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Regulatory approaches to the challenges posed by the energy and digital transitions: global lessons from 20 leading electricity distribution system operators (DSOs)

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Abstract : This paper examines how electricity distribution system operators (DSOs) and their regulators are responding to the operational challenges posed by the energy and digital transitions. Focusing on a sample of 20 advanced DSOs in Europe, North America, and Asia-Pacific, we identify four challenges (the "4Cs"): distributed energy resources, electric vehicles, electrified heating and cooling, and data centres. Using a review of DSO and regulator reports, we create a typology and map of regulatory responses designed to incentivize DSOs to address these challenges. Despite differences in system conditions and institutional settings, a convergence in regulatory approaches is observed especially in moving from a reinforcement-led model toward active system management based on flexibility mechanisms, revised connection regimes, adaptive planning and more cost-reflective tariff structures.

Interpreting these developments through the lens of the "learning regulator" we show that regulatory responses display dynamic, adaptive, and responsive features, as regulatory authorities experiment with new tools to cope with the uncertainty of the energy transition. The findings suggest that common patterns are emerging that can inform jurisdictions at earlier stages of the transition.

Keywords : Distribution System Operators, energy transition, regulation

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Regulatory approaches to the challenges posed by the energy and digital transitions: global lessons from 20 leading electricity distribution system operators (DSOs)[1]

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1. Introduction

Distribution system operators (DSOs) are central to both the energy and the digital transition. They sit at the interface between bulk networks and end users and are the part of the system where most distributed resources and new electrified uses connect. As decarbonization accelerates, DSOs are expected to become active, i.e., to enable the integration of new technologies such as distributed energy resources, electric vehicles charging, heat pumps, data centres and others.

The energy and digital transitions are currently posing four major challenges to DSOs (the 4Cs): (C1) distributed energy resources (DERs), especially rooftop PV, which can lead to reverse power flows or congestion and are connected at the distribution level; (C2) electrification of transport through electric vehicles (EV) and associated charging infrastructure, which can create spatially concentrated and potentially coincident peaks; (C3) electrification of heating and cooling via heat pumps (HP), which increase seasonal peak demand; and (C4) large, new, fast-growing and concentrated loads such as data centres (DC), which create problems of connection queues and demand uncertainty. The first three (C1 to C3) are the results of the energy transition and have similar operational implications, but with temporal and scale differences that justify keeping them as distinct. The last (C4) is specific to the digital transition due to the scale, pace of deployment and specific needs as large electricity consumers (different and novel enough from other industrial loads to justify its special treatment).

The challenges (the 4Cs) and the responses to them are relevant because they drive up costs and investment needs in the network component of the energy system. The IEA expects the global grid investment needs to rise substantially by 2030 to accommodate electrification and renewable integration (IEA, 2023). DSOs have indicated that annual investment volumes are expected to increase over the coming decade compared to historical levels, as they need reinforcement and expansion to overcome severe capacity constraints. Higher connection volumes, reinforcement of low-voltage grids, digital infrastructure deployment (within the grid itself), and more complex system operation will translate to higher distribution costs. This impacts traditional cost recovery models. Investment needs are uncertain and often required in anticipation, affecting the traditional CAPEX-based regulatory periods setup. In addition, when demand is highly variable or potentially speculative (like data centres), volumetric cost allocation may become inadequate. Hence, regulatory reforms need to balance between the need for investment (despite uncertain demand growth) and adequate incentives, on one hand, and prudent cost management to keep tariffs in check, on the other.

Regulatory responses to distribution level challenges exhibit significant variation in terms of instruments and approaches, which reflects differences in energy mix and market structure, but also institutional architectures and regulatory culture. Governments, regulators and DSOs are operating under significant uncertainty regarding the appropriate institutional and regulatory responses to the energy and digital transitions (Covatariu and von der Fehr, 2024). In this context, examining how advanced regulators and DSOs are responding to similar pressures can provide valuable learning opportunities. Comparative analysis can help identify approaches which may be transferable, offering guidance to other mature regulatory systems and to jurisdictions that are only beginning to confront these transition-related challenges.

In this paper we select 20 DSOs from around the world deemed to be most exposed to the 4Cs. We then examine how these DSOs report on the 4Cs, in terms of grid stress, congestion, curtailment, connection backlogs and others. Then, we identify high level regulatory responses designed to create appropriate incentives for these DSOs to manage the 4Cs, while managing uncertainty and limiting costs.

2. Methodology

We select[2] 20 DSOs globally based on their exposure to the 4Cs. For each of the Cs, we identify an existing ranking at the country level – decentralized solar capacity for C1, EVs as a percentage of the total vehicle fleet for C2, HPs per 1000 households for C3 and data centre (DC) electricity consumption as a percentage of total electricity consumption. Looking at indicators at the country level for a particular challenge may fail to capture all the DSOs exposed to the stress. However, we attempt to select the DSOs who are likely to be the most exposed. For example, Finland is selected for HP penetration. To ensure that the DSO selected is relevant, we avoided the ones that are predominantly urban (like Helen), where district heating is prevalent. Of the DSOs that serve more detached houses, such as Elenia and Caruna, we chose the latter. Both may be relevant, but the regulatory response is likely to be identical in a country like Finland. In addition, this keeps the number of DSOs at a manageable level.

The rankings are generally of OECD (C1, C2, C4) or EU countries (C3). We adjust these rankings where data is available by including other countries where relevant (e.g. China to OECD rankings, or the UK to EU rankings). To the list of countries, we add jurisdictions that are more relevant than the national level in terms of the 4Cs, such as California (C1, C2) or Virginia (C4) in the US or Quebec in Canada (C3). This results in a list of top 10 jurisdictions for each of the 4Cs. The most relevant DSOs are then identified for each of the jurisdictions and the final list contains 20 DSOs (Table 1).

Table 1: List of 20 DSOs for our sample

#		DSO	Country / region	Dominant Cs	Justification
1		Wiener Netze	Austria	C1, C2	High rooftop PV, EV
2		Fluvius	Belgium	C1, C2	High rooftop PV, EV
3		Radius	Denmark	C2, C3, C4	High EV, HP,DCs

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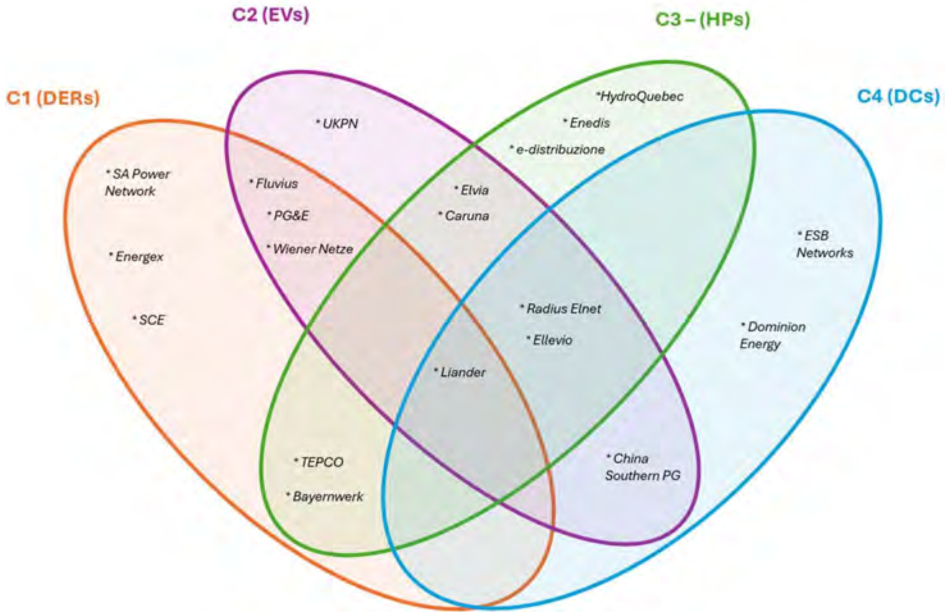
[2] The full ranking methodology and selection criteria are presented in Annex I.

