory framework:
ESO	Bulgaria	Hybrid (Rate-of-Return combined with cap on prices)	1 year	No explicit reference

Regulatory provisions and/or financial incentives for innovative projects:

- No evidence of incentives for innovative projects

National Regulatory Authority connotation and interpretation of "innovation":

- n.a.

TSO:	Country:	Regulatory mechanism:	Regulatory period length:	National regulatory framework:
IPTO	Greece	Hybrid (incentive based revenue cap) in relation to OPEX and cost-of service in relation to (CAPEX).	4 years	No explicit reference

Regulatory provisions and/or financial incentives for innovative projects:

Implicit/partial incentives for innovative projects:

- Premium rate of return for projects of major importance may encourage investment in projects with innovative elements.

National Regulatory Authority connotation and interpretation of "innovation":

- "novel infrastructure solutions which are adequately reliable in terms of security of supply – already tested to some extent as HVDC and Dynamic Line Rating (DLR) in the electricity sector – and proved to be more cost and/or energy-efficient and socially beneficial in relation to conventional solutions."

TSO:	Country:	Regulatory mechanism:	Regulatory period length:	National regulatory framework:
National Grid	UK	Hybrid (price cap regulation evolved to incorporate new features and incentives)	8 years (moving to 5 years from 2021)	Explicit reference to innovation or related concepts

Regulatory provisions and/or financial incentives for innovative projects:

Specific incentives for innovative projects:

- One of the objectives of RIIO is to encourage innovation.
- RIIO adopts a TOTEX approach

- RIIO incentivises innovation as part of the price control review by defining a set of outputs and targets. Network companies need to report their performance for each category of output and their revenue will be adjusted upward when they exceed the target and downward when they fail to meet the target.
- An additional package of financial mechanisms encourage innovation: Network Innovation Allowance (NIA) and Network Innovation Competition (NIC); Innovation roll-out mechanism (IRM). Innovation Link.

National Regulatory Authority connotation and interpretation of "innovation":

- "Is important to ensure that network companies support the transition to a smarter, more flexible, sustainable low-carbon energy system and reduce costs to consumers by finding new ways of operating and developing their networks"

TSO:	Country:	Regulatory mechanism:	Regulatory period length:	National regulatory framework:
REN	Portugal	Hydrid (Combined model of Price Cap for OPEX, standard costs in new investments and Rate-of Return for CAPEX)	3 years	No explicit reference

Regulatory provisions and/or financial incentives for innovative projects:

No evidence of incentives for innovative projects:

- Projects to develop the transmission network have to be approved on a case by case basis.
- The main focus in the recent past has been on urgent projects and security of supply projects and this has resulted in limited funding for innovative projects.
- There is also a great deal of pressure to keep costs down and qny investment that is not absolutely required will not be approved.

National Regulatory Authority connotation and interpretation of "innovation":

- Automation solutions to reduce their operational expenditures (OPEX) and increase the quality of service are an example.
- "The deployment of demonstration pilot projects after the R&D stage".

TSO:	Country:	Regulatory mechanism:	Regulatory period length:	National regulatory framework:
Trans-electrica	Romania	Incentive-based Revenue Cap	5 years	Explicit reference to innovation or related concepts

Regulatory provisions and/or financial incentives for innovative projects:

Implicit/partial incentives for innovative projects:

- The transition to a smart transmission network and investments in R&D are encouraged.
- OPEX includes provision for research and study costs.

National Regulatory Authority connotation and interpretation of "innovation":

- should be regarded as use of technical and technological solutions.
- The application of these innovative solutions should lead to improvement of key performance indicators of the system, increase of welfare (in monetised and/or non-monetised terms) and increase of flexibility and adaptability of the system for a successful and timely integration of production and consumption units, as well as the dynamic interaction with distribution systems.

TSO:	Country:	Regulatory mechanism:	Regulatory period length:	National regulatory framework:
Energinet	Denmark	Other (Annual break even process)[18]	1 year	Explicit reference to innovation or related concepts

Regulatory provisions and/or financial incentives for innovative projects:

Implicit/partial incentives for innovative projects:

- "Seen as favouring investment subject to NRA approval based on socio-economic value" (European Commission, 2019a)
- Energinet is not subjected to any effciency requirements. Investments costs are recovered through transmission charges and fees which reflect the "break-even" policy (Break-even is the point of balance making neither a profit nor a loss) subject to approval by the regulator.
- Break-even principle will be abandoned and replaced by a revenue cap regulation accompanied by efficiency goals.

National Regulatory Authority connotation and interpretation of "innovation":

- "Technical or market-based solutions that replace, supplement or significantly improve the current infrastructure catalogue by providing additional services or noticeable cost savings to the users of the transmission systems".

Appendix 4: Interview guides

Final order of the questions:

Innovation Approach and Technology trends:

- How do you map technology trends and select technologies to focus for your innovation developments?
- Which technologies are you currently considering most relevant and where are you focusing your innovation projects (with reference to both energy/grid and digital technologies)

Best Practices:

- Do you observe other tech and trends that are currently developed by our peers and that you consider significant for future developments?
- What are the emerging best practices regarding your investments in research, innovation, and new energy and digital technologies?

Special focus on Non-Wire Alternatives (NWAs):

- Did you consider to refer to the cluster of NWA in your technology scenario/approach?
- Do you consider NWA more as a threat or an opportunity for the profitability of TSOs?

