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Toward an operational definition and a. methodology for measurement of the active DSO (distribution system operator) for electricity and gas

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Keywords distribution system operator, distributed energy resources, decarbonisation

JEL Classification L94, L95

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Toward an operational definition and a methodology for measurement of the active DSO (distribution system operator) for electricity and gas[1]

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Abstract

There is growing consensus that the role of the distribution system operator (DSO) is changing given the implications of net zero. The transition process requires additional roles for the DSO in facilitating the new technologies and business models that will contribute to decarbonization. Discussions on the active DSO abound yet a working definition is still missing. This paper aims to propose such a definition and a workable methodology for measuring the extent to which a DSO is active. The methodology will be applied to electricity and gas DSOs in the UK and the challenges will be presented and analyzed.

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1. Introduction

The ongoing transformation of the energy system toward decarbonisation is affecting the traditional network activities of electricity, gas and heat distribution system operators (DSOs) (Pereira et al., 2020). The energy system required for net zero entails decarbonised end use sectors such as transport and heating. This will require greater amounts of renewable power and enabling carriers and

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[1] This study is inspired by and develops Pollitt, Giulietti, Covatariu and Duma (2021) written for the Centre on Regulation in Europe (CERRE, www.cerre.eu). The original study is available at: https://cerre.eu/wp-content/uploads/2022/09/CERRE_DSO_FinalReport_2709.pdf . The study and this article reflect to views of the authors only; it may not reflect the views of CERRE or its members.

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technologies, like battery storage, power-to-gas, biogas, hydrogen, demand management, energy efficiency, digitalization and others. These evolutions are likely to impact the role of the DSOs (IRENA, 2019). They will face potentially accelerated processes of electric and renewable gas based transport, electrified heating and gas decarbonization, demand management and flexibility. At the system level, better integration and planning between electricity and gas DSOs will be needed to optimize this process. Ultimately, innovation will be needed for new technologies and business models to be explored and adopted to face the new challenges.

DSOs are highly regulated as natural monopolies. Hence, DSOs will become active if policy and regulation create the right incentives. In recent years, regulation has changed and continues to adapt in order to encourage DSOs to take on new roles (Pollitt et al., 2021, p. 26). A more accurate definition and a conceptual framework for measurement are required for regulators to be able to operationalize and monitor progress on DSOs becoming active.

To contribute to the decarbonization process, the DSOs will increasingly need to deal with distributed generation and demand-side management, storage, advanced metering and data management, gas decarbonization, EV charging, heat pumps, coordination with transmission system operators (TSOs) and other parties (Thomas, 2018). The breadth of new activities will require new capabilities, which may amount to a new role, on top of the established functions. DSOs will no longer simply distribute power from transmission to final customers but will increasingly have to manage a two-way network of flexibility resources. The DSO of the deep decarbonization age will have to face "intermittency and unpredictability of renewable sources, reverse power flow, increasing balancing load and generation" (Pollitt et al., 2021, p. 41).

In this paper, our aim is to help clarify the definition of an active distribution system operator (DSO). This is important because regulators across Europe are seeking to encourage the DSO to be more active, without clear agreement on how the active DSO is defined and on how we might measure the degree of activation of the DSO(CEER, 2015; Ofgem, 2019). Measurement is important because it would allow us to better compare progress over time and between companies in their journey to become a more active DSO. This would allowing leading DSOs to be identified and, in the longer term, for regulators to assess whether more active DSOs are actually delivering for society.

The paper is divided into five sections. Section 2 reviews the literature around five areas where we might expect to find the DSO becoming more active. Section 3 proposes a definition of the active DSO and a framework for thinking about how activation might be measured. We do this in the context of the recent development of incentive regulation of DSOs. Section 4 applies the framework to DSOs from Great Britain in order to demonstrate how measurement of the active DSO might work in practice. This allows us to suggest which elements of measurement are currently accessible and which are not. Section 5 offers a conclusion.