4	Europe	Caruna	Finland	C2, C3	High EV, HP
5		Enedis	France	C3	High, growing HP
6		Bayernwerk	Germany	C1, C3	High rooftop PV, HP
7		ESB Networks	Ireland	C4	Highest DC in Europe
8		e-Distribuzione	Italy	C3	High HP
9		Liander	Netherlands	C1, C2, C3, C4	High PV, EV, HP, DC
10		Elvia	Norway	C2, C3	Highest EV and HP
11		Ellevio	Sweden	C2. C3, C4	High EV, HP, DC
12		UKPN	UK	C2	High EV
13	Global	Energex	Australia (Queensland)	C1	High PV
14		SA Power Networks	Australia (South Australia)	C1	High PV
15		HydroQuebec	Canada (Quebec)	C3	Distinctive approach to heating
16		China Southern PG	China	C2, C4	High EV and DCs
17		Tepco PG	Japan	C1, C3	High PV, distinctive heating-cooling approach in megacity
18		Dominion Energy	USA (Virginia)	C4	Highest on DC
19		PG&E	USA (California)	C1, C2	High PV, EV
20		SCE	USA (California)	C1	High PV

Figure 1 illustrates the overlap between challenges for each of the DSOs in our sample.

Figure 1: The 4Cs and the 20 selected DSOs



The next step is to examine DSO annual reports and identify language indicating the strain caused by one or more of the 4Cs to verify whether the exposure is acknowledged by DSOs themselves. We limit the documents to be analyzed to official DSO annual reports published on the website. Next, we identify recent or planned regulatory innovations intended to incentivize DSOs to respond to these challenges. Similarly, for comparability, we only include official regulator annual reports or specific documents that deal with one or more of the 4Cs. We consider the decision of DSOs and regulators to mention a source of stress, a new approach or a regulatory change in their annual activity report to represent a 'salience threshold', ensuring that we only include elements that are material enough to be significant for our high-level analysis. For example, if a DSO mentions EVs as a challenge to the operation of their network or a regulator describes a new measure in response to those challenges, both will be included in the analysis as having passed the 'salience threshold'. Finally, after identifying the DSO strain, approaches and regulatory responses, we compare jurisdictions to identify typologies and patterns in regulatory responses and conclude with a discussion of the main observations.

The methodological approach suffers from a number of limitations that will be considered and mitigated. First, analyzing only official DSO and regulator reports has an inherent weakness, especially due to the difference reporting practices by DSOs and regulators in different jurisdictions. Some DSOs and regulators publish regular and comprehensive reports, while others report as part of vertically integrated or multinational groups. Another limitation comes from the fact that we focus on recent responses to current challenges. They may be determined by path dependency, i.e. early action or features of the country or the regulatory regime. As much as possible, these aspects will be taken into account, even without making a full regulatory or energy system profile of each country.

3. The current challenges faced by DSOs in their journey to becoming 'active DSOs'

Distribution networks are where many transition technologies connect and where operational complexity is rising fastest. The IEA explains that distribution networks account for the vast majority of grid length (and a large share of asset exposure), while electrification and VRE growth are already producing congestion, curtailment and connection backlogs, which are all signals that grid constraints are becoming material for the energy transition (BCG, 2025; Pollitt *et al.*, 2026).

Selecting and defining the 4Cs

The 4Cs represent a categorization of distribution-level 'stressors'.

Distribution-connected VRE/DERs (**C1**) are associated with reverse power flows, local thermal congestion, curtailment and redispatch needs (Heptonstall and Gross, 2021). PV reverse flows affect grid conditions and can require active voltage and congestion management (Iioka *et al.*, 2019). Curtailment is seen as a last-resort congestion response and rising curtailment may be seen as a symptom of inadequate network capacity and/or operational tools. To ensure we capture distribution level stress and not transmission connected VRE, the indicator we select as a proxy for the size of C1 is the total cumulative capacity in decentralized PV per capita at the country level.

EVs and charging infrastructure (**C2**) generate risks of spatial concentration and simultaneity (Ahmed *et al.*, 2026). This increases probability of transformer and feeder overloads and voltage deviations. Recent review work synthesizes a large empirical and modeling literature that identifies transformer overloading and voltage deviations as evidence of strain (Sarda *et al.*, 2024; Ahmed *et al.*, 2026). Some regulators are implementing or considering new tariff signals and controlled-load provisions to keep connections feasible without reinforcement (Wu *et al.*, 2025). The indicator for C2 will be the total stock of EV and plug-in hybrid (PHEV) as a percentage of total passenger car fleet at the country level.

HPs and electrification of heating/cooling (**C3**) introduce seasonal weather-related peak risks. Modeling evidence indicates that high heat electrification can substantially increase winter electricity demand in cold climates, with implications for peak capacity and planning (Peacock, Fragaki and Matuszewski, 2023). The same can be said of summer cooling, which is also projected to increase substantially over the next decades. In absence of better data, to estimate the level of C3, we use the number of HPs per thousand households in the country.

DCs and other large new concentrated loads (**C4**) create localized grid stress through large changes in demand and planning uncertainty (including connection queues, capacity reservation and risk of underutilization) (Mytton *et al.*, 2023). The Irish regulator recent data-centre connection policy illustrates how regulators can respond by conditioning access on system-support obligations (dispatchable onsite/proximate generation and/or storage; renewable supply requirements; and demand flexibility provisions). Complementing this, alternative connection agreements with “use-it-or-lose-it” approaches address contractual congestion arising when users reserve more capacity than they utilize. At a macro level, the IEA projects strong growth in data centre electricity use this decade (IEA, 2025a). The indicator for C4 will be the total electricity consumption of data centres as a percentage of total electricity consumption at the country level.

The 4Cs as reflected in DSOs’ own reports

To live up to these challenges, DSOs need to become “active”. The active DSO enables the energy transition beyond connection and network management. It is conceptualized based on clustering new DSO tasks into transport, heating, flexibility/DER integration, adaptive planning, and innovation, areas that are related to the operational requirements implied by the 4Cs (Duma *et al.*, 2024). The policy literature also frames the future DSO role as including greater responsiveness, innovation, and expanded DSO-TSO coordination in the context of rising distribution-connected generation and smart technologies (IEA, 2023).

While all selected DSOs operate within the broader pressures of the energy transition, the extent to which these challenges translate into operational strain differs significantly across jurisdictions. DSOs vary greatly, even within the OECD, in terms of size, ownership, structure, age of assets and many others (Pollitt *et al.*, 2025), it is to be expected for the intensity of the strain to differ as well. The following information is extracted from each DSO's reports. [3]

Table 2: Mentions of the 4Cs in DSO reports

DSO	C1 - PV	C2 - EV	C3 - HP	C4 - DC
Wiener Netze	**Present**	Present	Present	
Fluvius	**Present**			
Radius	Present	Present	Present	
Caruna			Present	
Enedis	Present		Present	
Bayernwerk	**Present**		Present	
ESB Networks				**Present**
e-Distribuzione	Present		Present	
Liander	**Present**	**Present**	**Present**	**Present**
Elvia	Present		Present	
Ellevio	Present	Present	Present	Present
UKPN	Present	Present		
Energex	**Present**			
SA PN	Present			
HydroQuebec			Present	
China SPG	Present	Present		Present
Tepco PG	**Present**		Present	
Dominion Energy	Present			**Present**
PG&E	**Present**	Present		
SCE	**Present**			

*Present means the challenge is mentioned. Bold font signifies that the challenge is mentioned as a source of strain. An empty cell means that the challenge is not mentioned.