Challenges and Future Evolution:

- Which are the most relevant challenges that you expect will come from the adoption of new technologies that you're addressing with innovation program or, more broadly, from the transformations occurring in the sector?
- What is the impact you expect in terms of results and eventually the change of business model from the adoption of new technologies in your company and, more broadly, how do you see the role of the TSO in the future?

Initial order of the questions:

Innovation Approach and Technology trends:

- How do you map technology trends and select technologies to focus for your innovation developments?
- Which technologies are you currently considering most relevant and where are you focusing your innovation projects (with reference to both energy/grid and digital technologies)

Best Practices:

- What are the emerging best practices regarding your investments in research, innovation, and new energy and digital technologies?
- Do you observe other tech and trends that are currently developed by our peers and that you consider significant for future developments?

Special focus on Non-Wire Alternatives (NWAs):

- Do you consider NWA more as a threat or an opportunity for the profitability of TSOs?
- Did you consider to refer to the cluster of NWA in your technology scenario/approach?

Challenges and Future Evolution:

- Which are the most relevant challenges that you expect will come from the adoption of new technologies that you're addressing with innovation program or, more broadly, from the transformations occurring in the sector?
- What is the impact you expect in terms of results and eventually the change of business model from the adoption of new technologies in your company and, more broadly, how do you see the role of the TSO in the future?

Appendix 5: International Benchmarking Analysis Results

Europe:

Table 13 Benchmarking analysis of European TSOs, ranked by their average score across eleven technologies on a scale of 0-3

Country	TSO	SF6 alternatives	Hypergrid	V2G	DLR	Microgrids and Energy communities	Wireless electricity	5G	Industrial Robots	Drones	AI	6G	Average
Spain	REDEIA	3	2	1	3	1	0	3	2	2	3	0	**1.8**
Great Britain	NATIONAL GRID	2	3	3	2	2	0	1	1	2	3	0	**1.7**
France	RTE	3	2	2	2	1	0	1	1	3	2	0	**1.5**
Germany & Belgium	ELIA	2	3	2	3	1	0	0	2	2	2	0	**1.5**
Italy	TERNA	2	3	2	2	1	0	1	2	2	2	0	**1.5**
Norway	STATTNET	2	2	2	2	2	0	0	2	2	2	0	**1.5**
Germany & Netherlands	TENNET	2	3	3	2	0	0	1	2	1	1	0	**1.4**
Denmark	ENERGINET	1	3	3	3	0	0	0	1	2	1	0	**1.3**
Great Britain	SSEN	2	3	2	2	1	0	0	1	2	1	0	**1.3**
Germany	AMPRION	2	3	2	2	0	0	0	0	2	2	0	**1.2**
Germany	TRANSNETBW	2	3	3	1	0	0	1	0	1	1	0	**1.1**
Finland	FINGRID	2	2	1	2	1	0	0	0	1	2	0	**1.0**
Greece	ADMIE/IPTO	0	2	0	1	1	0	2	1	1	1	0	**0.8**
Great Britain	SP NETWORKS	2	2	0	2	0	0	0	0	2	1	0	**0.8**
Austria	APG	1	0	0	2	0	0	0	1	2	2	0	**0.7**
Switzerland	SWISS GRID	0	1	1	2	0	0	1	0	2	1	0	**0.7**
Romania	TRANSELECTRICA	0	1	0	1	0	0	0	0	2	1	0	**0.5**
Bulgaria	ESO	0	1	0	1	1	0	1	0	0	0	0	**0.4**
Portugal	REN	1	1	0	1	0	0	0	0	1	0	0	**0.4**
Average		**1.5**	**2.1**	**1.4**	**1.9**	**0.6**	**0.0**	**0.6**	**0.8**	**1.7**	**1.5**	**0.0**	
		Energy/Grid Domain						Digital Domain					
		1.3						**0.9**					

America:

Table 14 Benchmarking analysis of American TSOs, ranked by their average score across eleven technologies on a scale of 0-3