2. Areas where we see DSOs under pressure to be more active

We suggest that the issues encouraging DSOs to become more active can be grouped into five main categories: transport, heating, flexibility and integration of distributed energy resources (DERs), adaptive indicative planning, and innovation. In each case we review relevant literature on the active DSO in these areas.

Transport

Several papers have looked at the impact of increased penetration of electric vehicles (EVs) on the distribution network, but the potential role of DSOs in establishing public and private EV charging points and gas refuelling stations is a less developed topic of research. Knezović *et al.* (2017) and Wargers *et al.* (2018) point out the risks associated with charging at peak time but also the opportunities offered by involving EVs the active management of networks. Schittekatte *et al.* (2021) discuss an Italian DSO project for the delivery of public EV charging points and identify transparency as key for the role of the DSO, particularly in reporting on the number of charging events, recharged energy, charging duration and occupation time of the charging points. LaMonaca and Ryan (2022) discuss the case of Ireland, where the DSO built a national public charging network, with the regulator subsequently deciding to promote a competitive market for charging services and requiring the DSO to sell off the charging assets. In line, with this Dougherty and Nigro (2014) highlight the potential role of financial actors in creating a secondary market for infrastructure assets.

For gas DSOs, there may be a role in providing biomethane and/or hydrogen for vehicles, particularly heavier duty ones. Pollitt et al. (2022) discuss bus projects, which include the gas DSO, in France which involve both buses running on biomethane (in the Ile de France region)[3] and a hydrogen-methane (in Dunkerque[4]).

Heating

The current thinking on heat decarbonisation is that it will involve partly electrification through heat pumps and partly gas decarbonization, through biomethane or hydrogen injections. Where gas networks exist, an joint optimization between increased electrification, natural gas and, the increase of biomethane and hydrogen will be required.

Fischer and Madani (2017) find that integration of renewable energy, variable electricity pricing, and stable power grid operation are three use cases for heat pumps. They find that heat pumps can enable the transition to a decentralized energy system, with a greater number of prosumers and renewable energy, provided that the system, including the grid, is prepared to integrate them fully. With the right control, enabled by a digitalized grid, heat pumps are shown to potentially help voltage control, critical hours and peaks.

Quarton and Samsatli (2020) examine the potential and conditions under which hydrogen can used for heating and injected in the gas grid. They underline the limits to injections in grid in their current state and discuss the opportunity of building a dedicated hydrogen gird versus full electrification.

Flexibility and integration of DERs

The integration of distributed energy resources (DER) into distribution networks implies that DSOs need to deal with the intermittency and unpredictability of renewable sources. At the same time, DER assets, controllable loads, EV batteries, etc., connected at different voltage levels, represent both a challenge and an opportunity for DSOs to solve network constraints, congestion etc., by procuring/contracting flexibility services from them. On the gas side, flexibility may require optimization with electricity (e.g. via dual fuel heat pumps) and power to gas technologies for energy storage purposes.

Based on a Danish case study, Knezović *et al.* (2017) highlight the need for regulation which creates incentives for DSOs to procure flexibility services, possibly with the support of local trading platforms. Proka, Hisschemöller and Loorbach (2020) use the case of a neighbourhood battery initiative in the Netherlands to investigate the benefits that can arise from the collaboration between DSOs and local energy initiatives. Valarezo *et al.* (2021) compared a set of 18 market and aggregator platforms across

[3] https://www.iledefrance-mobilites.fr/transition-energetique
[4] https://grhyd.fr/

Europe and find evidence that these are promising in addressing local congestion problems. Dudjak *et al.* (2021) have carried out an extensive literature review of international demonstration and pilot projects involving the integration of local energy markets (LEMs), defined as user-centred energy markets, into the distribution network. They point out that '... if managed intelligently DERs can provide ancillary services to system operators... as well as local services to the DSO to solve issues related to voltage regulation, power quality and ... network congestion.' (p.2)

Gjorgievski *et al.* (2021) provide a review of 34 large projects for power-to-heat demand response, some of which can provide real time balancing and frequency response at smaller scale. They claim that economic and policy frameworks have significantly contributed to the diffusion of power-to-heat demand response, leading them to conclude that market rules need to be carefully tailored in order to promote the availability of flexibility resources in general.