Looking at the 4Cs, the DSO reporting shows that **C1** (DERs) is the most universal challenge, though its severity varies (Table 2). Many DSOs mention it and some of them identify it as a major source of strain. Liander, Fluvius, SA Power Networks, and Energex highlight C1 as a significant driver of their recent strategies, needed to adapt to the growing strain.

EVs (**C2**) are recognized and mentioned but rarely presented as a challenge. The DSO in the leading country of Norway barely mentions EVs in its reports. Even global EV hotspots like California or Southern China, while reporting on significant growth in charging, do not seem to be severely affected.

Electrification of heat (**C3**) in cold-climate countries is mentioned as a challenge by some DSOs. Caruna, Bayernwerk, e-Distribuzione, Liander and HydroQuebec all mention HPs as relevant drivers of demand, sometimes interacting with EV uptake. In contrast, France appears better positioned due to its long-standing reliance on electric heating infrastructure. Similarly, in Norway or Sweden, the countries with the higher penetration of HPs, the technology is typically not replacing fossil fuels (which are no longer in use for heating) but other electric technologies with lower efficiency, so the impact is a reduction in electricity

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[3] All the information has been extracted from DSO reports. The full list of DSO reports consulted can be found in the Annex.

consumption (Rosenow, 2023). Also, Denmark, Finland and Sweden are heavily reliant on district heating. In Italy, e-Distribuzione mentions HPs as a driven of future consumption rather than a source of strain in the present

DCs (**C4**) represent a more localized disruptive source of demand growth and uncertainty. The jurisdictions under severe strain like Ireland, the Netherlands and Virginia do mention DCs prominently in their reports and are devising strategies to dampen and accommodate their impact.

Matching the DSO reports with the stress rankings by country, many of the challenges are confirmed (C1 as quasi universal, C3 in some cold climate countries, C4 in known data centre hotspots), but others are not. EVs do not seem to be a major source of strain even in the highest penetration regions.

4. The learning regulator - regulatory responses to the 4Cs

Based In regulated sectors like electricity distribution, the actions of operators (DSOs) are determined by the incentives set by regulators. Regulators and the regulation regimes, like DSOs, also differ greatly between jurisdictions, being influenced by the energy mix, the size of the economy and institutional path dependency. As such, regulators have different tools and approaches with varying degrees of effectiveness at their disposal. In order to get DSOs to perform new actions in response to these challenges, regulators need to adjust incentives. Regulatory innovation is determined by shifts in technologies and markets and requires learning, experimentation, and institutional adaptability in face of major changes affecting regulated sectors (Black, Lodge and Thatcher, 2006).

The energy and digital transitions are generating significant and rapid changes in a system that was traditionally accustomed to stability. Predicting the evolution of the 4Cs, in terms of magnitude, pace or even location is difficult. Reaching resolutions, enacting decisions and implementation are also lengthy and complex processes, involving several layers of legislation, stakeholders and risks. In this context, regulators need to contemplate changes to their approach, in order to keep up with the shifting landscape of the industry they are overseeing.

This perspective is consistent with the notion of adaptive regulation seen as a planned adjustment process designing triggers and revision paths that balance between stability and change when sectors are affected by uncertainty. Also in regulated network industries, dynamic regulation represents iterative information updating across regulatory periods relying on feedback loops and adjustment mechanisms. Finally, responsive regulation is defined as an approach to regulation that seeks middle ground between rigid rule-based enforcement and laissez-faire self-regulation, by matching the regulatory tools to the behavior and context of the regulated entities.

Putting together the three attributes, responsive, adaptive and dynamic, the "learning regulator" is meant to live up to the challenge of net zero (Duma, Pollitt and Covatariu, 2024). Both regulators and regulated firms face uncertainty about the pace of technology uptake (EVs/heat pumps) and the required investment timing. The menu of possible options stemming from this uncertainty is also fairly wide. It can include regulatory reform in planning, uncertainty mechanisms, incentives, financing, stakeholder engagement, innovation processes, and governance. The implication for DSO regulation is that "learning" is forced by the 4Cs and requires some level of experiment with new activities and approaches. Assessing performance is becoming more complicated with metrics that reflect short-run operational outcomes (congestion, curtailment, queue reduction) and long-run efficiency (deferral vs reinforcement tradeoffs and consumer impacts). At a concrete level, regulators need to respond to these challenges, to get DSOs to mitigate the existing or expected strain in the network. The next subsection will present such responses from the regulators of the selected DSOs.

Regulatory responses to the 4Cs

This section is based entirely on information extracted from regulator reports.[4]

Austria's regulatory response to the bottlenecks stemming from C1 are centered on enhanced planning and access reform, with elements of flexibility. Measures include "alternative connection agreements", the publication of available connection capacity, and the introduction of biannual network development plans to improve transparency and coordination. The regulator (E-Control) frames flexibility as a complement to grid reinforcement, requiring network plans to indicate future flexibility needs and giving the regulator new competences on flexibility procurement and modernized network charging. The ongoing ElWG policy reform at the country level aims to introduce a more cost-reflective tariff structure based on network usage rather than consumption.

In Belgium, the Flemish regulator VREG introduced the "flex pyramid", with timely grid investment and targeted tariff incentives at the base, moving up to smart use of flexibility by grid users, and finally direct technical intervention by the DSO only as a last resort. VREG allows temporary flexible connection agreements in congested areas, encourages market-based flexibility procurement and requires DSOs to assess whether flexibility can be a cost-effective alternative to grid expansion. As a regional regulator, VREG stresses coordination beyond the Flemish network, requiring alignment with other regions and the federal level.

In Denmark, the Danish Utility Regulator allows DSOs to introduce Tariff Model 3.0 with stronger time differentiation. It has also approved limited grid access on the generation side, meaning producers may accept curtailment instead of waiting for grid reinforcement. At the

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[4] The full list of regulator reports can be found in Annex 2.

same time, a political agreement provides DSOs with an electrification surcharge to fund network expansion. Denmark has also introduced "geozones" – areas defined by the balance between generation and consumption that determine connection charges for producers. From 2024, these geozones must be updated weekly instead of annually.

Finland also promotes time of use grid tariffs and requires DSOs to consider flexibility, demand response, storage and energy efficiency as alternatives to traditional grid investments. From 2024, Finland also introduced a flexibility incentive for DSOs, covering costs (up to 1% of total annual turnover) related to demand response solutions with a cost benefit ratio that does not make it yet mature. The country is also introducing a market-based end-user load control framework, set to enter into force in September 2026. The framework is meant to enable third-party aggregators to control distributed loads such as HPs and EV chargers.