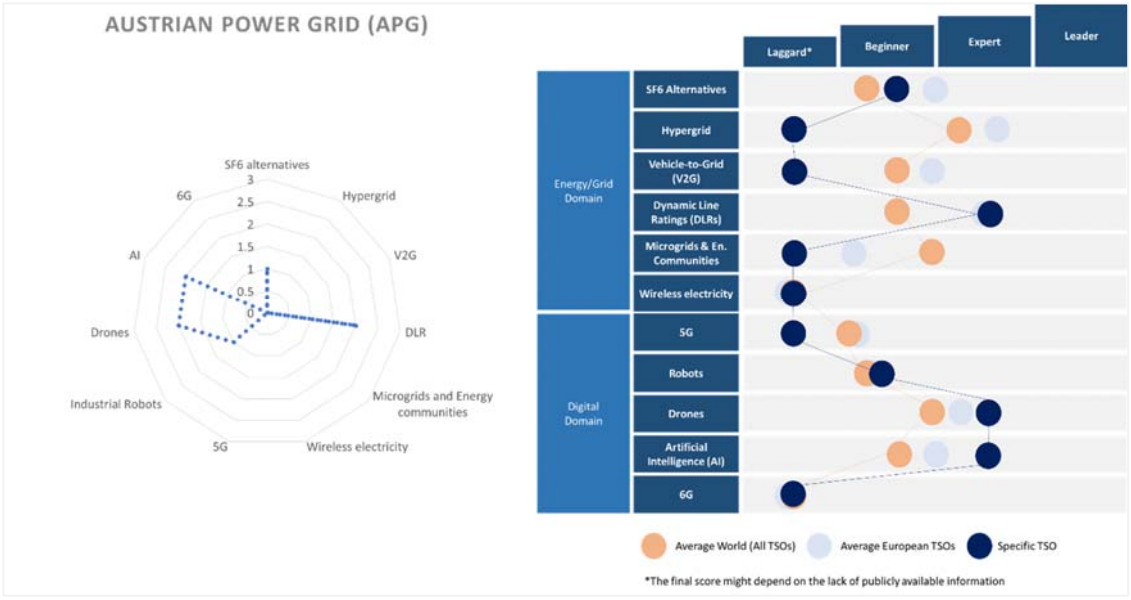
Country	TSO	SF6 alternatives	Hypergrid	V2G	DLR	Microgrids and Energy communities	Wireless electricity	5G	Industrial Robots	Drones	AI	6G	Average
Canada	HYDRO-QUEBEC	0	3	3	2	2	0	0	3	3	1	0	**1.5**
USA	CON EDISON	2	3	2	2	3	0	0	2	1	2	0	**1.5**
USA	PG&E	2	0	2	0	3	0	0	2	2	2	0	**1.2**
USA	EVERSOURCE	2	1	2	0	3	0	0	1	1	2	0	**1.1**
USA	AEP	0	2	1	2	2	0	0	1	2	1	0	**1.0**
USA	XCEL ENERGY	0	0	2	1	3	0	1	0	2	2	0	**1.0**
USA	NextEra	0	1	2	0	2	0	1	1	2	1	0	**0.9**
Canada	IESO	0	1	3	1	3	0	0	0	0	1	0	**0.8**
USA	PJM	0	3	2	3	1	0	0	0	0	0	0	**0.8**
Canada	HYDRO ONE	1	1	0	0	1	0	0	0	2	2	0	**0.6**
USA	NEW YORK ISO	0	3	0	1	3	0	0	0	0	0	0	**0.6**
USA	MISO	0	3	0	1	2	0	0	0	0	0	0	**0.5**
Canada	ALTALINK	0	2	0	2	0	0	0	1	0	0	0	**0.5**
USA	CAISO	1	3	0	0	1	0	0	0	0	0	0	**0.5**
USA	ISO NEW ENGLAND	0	3	1	0	1	0	0	0	0	0	0	**0.5**
USA	ERCOT	0	3	0	0	1	0	0	0	0	0	0	**0.4**
USA	HEI	0	0	0	0	3	0	0	0	1	0	0	**0.4**
Chile	TRANSELEC	0	2	0	0	0	0	0	0	1	1	0	**0.4**
USA	SPP (SouthWest Power Pool)	0	3	0	0	0	0	0	0	0	0	0	**0.3**
Canada	AESO	0	1	0	1	0	0	0	0	0	0	0	**0.2**
Chile	Coordinador Eléctrico Nacional	0	2	0	0	0	0	0	0	0	0	0	**0.2**
USA	AEL&P (Alaska Electric Light & Power)	0	0	0	0	0	0	0	0	0	0	0	**0.0**
USA	ASCC - Alaska Interconnection	0	0	0	0	0	0	0	0	0	0	0	**0.0**
Average		**0.3**	**1.7**	**0.9**	**0.7**	**1.5**	**0.0**	**0.1**	**0.5**	**0.7**	**0.7**	**0.0**	
		Energy/Grid Domain						Digital Domain					
		0.9						**0.4**					

Asia:

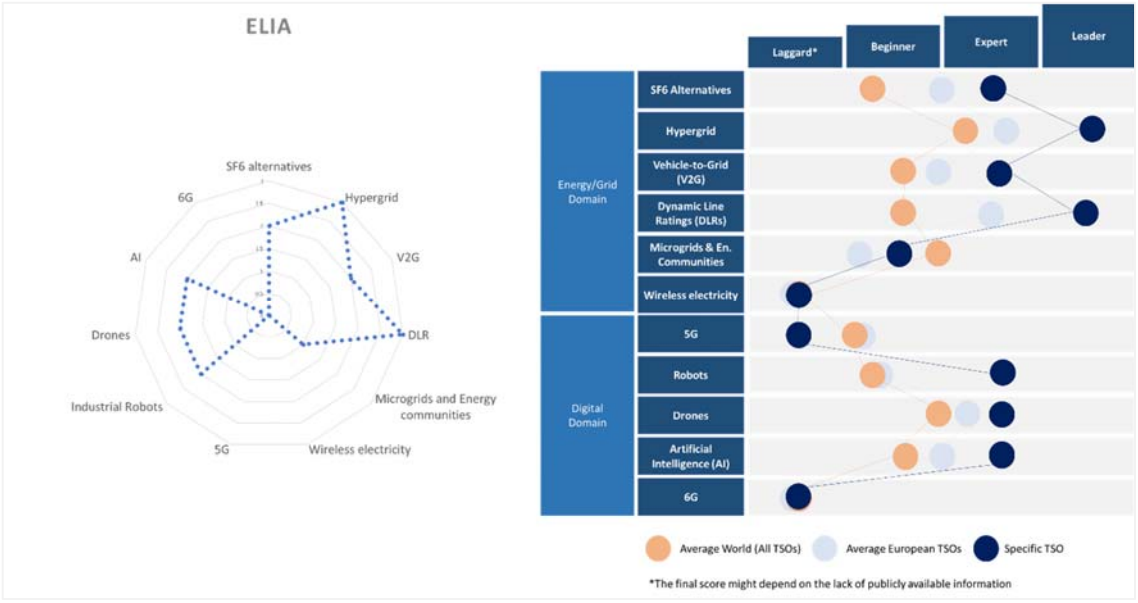
Table 15 Benchmarking analysis of Asian TSOs, ranked by their average score across eleven technologies on a scale of 0-3