Henni *et al.* (2021) propose a method that would allow DSOs to identify future grid constraints and address them using power-to-gas technology. This would allow the exploitation of the existing gas infrastructure to integrate surplus electricity generation. They apply the modelling method using data from the German region of Baden-Württemberg.

Adaptive indicative planning

Karagiannopoulos, Aristidou and Hug (2017) discuss the need for optimizing between the planning and operation phases of a DSO with increased penetration of DERs, by using real time local level data and thus moving beyond the paradigm of grid reinforcement as the main solution to voltage and congestion issues in networks. Maleki Delarestaghi (2021) find that increased DERs and the existence of peer to peer trading impacts grid planning and reduces the DSO's investment needs. Dudjak (2021) discuss the increased complexity of the grid planning process with the greater penetration of DERs. Potential postive effects such as reduced need for redundancy, greater matching of supply and demand locally, but also negative impacts such as voltage variations, phase imbalances need to be taken into account. Klyapovskiy (2019) suggests that to benefit from market procured flexibility services, the planning horizon for the local energy system should be reduced from 10 to 5 years to ensure precision and reliability in the estimates.

If the value and complexity of planning is increasing for the electricity DSO, it is an order of magnitude more difficult for the gas DSO. While electricity DSOs are expected to experience increased underlying demand for withdrawals and injections into their networks, gas DSOs face existential threats from decarbonisation.[5] Gas networks face the expectation of declining demand for methane; the uncertainty of how much biomethane or biogas might be increased; and the possibility of whole new networks being created to transport hydrogen, possibly via the repurposing of some of their existing assets (see Chyong et al., (2021). In addition there is the strong possibility that different DSOs within the same country will experience very different energy transitions. Clearly the ability of gas DSOs to adapt to emerging trends and policy developments will be critical to their relative financial success and their significance in supporting decarbonisation.

[5] For Great Britain, (NG ESO, 2022) produces four scenarios for the energy system. In all, methane demand declines substantially, but in one the methane network distributes 65% of today's volume in 2050, but in another just 3% (i.e. varies by a factor c.20) (NG ESO, 2022, p.215). In one, total hydrogen use is 400 TWh, while in another it is very low in 2050 (i.e varies by a factor of >>20) (NG ESO, 2022, p.206). Electricity distribution networks deliver 90% more by 2050 (relative to 2021) in the least ambitious scenario and 145% more by 2050 in the most ambitious scenario (i.e. varies by a factor of less than 2) (NG ESO, 2022b).

Innovation

The new roles for the DSO require experimentation with new technologies and business models, which requires new approaches to innovation from the regulators, including tools such as "sandboxes and demonstration projects, involving regulators, regulated companies and new market actors, in order to identify efficient and novel regulatory frameworks" (Pollitt et al., 2021, p. 26).

Anaya and Pollitt (2021) review potential options for DSO innovation in flexibility procurement and conclude that DSOs may be encouraged to opt for innovative investments, to a different extent depending on the nature of regulatory incentives. van der Waal, Das and van der Schoor (2020) discuss decentralised experiments on energy production and trade led by local communities in the Netherlands as part of regulatory sandboxes. They point out the reduced involvement and interest of the DSOs in the experimentation with the new local functions due to the limited upside potential. Lode *et al.* (2022) highlight the limited involvement of DSOs in four Flemish pilot studies on energy communities.