In France, CRE recognizes rapid growth in requests to connect renewable generation which leads to delays. As such, it introduced smart connection offers (offres de raccordement intelligentes) and alternative connection offers with power modulation (ORA-MP), which allow users to connect faster or at lower cost by accepting limits on injections or withdrawal during grid stress. CRE admits that progress in take-up is slow but aims to incentivize the DSO to accelerate their use, including through a bonus of 20% of the gains from flexibility. In addition, CRE introduced the "Reflex" project, aimed at the monitoring of transformers to gradually enable real-time local grid management. It also pushes for wider use of local flexibility tenders and introduces tariff options for storage connected at medium and high voltage.

In Germany, from 2021, Bundesnetzagentur (BNetz) has implemented Redispatch 2.0, bringing distribution-connected renewables above 100 kW into mandatory and coordinated congestion management, with compensation and settlement rules. DSOs can now curtail distributed wind and solar generation, rather than relying on transmission-level redispatch alone. At the same time, under section 14a of the Energy Industry Act, DSOs are allowed to temporarily limit ("dim") the electricity consumption of certain controllable devices, such as EV chargers or HPs, when local grid congestion occurs. All new controllable consumption devices above 4.2 kW installed after 1 January 2024 must participate in this control scheme, and in exchange consumers receive reduced network tariffs for the electricity used by these devices. A consequence of this rule is that network operators are no longer allowed to refuse connections for EV chargers or HPs due to local capacity constraints, because they can rely on this control mechanism to prevent overloads. For now, the number of participating consumers is relatively low, due to the surprisingly slow rollout of smart meters in Germany, but, with the planned acceleration in deployment, the system is expected to become significant. Another significant upcoming German development is AgNes (Festlegung der allgemeinen Netzentgeltsystematik Strom), through which BNetzA is seeking a fundamental redesign of electricity network charges. As described in a discussion paper in 2025, the reform would move toward a charges system that better reflects when and how the grid is used, including stronger capacity- and time-based elements, possible charges for generators, and eventual inclusion of storage. AgNes will be decided in 2026 and implemented from 2029, and will sharpen price signals for flexibility, making tariffs a more active tool for managing congestion and integrating renewables, storage, and flexible demand.

In Ireland, the Commission for Regulation of Utilities (CRU) has tightened the connection policy for large energy users, especially DCs. The moratorium on new DCs has been replaced with a new system whereby new applications are assessed based on security of supply and system stability criteria, including location in constrained regions, provision of onsite or nearby dispatchable generation or storage, participation in wholesale markets, and the ability to offer demand flexibility. Applicants are also expected to report annually on emissions and renewable energy use. The system is being trialed at present and is expected to become a learning opportunity for all DSOs facing severe DC related constraints.

In Italy, from the 2024 regulatory period, ARERA moved from traditional cost-based regulation toward Regulation by Spending and Service Objectives, a TOTEX based system meant to remove the capital expenditure bias and incentivize flexibility and digital solutions that are generally covered under operational expenditures. This shift in regulatory regime is going to impact how DSOs are incentivized to invest and manage uncertainty. ARERA also introduced more frequent (every 2 years) mandatory public consultation of distribution network development plans for DSOs with more than 100,000 customers. The regulator may also allow connections in excess of currently available capacity, introducing a “flexible connection” model aimed at optimizing infrastructure use and accelerating the connection of renewables and storage systems.

The Netherlands stands out in terms of regulatory response, in proportion to the intensity of the challenges. The Dutch DSO in our sample is affected significantly by all 4Cs. The Dutch regulator recognizes electricity grid congestion (“netcongestie”) as the main challenge and that network reinforcement and expansion will take at least 10 years to resolve it fully. As such, exceptional mitigation measures are being implemented to deal with the acute problems while also incentivizing longer term solutions. ACM introduced a new prioritization framework so that projects of high societal value such as housing and hospitals receive priority grid access. It has strengthened congestion management rules, compensating users who reduce peak consumption, and offering large consumers discounts of up to 65% if they shift use to off-peak hours. They have also introduced the possibility for companies to share one connection point through cable pooling arrangements and for network operators to experiment with group service agreements. It has also revised congestion contracts through the *capaciteitssturingscontract*, allowing DSOs to contract maximum or minimum capacity with clear variables. With a longer-term perspective, ACM made it mandatory for DSOs to submit network development plans every two years showing where and when they intend to expand the grid and to make adjustments to it as the need arises. Also, from 2027, it will assess investment costs ex-ante, which is expected to lead to more (and more efficient) investment.

In Norway, the regulator highlights the surge in license applications and electrification-driven demand. It promotes stronger coordination between transmission and distribution planning, greater transparency by introducing the PlanNett platform offering visibility of all grid development projects, and a more cautious connection process that involved a maturity assessment of the project requesting connection (Sandvik, Mattsson Sperre and Tannum, 2025). The Norwegian regulator also supports a shift from volumetric to capacity-based tariffs to better align network charges with peak usage. From 2021, Norway also introduced non-firm load connections for commercial and industrial customers enabling DSOs to curtail consumption on terms that are agreed upon between the parties.

In Sweden, EI reports increased shortages in grid capacity and, as such, developed a new strategy to promote flexibility. The strategy rests on the three pillars of markets, flexibility incentives for grids, and flexible consumer behavior. The strategy will guide the regulator's program until 2028. In addition, by 2027 all Swedish DSOs must introduce network tariffs with a power (capacity) component, combined with time-differentiation to encourage demand shifts.

Great Britain represents one of the most comprehensive regulatory regimes in adapting (or preparing) the electricity distribution networks to the 4Cs. It was very early in introducing time of use grid tariffs, output-based incentives, innovation allowances and 'flexibility before reinforcement' approaches. Many other regulators are now implementing similar measures based on the success and challenges of Ofgem. In recent years, Ofgem has implemented a series of reforms aimed at transforming distribution networks into active facilitators of electrification and DERs. A key element has been the functional separation within Distribution Network Operators (DNOs) of operationally independent Distribution System Operators (DSOs), capable of actively managing power flows and coordinating with the transmission system with the goal of integrating large volumes of distributed generation such as rooftop solar. This has been accompanied by the development of local flexibility markets, through which DSOs can already procure services from distributed resources, such as battery storage, demand response, or flexible EV charging, to relieve local network constraints instead of relying solely on grid reinforcement. Last year, a market facilitator – Elexon – has been appointed to secure easier access to the flexibility market by smaller DERs. The wider RIIO-ED2 price control framework (2023–2028) encourages, networks to invest in digitalization and additional capacity to accommodate electrification, while also procuring flexibility where it is more efficient than building new infrastructure. The framework also allows anticipatory investment to reinforce parts of the grid in advance of expected demand growth from EVs (already significant), HPs (less sustained), and others. Another intervention by the regulator (and other entities) is aimed at reforming the connection queues, moving from “first come, first served” to “first ready and needed, first connected”.

Outside Europe, regulators in Australia, Canada, China, Japan and the USA (California and Virginia) are also dealing with the 4Cs.

In Australia, regulatory responses are shaped primarily by strong rooftop PV penetration (C1). The Australian Energy Regulator (AER) has introduced tariff structure reforms like export pricing and two-way tariffs, allowing DSOs to charge for and signal the value of exporting distributed generation to the grid, directly addressing congestion from rooftop PV. As a result of these provisions and the innovation projects allowed by AER, DSOs have introduced dynamic operating envelopes - flexible export limits depending on near-real time conditions instead of fixed limits. In parallel, AER has strengthened incentives for demand-side participation and flexible resources through rule changes that facilitate distributed energy resource (DER) integration and aggregation. Energy Networks Australia frames this evolution as “the age of DSO,” reflecting the transition of DNSPs into active DSOs that orchestrate flexible demand and generation in real time (similar to what the GB is experiencing). In addition, planning and transparency obligations have been reinforced, with distribution annual planning reports (DAPRs) requiring more granular forecasts of DER uptake and hosting capacity and requiring more stakeholder consultation.