Country	TSO	SF6 alternatives	Hypergrid	V2G	DLR	Microgrids and Energy communities	Wireless electricity	5G	Industrial Robots	Drones	AI	6G	Average
China	State Grid Corporation of China	1	3	3	0	2	1	3	3	3	3	1	**2.1**
China	China Southern Power Grid	0	3	0	0	2	1	3	3	3	3	0	**1.6**
Japan	TEPCO	1	1	3	1	3	0	1	1	3	3	0	**1.5**
South Korea	KEPCO	1	3	3	0	3	0	1	1	3	2	0	**1.5**
Japan	Chubu Electric	1	1	2	0	3	0	1	2	3	2	0	**1.4**
Japan	Kansai Electric	0	2	2	0	2	0	2	1	2	3	0	**1.3**
Japan	Kyushu Electric	0	2	2	0	3	0	1	0	3	1	0	**1.1**
Australia	AUSNET SERVICES	0	1	2	2	3	0	0	0	1	2	0	**1.0**
Australia	TRANSGRID	0	1	1	3	2	0	0	0	2	1	0	**0.9**
Australia	POWER LINK	0	1	0	2	3	0	1	0	1	1	0	**0.8**
Japan	Hokkaido Electric	0	1	0	1	2	0	1	1	2	1	0	**0.8**
Australia	TASNETWORK	0	1	1	2	2	0	1	0	0	1	0	**0.7**
Japan	Chugoku Electric	0	0	0	1	1	0	0	0	3	3	0	**0.7**
Japan	Hokuriko Electric	0	0	0	0	1	0	0	2	3	2	0	**0.7**
Australia	ELECTRANET	0	1	0	2	2	0	0	0	1	0	0	**0.5**
Japan	Okinawa Electric	0	0	0	0	3	0	0	0	2	1	0	**0.5**
Japan	Shikoku Electric	0	1	0	0	1	0	1	0	2	1	0	**0.5**
Japan	Tohoku Electric	0	1	1	0	1	0	1	0	1	1	0	**0.5**
Australia	APA Group	0	2	0	0	1	0	0	0	0	0	0	**0.3**
Average		**0.2**	**1.3**	**1.1**	**0.7**	**2.1**	**0.1**	**0.9**	**0.7**	**2.0**	**1.6**	**0.1**	
		Energy/Grid Domain						Digital Domain					
		0.9						**1.1**					

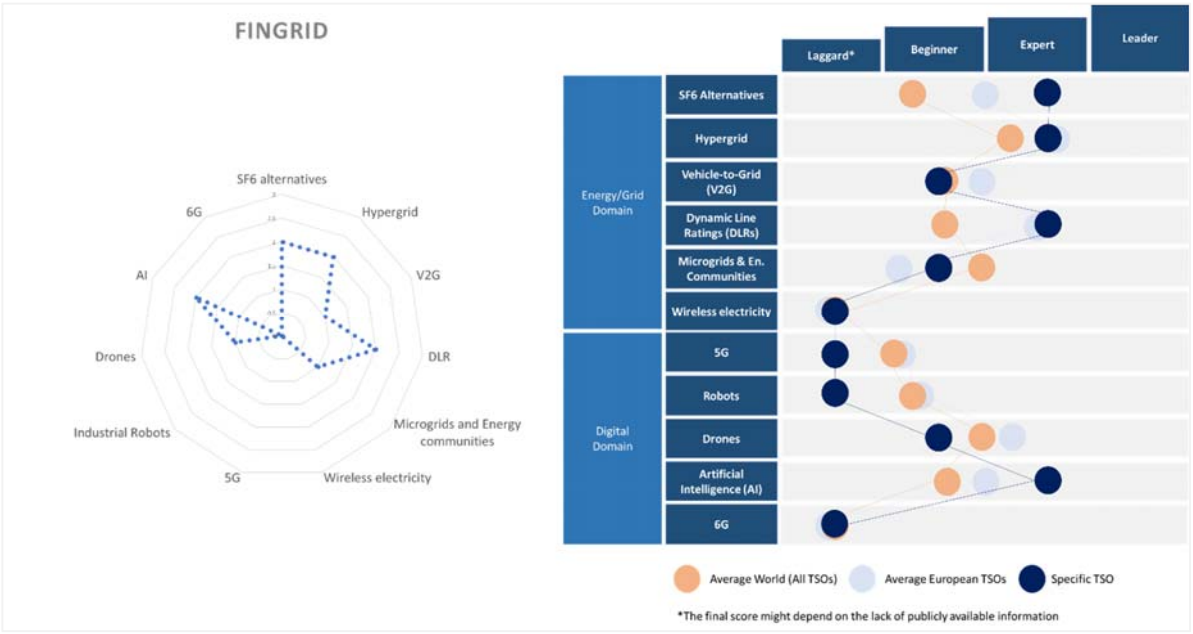
Appendix 6: Comparative benchmarking charts