Schittekatte *et al.* (2021) investigate the barriers to the uptake of energy technologies in Europe and identify incentive regulation as a key factor to overcome the slow uptake of these technologies, suggesting in particular that competitive funding models can be a powerful tool to promote innovation. Psara *et al.* (2022) review projects on innovative data-driven services in five European countries and recommend '... taking complex big-data-related issues away from the hands of the organisations and offering them data-as-service mechanisms that safeguard data confidentiality and increase data quality' (p.20). Schittekatte *et al.* (2021) provide a useful review of regulatory experimentation in the Netherlands, the UK and Italy, and find that regulatory experimentation has proven successful at the national level and suggest an EU umbrella for the sandbox approach.

3. A proposal for a definition and measurement framework

While a number of definitions of the active DSO have been attempted with some success e.g. (CEER, 2015), there are no widely agreed upon indicators that can measure the degree to which a DSO qualifies as active.

Measuring the active DSO is equivalent to estimating the extent to which the DSO performs a new role, new tasks, in relationship with new actors, in a way that enables a decarbonized energy system.

This is complicated by a number of factors.

First, there are several paths to decarbonization – which may translate into *different roles for DSOs* in different countries or regions. For example, some countries have no (or very little) role for gas[6], while others consider low-carbon gases as relevant in the net zero mix (e.g. the UK on hydrogen[7] and France

[6] Across Europe, national gas networks are at very different starting levels of significance for space heating: only 5 (including the UK, Netherlands and Italy) serve 55% plus of households; 5 (including France) serve between 30% and 55% of households and 14 serve between 5% and 30% (e.g. Ireland and Switzerland) and 6 serve less than 5% of households (e.g. Norway and Cyprus). This suggests very different outcomes for gas networks are likely across Europe, because starting points are so different. Across the EU-27 only around 40% of households are connected to the gas network, but less use gas for heating.
See https://acer.europa.eu/en/Gas/Documents/ACER_FACT-SHEETS_2021-07_02.pdf. For country totals we consider EU-27 + Norway + UK + Switzerland. For data on spacing heating shares: for EU-27 see Eurostat (nrg_d_hhq); for Switzerland see https://www.swissinfo.ch/eng/business/some-58--of-swiss-buildings-heated-with-fossil-fuels/47958720; for UK see https://www.statista.com/statistics/426988/united-kingdom-uk-heating-methods/

[7] https://www.gov.uk/government/publications/uk-hydrogen-strategy

on biomethane [8]). This requires adequate contextualization to capture different versions of the active DSO. In some countries the potential for additional distributed electricity generation might be limited (e.g. the south of England), while in others there might be considerable opportunity for the injection of renewable gas into the local gas grid (e.g. rural France or Denmark). This will influence both the extent and direction of where and in what areas DSOs become more active.

Second, the DSO operates in fully regulated environment(Eurelectric, 2020). Decisions of the DSO are required to be in response to *incentives set by the regulator*. In many ways, for the DSO to change, it needs to be "activated" by regulation (Cretì and Fontini, 2019). The latter is also conditioned by policy and market evolutions that create demand for certain regulatory interventions. When measuring the active DSO, what gets captured is the result of various forces including economic development, energy mix, decarbonization path, regulatory performance, and ultimately, responsiveness to regulation and managerial performance at the level of the DSO itself. As such, in absolute terms, it is likely that most active DSOs will be in the most advanced countries with the most ambitious decarbonization plans. For example, Western Europe, the US and Australia dominate the Smart Grid Index of utilities in 2022[9]. In the top 20 there are 7 utilities from the USA, 5 from the UK and 4 from Australia. In theory, regulatory unbundling rules could both limit the active role of the DSO and promote third parties, such as retailers and aggregators, to actively make use the distribution network. In practice, however, the DSO must play a role in facilitating activation across their network and we would label a DSO which successfully works with third parties to achieve activation across its network an active DSO.