China’s regulatory response to the 4Cs is characterized by a strongly centralized and planning-driven approach. It is based on China’s policy framework for “electricity substitution” promoting electrification of heating, transport and deployment of DERs for self-consumption (on top of the enormous utility scale PV and wind capacity). Both EVs and DCs are seen as flexible resources, expected to participate in system support. The regulator emphasizes system-wide coordination, including the digital assessment of hosting capacity for distributed generation and the strategic siting of energy-intensive DCs in regions with abundant renewable generation. The Chinese approach relies on enhanced planning, controlled access, and elements of direct system management, with complementary reliance on tariff reform (time of use bundled tariffs), but less of a role for incentive-based regulation.

In Canada, Hydro-Quebec is operating under the oversight of the Régie de l’énergie within a vertically integrated and state-owned structure. Addressing the impact of the winter peaks and the response consists of tariff design and program-based demand management. A distinctive element is the dual-energy (bi-énergie) system, under which households switch from electricity to gas at very low temperatures, significantly reducing peak load on the electricity network. This is complemented by time of use tariffs[5] and demand response programs but

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[5] In countries with integrated utilities, the grid tariff is not so clearly separated from the energy component, so the time of use is based on the full tariff or electricity that the utility offers to customers.

with a more direct approach and a lower apparent role for flexibility markets. Planning and coordination are largely internalized within the integrated utility, and there is less visibility of any market-based or incentive-driven mechanisms.

In Japan, the regulatory response is also policy-level and centralized, provided by the Electricity and Gas Market Surveillance Commission under the Ministry of Economy, Trade and Industry (METI). A key feature of the regulatory response is nationwide non-firm connection regime, allowing distributed renewable generation to connect without waiting for network reinforcement, in exchange for exposure to curtailment. While the mechanism was initially developed at transmission level, it applies in practice to distribution-connected resources, with curtailment coordinated across voltage levels. This is reinforced by reforms to the curtailment priority order, shifting from connection-based rules to a more system-wide optimization of congestion management. In a way, curtailment is institutionalized as an operational tool, enabling integration of rooftop PV and other DERs. The approach is complemented by strong central planning and coordination between transmission and distribution, while market-based flexibility mechanisms and tariff-driven demand response remain limited.

In California, the regulatory response includes tariff reform and procurement frameworks. CPUC regulates both PG&E and SCE, both highly relevant DSOs from a C1 and C2 point of view. A central element of the response to the challenges is the reform of net metering toward time-varying export compensation, incentivizing self-consumption and storage in response to high rooftop PV penetration. This is complemented by mandatory distribution resource planning, including hosting capacity maps and the systematic evaluation of non-wires alternatives. CPUC also mandated utility-led EV infrastructure programs and encouraged time-of-use tariffs, while storage and demand response are actively procured as grid resources under the “preferred resources” framework. The regulator has also introduced measures to accelerate grid connections and improve planning processes. The regulator’s planning processes are also in coordination with TSO, the California Independent System Operator, ensuring alignment between distribution-level developments and broader system needs.

In Virginia, the State Corporation Commission requires DSOs to absorb rapidly growing demand, driven in part by DCs and other electrification trends, with forecasts indicating annual growth rates of around 5.5% and a potential doubling of demand by 2039. SCC is focused on physical grid resilience, incentives for CAPEX-based reinforcement, including feeder hardening, fault location and service restoration systems (FLISR), and targeted reliability improvements affecting specific network segments and customers. In 2025, SCC introduced a dedicated tariff class (GS-5) for high-energy consumers demanding 25MW or more and have a monthly load factor exceeding 75%, which includes primarily data centers and other large industrial users. The rate includes higher minimum demand charges and long-term contractual commitments (14 years), ensuring that DCs contribute more predictably to network costs even if their actual usage fluctuates. This is meant to require these large consumers to cover the costs (and share the risks) of the required grid infrastructure improvements that enable their activity.

5. Discussion: a typology of regulatory responses and patterns

Looking at the reports of the selected regulators, many are implementing or planning significant responses to the 4Cs. A simple typology of regulatory responses can help in mapping them by regulator. Looking at the results of our regulator report examination, we identified six broad categories of responses (Table 3).

Table 3: A typology of regulatory responses to the 4Cs

Type	Description
A. Differentiated grid tariffs	Tariff and price-signal reform that redesign network charges (capacity-based and/or time-differentiated) to discourage peaks and influence consumer behavior and adoption of digital solutions
B. Access regime	Access and connection regime reform, offering conditional connection products (non-firm/flexible, shared, or "first ready" queues) to accelerate connections in conditions of scarcity
C. Flexibility markets	Flexibility procurement and markets, pushing DSOs to buy constraint relief from distributed resources (demand response, storage, smart charging) via tenders or markets
D. Direct control	Direct operational congestion control that standardizes curtailment or load-control actions (with compensation and settlement rules) to protect reliability in real time
E. Enhanced planning	Planning, transparency, stakeholder engagement, and coordination mandates (capacity maps, public and updated network development plans)
F. Incentive overhaul	Major changes in regulatory incentives and regime (TOTEX orientation, output incentives, bonus-sharing, ex ante cost review, targeted allowances)
G. Governance changes	Mandatory changes in governance arrangements such as separation of system operation from network operation

Putting everything together, we can now look at DSOs, their specific challenges and the bundle of regulatory responses of their regulator (Table 4).

Table 4: Regulator responses to DSO challenges

DSO	Challenges	Measures							Regulator
		A Tariffs	B Access	C Flexibility	D Control	E Planning	F Incentives	G Governance	
SA PN	C1	🟩	🟩	🟩	🟩				AER
Energex	C1	🟩	🟩	🟩	🟩				AER
SCE	C1	🟩	🟩	🟩		🟩			CPUC
UKPN	C2	🟩	🟩	🟩				🟩	Ofgem
Enedis	C3		🟩	🟩		🟩			CRE
e-Distribuzione	C3		🟩			🟩	🟩		ARERA
HydroQuebec	C3	🟩			🟩				RdE
ESB Networks	C4		🟩			🟩			CRU
Dominion	C4	🟩	🟩						SCCV
Fluvius	C1, C2	🟩	🟩	🟩		🟩			VREG

Wiener Netze	C1, C2		🟩			🟩			e-Control
PG&E	C1, C2	🟩		🟩		🟩			CPUC
Bayernwerk	C1, C3		🟩		🟩	🟩	🟩		BNetz
Tepco PG	C1, C3				🟩				EMSC
Elvia	C2, C3	🟩	🟩			🟩			NVE
Caruna	C2, C3	🟩		🟩	🟩	🟩	🟩		Virasto
China SPG	C2, C4				🟩	🟩			ENA
Radius	C2, C3, C4	🟩	🟩			🟩			DUR
Ellevio	C2, C3, C4	🟩		🟩					EI
Liander	C1, C2, C3, C4	🟩	🟩			🟩	🟩		ACM

Note: DSOs are grouped by the combination of challenges (Cs) affecting them. Green indicates the presence of each of the regulatory responses (A-G) in the regulator reports.

Some similarities emerge across countries in how regulators are responding to the 4Cs, even though instruments differ.