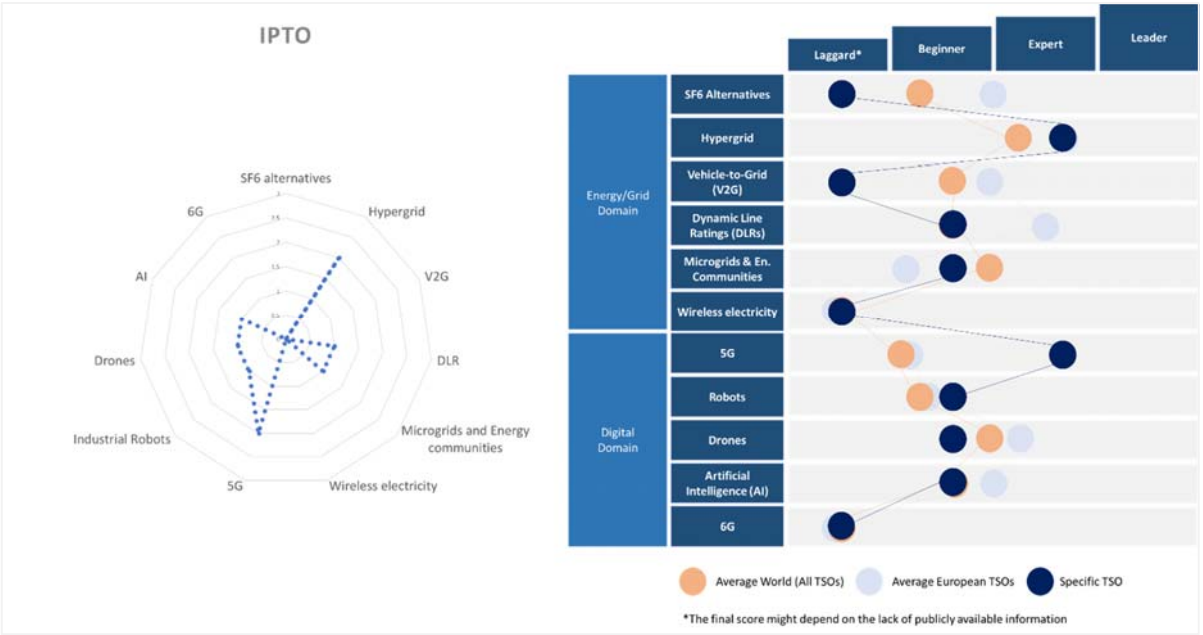
APG Radar chart and position compared to other TSOs



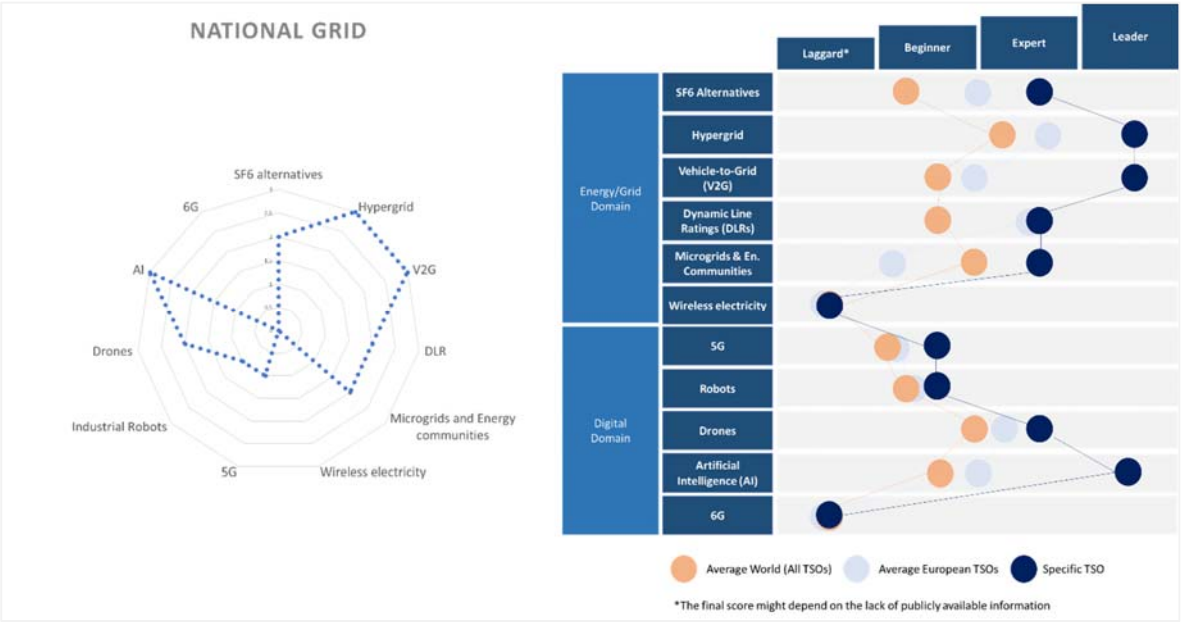
Elia Radar chart and position compared to other TSOs