Third, the extent to which any given DSO is active depends on *the opportunity to be active*. The opportunity is partly a function of external factors such as energy demand for power, heat and transport, the potential for renewable electricity and renewable gas and the nature of local system constraints caused by the history of network development and partly one of enabling investments in such things as local distributed generation and smart meters. Once opportunities and the potential to realise them technically are there, direct incentives on DSOs are required to encourage them to become active. Appropriate incentives result in, for example, the actual connection of distributed energy resources and the use of those assets to provide real time flexibility. This explains, as noted in Pollitt, Giulietti and Anaya (2021), why some DSOs in electricity appear much more active than others, despite similar external factors.

Fourth, a potential interpretation of the active DSO is in terms of *how relatively active* it is. This would amount to estimating the extent to which DSOs proactively take on new roles, propose new regulation and generally manage the grid in a way that prepares the system for decarbonization, independently of regulatory pressure and incentives. In this context, a DSO that promotes a more ambitious rollout calendar for smart meters would be seen as active in relative terms in a less advanced jurisdiction, despite smart meters being already mainstream in other jurisdictions. Given the difficulty of capturing what, in effect, is an indication of corporate leadership, and the complexity of holding regulatory differences constant, the active DSO in absolute terms seems to be a concept with higher explanatory power (and greater feasibility for operationalization).

Fifth, certain activities and tasks that would be suitable for the active DSO are still in their infancy and are, currently, *difficult to define and measure*. For example, as of 2019, biogas represented less than 4% of total gas demand in Europe (Sulewski et al., 2023), while at global level, EVs are expected to barely reach 1.5% of the total passanger vehicles in 2025 (Statista, 2023). Moreover, whether the DSO is playing a new role in decarbonization of transport is not captured fully by solely looking at the

[8] https://www.ecologie.gouv.fr/biogaz
[9] https://www.spgroup.com.sg/sp-powergrid/overview/smart-grid-index

number of EV chargers or RNG stations connected to the grid. Additional enabling activities such as the management of EV charging loads, V2G capabilities, and others would be highly relevant as well, but may be too early-stage to be effectively measured. This is why, at this stage, looking at the level of innovation pursued and integrated into the business is relevant for assessing the degree to which a DSO beoming active.

Keeping in mind the complexities discussed above, a definition of the active DSO can be formulated. **The DSO is active to the extent that in addition to its traditional roles, performs new tasks and engages with new actors to contribute to the decarbonization of the system. The active DSO goes beyond its core functions of developing and maintaining the grid and connecting customers, and takes an additional role as the facilitator of new processes, technologies and business models required for decarbonization.**