The clearest pattern is the much-increased role of flexibility as a substitute for (or complement to) grid reinforcement or expansion (types C and D). Almost all regulators require or incentivize DSOs to consider flexibility before investing in reinforcement. Perhaps Ofgem has gone furthest in institutionalizing local flexibility markets and governance rules to prevent bias toward asset-heavy solutions, but most other regulators are following through.

A second pattern in some countries, also linked to flexibility, is the shift from volumetric to capacity based or time-based tariffs to shift consumption and reduce peak demand (type A). This is common to all Nordic countries but also to the Australian, Canadian and US regulators in our sample.

A third shared response concerns reform of connection frameworks and queue management (type B). France, the Netherlands and others are introducing reforms to manage connection queues and deal with large (potentially) speculative projects where grids have already reached high levels of renewable deployment, electrification, and are facing scarcity of network capacity.

Learning regulator perspective

Looking at the mapped responses to the 4Cs, one can observe elements of the attributes of the learning regulator – dynamic, responsive and adaptive. The most visible are the traits of adaptive regulation. As the sector is undergoing these fundamental changes in an uneven fashion, the balance between stability and change tilts toward the latter, requiring adaptation by design, despite the difficulties of operating with so much uncertainty. For illustration, the Dutch ACM is requiring DSOs to update (and publish their) network development plans with an increased frequency to account for the rapid and relatively unpredictable evolutions in the sector. The

Danish DUR is also mandating the updating of ‘geozones’ with a weekly frequency instead of yearly.

Elements of dynamic regulation are present in all of the mapped regulatory regimes, but they can be seen as intensifying. In some countries, like GB after several rounds of the ‘regulatory game’, the revealed information and behavior of the regulated entities are being incorporated in new rules, outputs and incentives. In some countries, one can observe changes toward TOTEX regulation or ex-ante investment cost assessments, which can also be seen as elements of dynamic regulation.

Finally, responsive regulation as the balance between rigid rule making and laissez faire/self-regulation, seems to depend greatly on the regulatory culture. France and Germany seem more geared toward the former, while the Nordics seem to allow for more freedom to the regulated entities. Finding the right balance is more context specific and changes on the spectrum between the two extremes are more difficult to assess.

In any case, the attributes of the learning regulator do seem to be at play, determined in a way by the intensity of the challenges of the transition in the electricity distribution sector.

Institutional and cultural differences in regulatory functions

Regulators differ greatly among OECD countries, in terms of organization structure, stakeholder engagement approach and culture around interaction with the regulated parties.

Regulatory culture may explain some of the differences, including in reporting. The UK and the Netherlands show a tradition of elaborate and public incentive regulation and market-based instruments including significant stakeholder engagement with some level of contestation and a relatively adversarial approach between regulator and the regulated entity, including legal action (Energy UK, 2025). There are ample reports and discussion documents describing the significant changes to be implemented in response to the 4Cs. In contrast, some of the Nordic regulators focus more on technical solutions and keep reporting much shorter, perhaps reflecting the smaller impact of the 4Cs on their DSOs. France, Germany and Italy fall somewhere in the middle of these two extremes. They do organize significant consultations and their activity is under public scrutiny, but it does not appear to be as intense or as transparent as in GB and the Netherlands. In the case of Belgium, Canada, USA, there are also strong regional layers, with the regional regulator (Flanders, Quebec, California, Virginia) having to coordinate and share responsibility with national (federal) level authorities. In China and Japan, regulatory documents have a directive and prescriptive style, which differs markedly from the more analytical and consultative reporting in other countries in our sample. These documents typically take the form of "guiding opinions" or policy instructions, setting out what authorities, grid companies, and market participants are expected to implement

These differences influence the extent to which the regulatory responses, aims and justifications of choices, can be accurately identified. In the case of GB, the amount of publicly available information posted on the website is vast and allows for a fairly comprehensive picture of the regulatory environment both in terms of reporting completed activities and future plans. Many other countries like France, Netherlands and Italy also publish adequate information on their annual activity reports, while others do not have the same reporting practices, including Germany and the Nordics.

6. Conclusions

This paper shows that, although the transition challenges facing DSOs are widely shared, their intensity and combination vary across jurisdictions. Among the four challenges examined, distribution-connected renewables appear as the most universal source of stress, while EVs are more often treated as a driver of future demand growth. HPs appear as a medium- to long-term issue, being expected to add to winter peaks but not causing much strain at present time. Finally, DC are already highly material but geographically concentrated on a limited number of systems.

Despite the variation, a convergence in regulatory direction is visible. Across the jurisdictions examined, regulators are moving DSOs away from a reinforcement-first model and toward active system management. As regulators realize that other ways to keep up with the rising demand within a reasonable timeframe and budget are not feasible, this becomes an inevitable choice, even in jurisdictions that initially resist this approach. This includes greater use of flexibility, revised connection arrangements, peak-reducing tariff reform, stronger planning and transparency obligations, and in some cases new governance arrangements or changes in incentive regulations. The advanced DSOs studied are increasingly expected to actively facilitate the transition, to manage scarcity, coordinate new users and resources. At the same time, the comparison shows that flexibility is not replacing reinforcement. In most cases, it is being used as a complement or bridging tool in systems where physical expansion remains necessary but cannot be delivered quickly enough.

The findings also suggest that regulatory differences reflect system conditions and institutional history. Countries with acute congestion and rapid growth in renewables or new loads, such as the Netherlands, Ireland, Germany or Great Britain, have introduced the most visible and far-reaching reforms. On the other hand, systems with earlier electrification, stronger hydro resources, more established digital infrastructure, or lower congestion pressure can often rely on more incremental adaptation. The Nordic cases are important in this respect as they indicate that some systems need fewer fundamental interventions because existing network design, metering infrastructure, tariff structures, and generation mix already make them more resilient to the 4Cs. This shows that the scale of regulatory responses depends on how the inherited system was prepared for them.

Viewed through the perspective of the learning regulator, the mapped responses display some dynamic, adaptive, and responsive features. They are dynamic because regulatory frameworks are being updated in light of revealed information about technology uptake and DSO behavior, across successive regulatory periods. They are adaptive because regulators are increasingly designing frameworks that can be revised ‘by design’, for example through more frequent network planning updates or trial-based approaches to flexible access and congestion management. They are responsive because many regulators are trying to strike a middle ground between rigid command-and-control rules and more discretion for network companies, combining incentives, obligations, market mechanisms and operational tools according to national context.

The paper therefore suggests that the energy and digital transitions in some of the most advanced jurisdictions are changing regulatory approaches. Regulation of distribution networks is becoming more experimental and information intensive. For regulators not yet affected by these pressures, the experience of more exposed jurisdictions may offer useful lessons on flexibility (buying time and making the most of existing assets), through various instruments like markets, tariffs design and connection reforms when capacity becomes scarce. In this sense, the emergence of the active DSO is determined by the development of a learning regulator.

Annex 1 – DSO selection

In this annex, we describe the criteria, methodology and rankings for each challenge (including exceptions) and the resulting list of DSOs for each challenge and then the full list of DSOs to be included in this analysis.

C1 – Distributed Solar PV (Decentralised Generation)

IEA PVSP countries[6] were ranked by cumulative decentralised PV capacity per capita (W per capita) (IEA PVPS, 2024). Where stressors were highly geographically concentrated, the DSO serving the most exposed region was selected, even if the national average was not highly visible (PG&E and SCE in the US). Countries with highly fragmented DSO landscapes (e.g., Switzerland) were excluded for comparability reasons. In addition, while Sweden ranks 7th, the DSOs likely to encounter a large penetration of decentralized PVs are not the large ones (E.ON Energidistribution, Vattenfal Eldistribution or Ellevio) but local ones in relatively sunny hotspots (Malmö, Lund). Those are too small to include in the analysis.