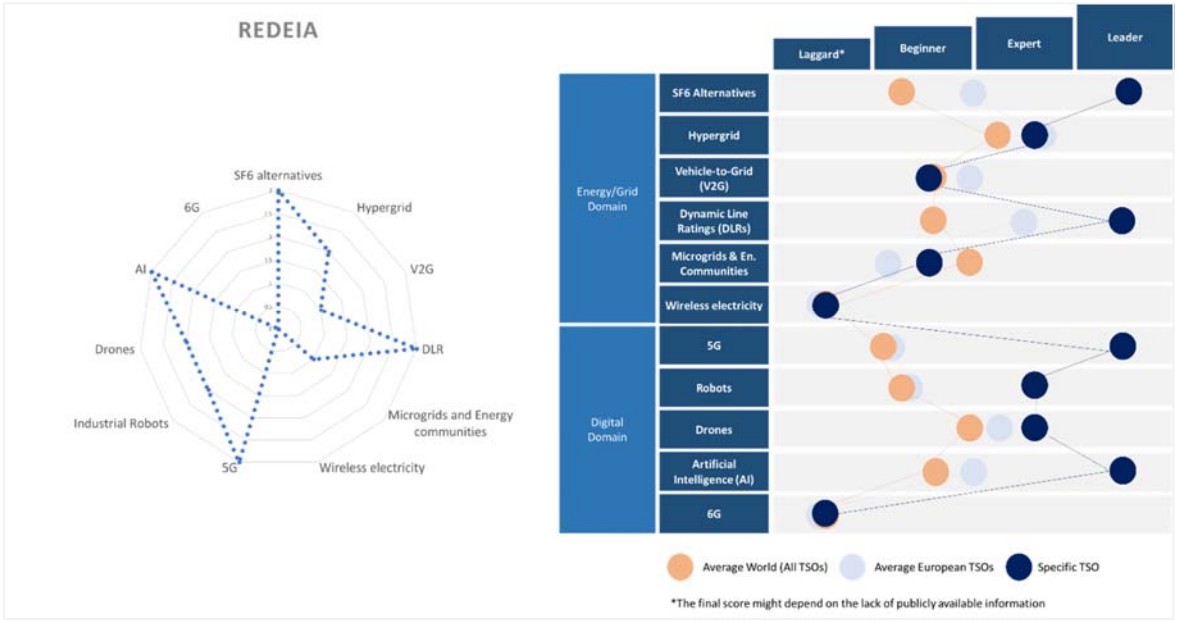
Fingrid Radar chart and position compared to other TSOs



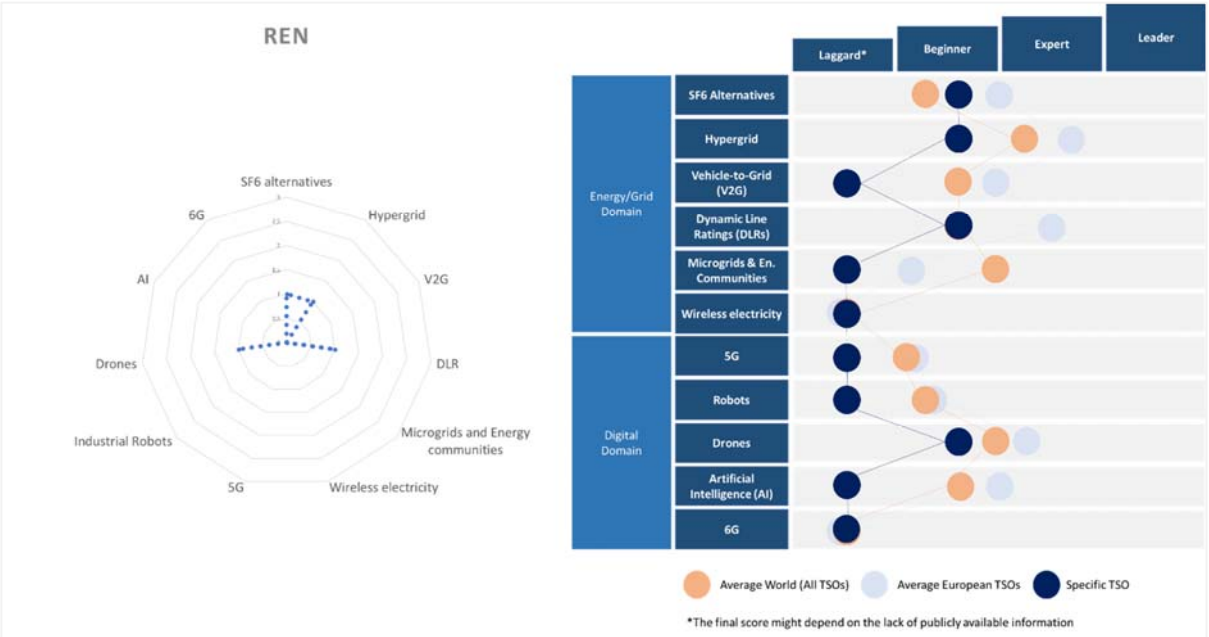
Ipto Radar chart and position compared to other TSOs