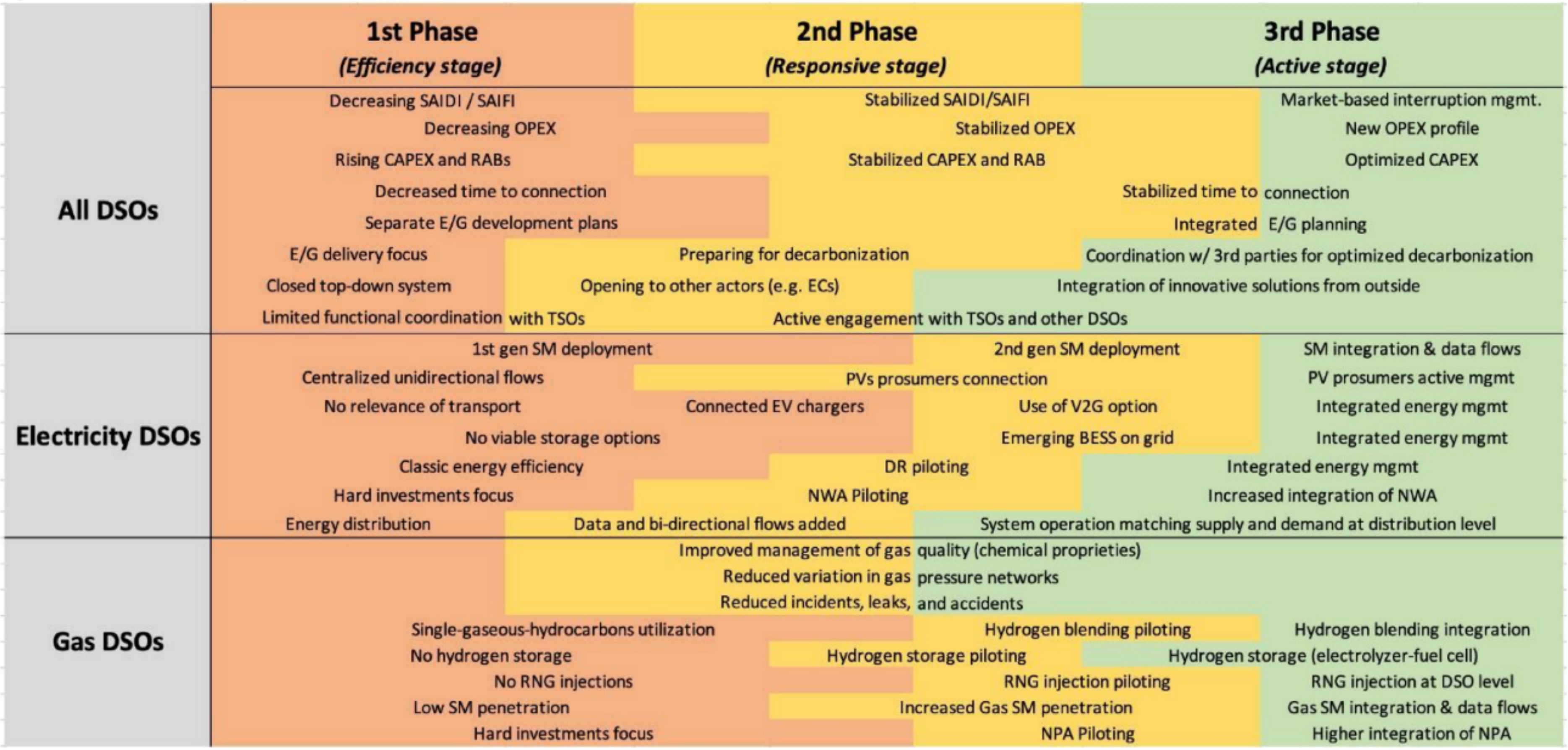
Based on this definition, we can trace the evolution of the DSO and divide it into three stages, from the traditional role, into a transitional one and finally, to the required active stage of the future, the one that can enable a decarbonised energy system. This is represented in Figure 1.0.

The first phase came with unbundling and efficiency-inducing regulation, as DSOs increased their investments in the regulated asset base, reduced operational costs and improved their processes, leading to better continuity of supply and generally technical and commercial quality of service: shorter lead times for connections, better billing, lower losses for electricity, higher safety and quality for gas.

The second phase started with the emergence of smart meters, EVs, PVs, battery energy storage systems (BESS) and prosumers in electricity and biomethane, hydrogen and power to gas technologies in gas, with the DSOs adapting and incorporating them in their existing processes.

The third phase, which is ongoing, is the shift towards the new focus on managing those extra grid resources in a manner that optimises their use and maximises the grid's overall contribution to climate goals and decarbonisation. This phase is partly about the need for real time flexibility at the distribution level, in terms of spatial, hourly and seasonal flexibility. A key aspect of this is that more responsiveness to third parties has the potential to reduce whole system costs, by reducing transmission level investment in both network capacity and transmission connected generation/gas production. It also delegates the matching of demand to supply, and real time power and gas quality resolution to the distribution level, rather than leaving it solely to the transmission level system operator. It also involves more active engagement with energy communities, between DSO and TSO, and among DSOs, both gas and electricity.

Figure 1.0: The Evolution of the Active DSO



Note: SAIDI-SAIFI = indicators of service continuity; RAB= regulated asset base; EC = energy community; SM = smart meter; DR = demand response; BESS = battery energy storage systems; V2G = vehicle to grid technology; NWA = non-wire alternatives; NPA = non-pipeline alternatives.