	Country	W / capita
1	Australia	891
2	Belgium	815
3	Germany	761
4	Switzerland	716
5	Austria	641
6	Netherlands	531
7	Japan	440
8	Sweden	358
9	Italy	356
10	Israel	347

This resulted in the following list of DSOs[7]:

	Country	DSO
1	Australia	SA Power Networks
2	Australia	Energex

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[6] IEA PPVSP (Photovoltaic Power System Program) Countries include IEA countries plus China and others. The list can be consulted here: https://iea-pvps.org/annual-reports/iea-pvps-country-updates-2025/

[7] The DSOs with the rank ‘x’ is the most relevant or one of the most relevant (in the case of Australia and the US) DSO in the country ranked ‘x’ on that specific challenge, after the exceptions are applied (size exceptions, regional clusters much higher than national averages, specific technologies).

3	Belgium	Fluvius
4	Germany	Bayernwerk
5	Austria	Wiener Netze
6	Netherlands	Liander
7	Japan	TEPCO Power Grids
8	USA	PG&E
9	USA	SCE

C2 – Electric Vehicle Penetration

Countries[8] were ranked by EVs and PHEVs as a percentage of the total passenger car fleet (IEA, 2025b). Subnational hotspots (e.g., California[9]) were added where relevant. Very small or fragmented systems (e.g., Iceland, Switzerland, Israel) were excluded for scale reasons.

	Country	**% of fleet**
1	Norway	36%
2	Iceland	25%
3	Denmark	23%
4	Sweden	16%
5	China	14%
6	Belgium / Netherlands	13%
7	Finland	13%
8	Switzerland	12%
9	Israel	8%
10	UK / Austria	7%

This resulted in the following list of DSOs:

	Country	**DSO**
1	Norway	Elvia
2	Denmark	Radius
3	Sweden	Ellevio
4	China	CSPG
5	Belgium	Fluvius
6	Netherlands	Liander
7	Finland	Caruna
8	UK	UKPN
9	USA	PG&E
10	USA	SCE

C3 – Heat Pump Penetration

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[8] The IEA data includes most countries in the world, with some exceptions. The sample does include the known leading EV deployment jurisdictions in the OECD and China. The data is also available here: Tracking global data on electric vehicles - Our World in Data.

[9] California was at 5.5% EVs in total light duty fleet in 2024 growth has continued since then and the current numbers may be higher (EIA, 2024).

Noting that HPs are currently being deployed predominantly in Europe, the ranking started from European[10] data, with countries ranked by the number of HPs per thousand households (EHPA, 2024). The cutoff was at 150 HPs/1000 hhs. Switzerland and Estonia were excluded due to system size. To that list, additional DSOs were included to reflect above-national-average regional penetration (e.g., Bavaria) and rapid gas-to-electric transitions that also interact with other challenges (e.g., Netherlands). This list includes traditional electrified heating countries (Nordics and France) and gas to electric transition countries or regions (Netherlands, Bavaria, certain regions of Italy). We also add two cases of non-European DSOs, one active on heating with integrated approaches with gas (HydroQuebec) and the other approaching heating and cooling with heat pumps in a megacity (Tepco Power Grids).

	Country	**HP/ 1000 hh**
1	Norway	635
2	Finland	512
3	Sweden	437
4	Estonia	360
5	Denmark	212
6	France	191
7	Italy	158
8	Switzerland	152
9	Austria	119
10	Latvia	108

This resulted in the following list of DSOs:

	Country	**DSO**
1	Norway	Elvia
2	Finland	Caruna
3	Sweden	Ellevio
4	Denmark	Radius
5	France	Enedis
6	Italy	e-Distribuzione
7	Germany	Bayernwerk
8	Netherlands	Liander
9	Canada	HydroQuebec
10	Japan	Tepco Power Grids

C4 – Data centres

There is currently no consistent data set allowing for cross-country comparison of DC electricity consumption as a share of total electricity consumption in the country. Existing estimates vary significantly depending on definitions and methodologies. Some data is considered sensitive, especially in the US and China. Hence, the ranking used here is based on the JRC study covering the EU (Kamiya and Bertoldi, 2024), complemented with known hotspots like Virginia. With this limitation, countries were ranked based on DC electricity demand as a share of total electricity consumption. Subnational hotspots (e.g., Virginia in the USA) were included. Luxembourg was excluded due to system size, while Syna – the German

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[10] EHPA includes all European countries, not just EU member states. HPs for heating are typical in Europe and rare elsewhere apart from some jurisdictions that will be included (Canada, Japan).

DSO covering areas around Frankfurt, with the biggest concentration of DCs in Germany – has very little data available online, and has also been dropped

	Country	**DC % of total (~)**
1	Ireland	18%
2	Netherlands	4%
3	Denmark	3.5%
4	Luxembourg	3%
5	United States	4.4%*[11]
6	Germany	2%
7	Sweden	2%
8	Belgium	2%
9	Japan	2%*
10	UK	2%*[12]

Final DSO list

#	Country	DSO
1	Ireland	ESB Networks
2	Netherlands	Liander
3	Denmark	Radius
4	Sweden	Ellevio
5	USA	Dominion Energy Virginia
6	China	China Southern Power Grid

Final list of DSOs

#	DSO	Country / region	Dominant C (country rank #)	Justification
1	Wiener Netze	Austria	C1 (#5) C3 (#9)	High rooftop PV and HP
2	Fluvius	Belgium	C1 (#2) C2 (#5) C4 (#8)	High rooftop PV
3	Radius	Denmark	C2 (#8) C3 (#5) C4 (#3)	High in EVs, HPs and DCs
4	Caruna	Finland	C3 (#2)	High HP
5	Enedis	France	C3 (#6)	High and growing HPs
6	Bayernwerk	Germany	C1 (#3) C3 (n/a) C4 (#6)	High rooftop PV, much higher than national average, increasing HP
7	ESB Networks	Ireland	C4 (#1)	Highest DC in Europe
8	e-Distribuzione	Italy	C1 (#9) C3 (#7)	High and growing HPs
9	Liander	Netherlands	C1 (#6) C2 (#7) C3 (n/a) C4 (#2)	Is affected by all Cs
10	Elvia	Norway	C2 (#1) C3 (#1)	Highest in both EVs and HPs

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[11] Different methodology, which may impact the ranking (Source)

[12] https://www.oxfordeconomics.com/resource/the-uks-data-centre-boom-growth-trends-drivers-and-the-rising-power-challenge/

11	Ellevio	Sweden	C1 (#8) C2 (#4) C3 (#3) C4 (#7)	In top 5 for EVs, HPs and DCs
12	UKPN	UK	C2 (#10) C4 (#10)	High EV
13	Energex	Australia (Queensland)	C1 (#1)	High rooftop PV penetration
14	SA Power Networks	Australia (South Australia)	C1 (#1)	High rooftop PV penetration
15	HydroQuebec	Canada (Quebec)	C3 (n/a)	Distinctive approach to heating dual energy
16	China Southern Power Grid	China	C2 (6) C4 (n/a)	High EV and DCs
17	Tepco Power Grid	Japan	C1 (#7) C3 (n/a) C4 (#9)	Significant rooftop PV, higher than national average, distinctive heating-cooling approach in megacity
18	Dominion Energy	USA (Virginia)	C4 (#5)	One of world's highest incidence of DCs
19	PG&E	USA (California)	C1 (n/a) C2 (n/a)	Large rooftop PV, important EV cluster in Bay Area
20	SCE	USA (California)	C1 (n/a)	High rooftop PV

Annex 2 – DSOs reporting on the 4Cs

C1

In Austria, Wiener Netze reports impressive numbers of rooftop PV connections, EV charging and HPs, but none of them are mentioned as major sources of stress, though connection queues are indeed cited.