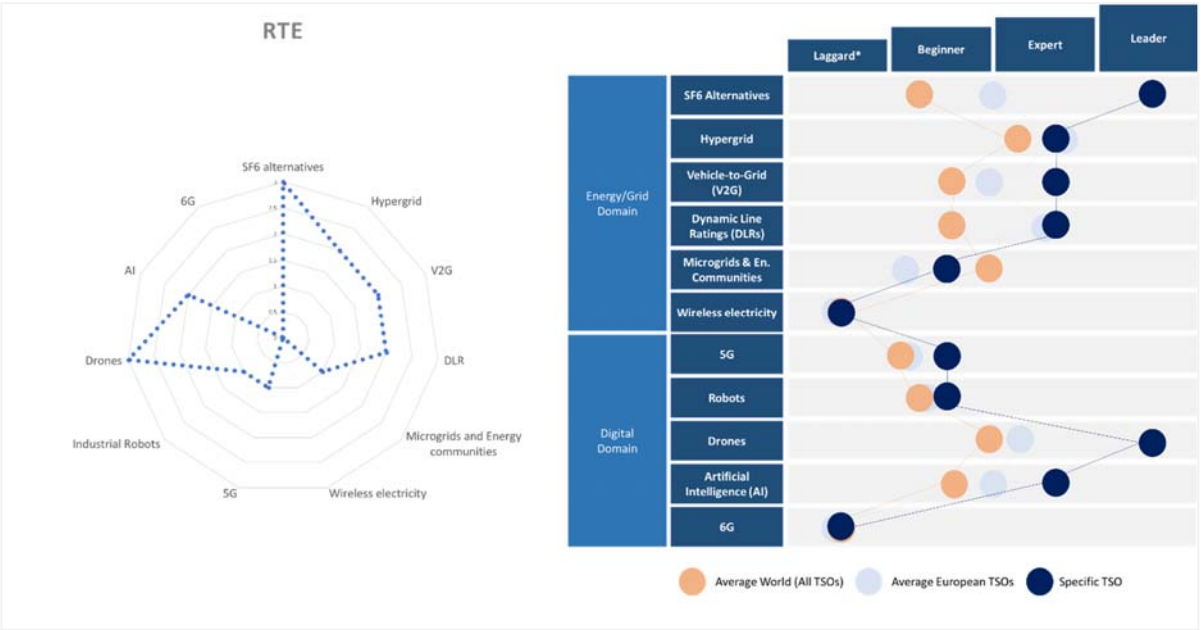
National Grid Radar chart and position compared to other TSOs



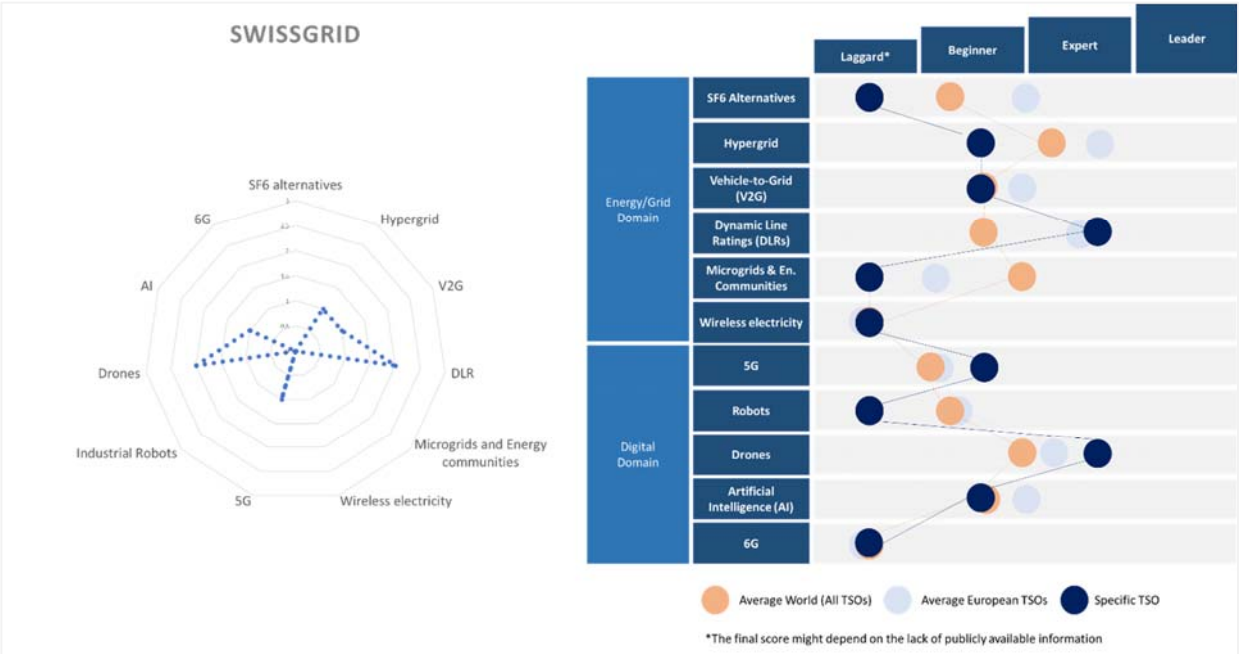
Redeia Radar chart and position compared to other TSOs