In Belgium, Fluvius reports steadily increasing volumes of solar energy injected into the grid, with high rooftop PV penetration in Flanders.

In Germany, Bayernwerk reports that it connects the majority of renewable generation at medium- and low-voltage levels, more than 1.2 million PV installations, and has an acute need of significant grid reinforcement.

In Italy, e-Distribuzione reports that the spread of distributed generation is changing network behavior, leading to reverse power flows and saturation of certain sections.

In the Netherlands Liander reports widespread congestion, with many substations already at or near their limits and a large proportion expected to be overloaded by 2035. Business customers face connection delays, and shortages of technicians, materials and space also constrain reinforcement.

In South Australia, SA Power Networks notes that 38% of customers had rooftop PV in 2024.

In Queensland, Energex hosts almost 900.000 solar systems - roughly 48 % of detached homes.

In Japan, TEPCO Power Grid increased renewable capacity from around 3.6 GW in mid-2024 to about 6.4 GW one year later, indicative of emerging stress.

In California, PG&E supplies one of the world’s largest rooftop-solar markets. In 2024, almost 900,000 customers had rooftop solar and over 120,000 customers had batteries, while the utility manages contracts for 4.6 GW of battery storage.

In China, China Southern Power Grid plans to invest about RMB 320 billion - nearly half its grid budget - on smart distribution networks to connect rural distributed PV, wind and microgrids and is developing source-grid-load-storage platforms to coordinate PV, storage and electric-vehicle charging.

C2

The leading country of Norway barely mentions EVs in its reports.

In Denmark, Radius notes record grid activity driven by EVs but frames electrification as progressing too slowly rather than too quickly.

In the UK, UKPN identifies EV uptake as a key planning uncertainty and works with local authorities to coordinate charge-point deployment but does not report immediate system stress.

In the Netherlands, Liander anticipates the need to double the rate of daily charging point connections, with bottlenecks emerging especially in neighborhoods where EV charging is being rolled out.

In California, SCE serves one of the largest EV fleets in the world: registered plug-in and battery EVs jumped from about 83.000, in 2016, to around 778.000 by 2024.

In California PG&E reports that more than 675.000 EVs already plug into its grid.

C3

In Finland, one of the global leaders in HP deployment, Caruna forecasts sharp electricity consumption and peak demand increases, partly due to electric heating.

In Germany, Bayernwerk already observes rising heat pump uptake and expects substantial penetration in both new and existing buildings.

In Sweden, Ellevio points to stress from industrial heat demand and winter peaks, particularly in metropolitan areas.

In the Netherlands, new housing areas without gas connections consume significantly more electricity than traditional neighborhoods, because of heat pumps, contributing to projected low-voltage bottlenecks.

In Canada, Hydro-Québec has made HPs central to its energy-efficiency strategy. Its LogisVert program offers financial assistance for efficient heat pumps and induction appliances, helping customers install over 100.000 energy-efficient appliances in 2024. HydroQuebec is also one of the few utilities offering integrated dual energy (bi-énergie) products to manage high winter peaks associated with electric heating. It involves equipping households with hybrid heating systems that combine electric heating with a backup gas system, which automatically switches on depending on outdoor temperature (around −12°C to −15°C), reducing pressure on the electricity grid at times of peak demand.

In Japan, TEPCO Power Grids is integrating HPs for both heating and cooling with batteries and PV in its urban-development projects. Its 2025 electrification portfolio lists HPs and hot-water systems alongside PV and battery storage.

C4

In Ireland, ESB Networks identifies DCs as one of the most significant risks to the network and is only now gradually preparing for the lifting of the ‘de-facto’ moratorium.

In the Netherlands, Liander expects a more than fivefold increase in electricity demand from DCs over the next decade, placing substantial pressure on grid capacity. Amsterdam struggled to cope with a boom in DCs and imposed a moratorium on new ones in 2019, which has been lifted and replaced with conditional connection offers.

In Virginia, Dominion Energy reports that DCs accounted for 26 % of its electricity sales in 2024, with 15 DCs (~1 GW of capacity in total) already connected. The utility anticipates 6.3% average peak annual load growth over the next decade and is investing heavily in upgrades.

China Southern Power Grid names DCs as emerging flexible loads that require high reliability and are included in its source-grid-load-storage integration scenarios (a strategic framework merging power generation, grid infrastructure, load management, and energy storage),but provides no project details.

Annex 3 DSO Reports

For each DSO, we accessed their website and searched for an annual activity report. Where available, we included the most recent three editions of the annual report. Where annual reports were not available, they were substituted with network development plans or financial reports.

Wiener Netze Austria

Wiener Stadtwerke. (2024). *Annual report 2024*. https://www.wienerstadtwerke.at/o/document/250513_final_wstw_fb_2024_en_interactive

Wiener Stadtwerke. (2023). *Annual report 2023*. https://www.wienerstadtwerke.at/o/document/240502_wstw_fb_2023_engl_final

Wiener Stadtwerke. (2022). *Annual report 2022*. https://www.wienerstadtwerke.at/o/document/wstw_annual_report_2022

Fluvius, Belgium

Fluvius. (2026). *System operator annual report 2025*. https://over.fluvius.be/sites/fluvius/files/2026-03/fluvius-system-operator-annual-report-2025.pdf

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Radius, Denmark

Radius. (2024). *Annual report 2024*. https://doc.andel.dk/rsrapporter/annual-report-2024/

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Caruna, Finland

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Caruna. (2024). *Annual report 2024*. https://caruna.fi/sites/default/files/docs/Caruna%20Annual%20Report%202024.pdf

Caruna. (2023). *Annual report 2023*. https://caruna.fi/sites/default/files/docs/Caruna%20Annual%20Report%202023.pdf

Enedis, France

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Bayernwerk, Germany

Bayernwerk. (2024). *Annual report 2024*. https://www.vnbdigital.de/gateway/files?serviceName=vnb&fileId=6631289899abd27c97c7cf14&preview=1

Bayernwerk. (2023). *Annual report 2023*. https://www.vnbdigital.de/gateway/files?serviceName=vnb&fileId=638db252e4972bf4e0f2afa1&preview=1

ESB Networks, Ireland

ESB. (2025). *Annual report and financial statements 2025*. https://cdn.esb.ie/media/docs/default-source/investor-relations-documents/esb-annual-report-and-financial-statements-2025.pdf

ESB Networks. (2023). *Distribution annual performance report 2023*. https://media.esbnetworks.ie/media/docs/default-source/publications/distribution-annual-performance-report-2023-accessibled434eedca532460d959ccfba328306eb.pdf

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Annex 4 Regulator reports

For each regulator, we accessed the website and downloaded the three most recent editions of the annual activity report. Where annual reports were not available, they were substituted with other regulator reports of the electricity market, monitoring reports, thematic reports on smart grids or flexibility strategies, annual plans or future work programs.

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