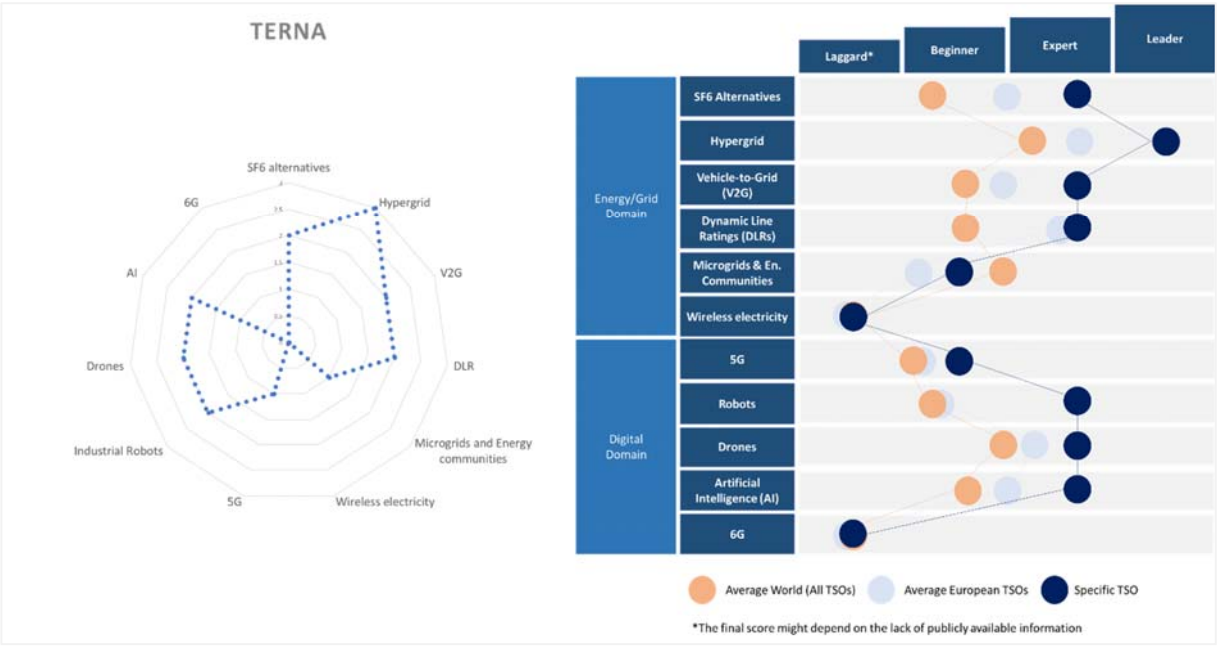
REN Radar chart and position compared to other TSOs



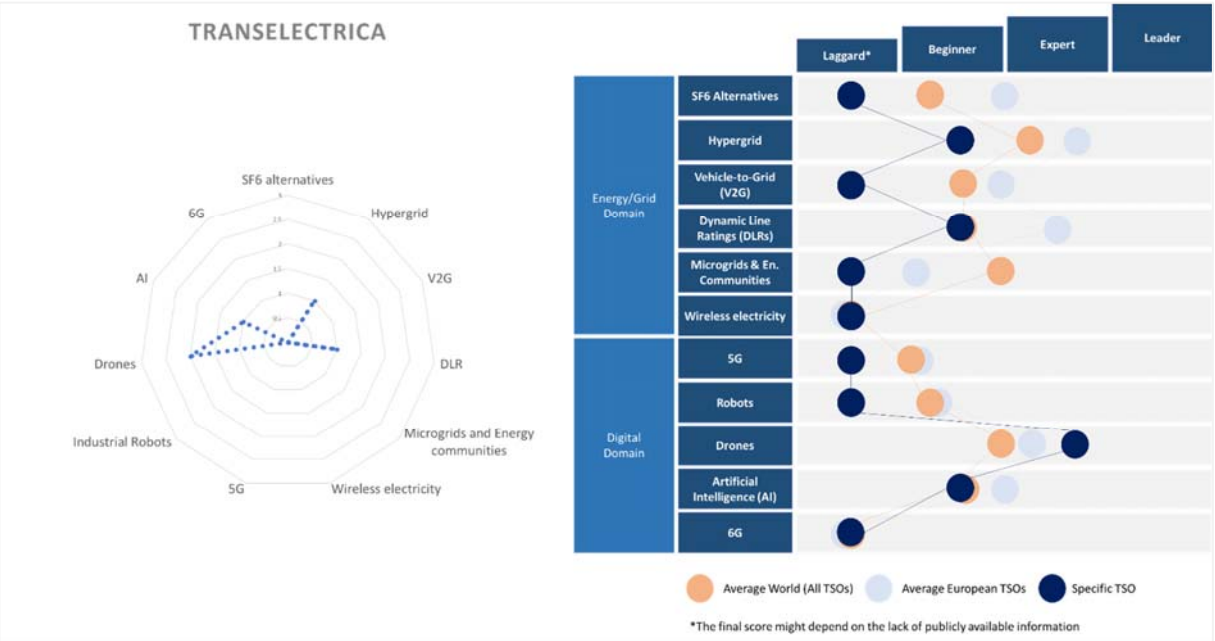
RTE Radar chart and position compared to other TSOs



SwissGrid Radar chart and position compared to other TSOs



Terna Radar chart and position compared to other TSOs



Transelectrica Radar chart and position compared to other TSOs