Figure 1.0 provides a visual approximation of the three change processes. While it does not aim to be an accurate description of any single DSO nor to cover all relevant processes, the evolution from left to right illustrates the challenges faced by DSOs and regulators in managing the significant shifts that have occurred or need to occur in the span of the period 2000-2030.

Interestingly the active DSO is related to but not the same as the 'smart grid'.[10] Firstly, the active DSO is about both electricity and gas DSOs. Second, our definition emphasises that the active DSO is focused on facilitating the decarbonisation of power, transport and heating. Third, the 'smart grid' emphasises automated control, while the active DSO is about responsiveness to third parties in a holistic sense. The fact that the active DSO and the smart grid are different concepts implies that their measurement should be different.

A methodology for measuring the active DSO

Moving to measurement, several indicators are proposed with the aim of capturing the different components of the definition and thus establish whether a DSO has evolved into the third – active - phase discussed above. The indicators are grouped based on the five dimensions: transport decarbonisation; heating and gas decarbonisation; flexibility and storage; integrated planning; and innovation.

On **transport**, we have established that an active DSO plays a facilitating role for the decarbonization of transport, either by EV integration, low-carbon gases (LCGs), or both. For an indicator to capture that role, it could measure the volume of EVs or LCG stations connected to the grid. However, connecting new loads to the grid, while fundamental, is a task that belongs to the pre-active stage of the DSO. To become active, DSOs need to manage the new loads, according to their particularities, and thus facilitate their role-out and their contribution to a decarbonized system. While the volume can be easily measured, the active management component requires further operationalization and, potentially, engagement with DSOs themselves. For example, the vehicle to grid (V2G) model that uses EV batteries to provide system services, would qualify for the definition of an active DSO on the transport dimension. However, such projects are still (almost entirely) in the pilot phase and cannot be quantified easily. Other DSO level facilitation services for EVs are also indicative of an active DSO – dedicated tariffs for EV charging, including time-of-use or other load management programmes. Most such programmes are in their infancy and are difficult to appraise, however, their presence can be considered as a sign of activity.

The indicators included for electricity are:

- Dedicated tariffs for EV charging *[Yes/No]*
- V2G piloting and other uses for EV batteries within the grid *[Number of projects per each technology]*
- Active EV load management and optimization *[Number of projects]*

On the gas side, quantification may be more feasible, but most programmes are also at an early stage. In addition, low carbon gas charging infrastructure may be developed without the involvement of the DSO.

The indicators included for gas are:

[10] The IEA (2022) defines a smart grid as 'an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demand of end users.'

- Operation or facilitation of low carbon gases fueling stations connected to the grid *[number of stations connected to the grid]*

On **heating**, the differences between electricity and gas are also significant. For electricity, an active role in heating is the accommodation of greater loads due to the roll-out of heat pumps or dual-fuel systems. Similarly with the case of EV chargers, grid reinforcements, while needed and welcome, do not indicate a new role for the DSO. Instead, new systems or programmes to manage the loads, enabling and managing the greater penetration of heat pumps would be indicative of an active electricity DSO in the heating segment.

For gas, quantitative indicators may be more relevant. The percentage of low carbon gases, for example, injected or blended in the networks could already point to a new role of the gas DSO. Since there are several options for gas decarbonization, progress toward either should be counted as "activity".

For both electricity and gas, the presence of dedicated programmes or systems to facilitate dual energy system will also be considered indicative of an active DSO.

The indicators included for electricity are:

- Programmes or systems dedicated to managing the increased penetration of heat pumps in the grid *[Yes/No + Number of users connected to the grid]*
- Grid level facilitation of dual energy systems[11] *[Yes/No + Number of users using dual energy systems]*

The indicators included for gas are:

- The percentage of low carbon gases injected and/or blended in the grid defined as: total volumes of low carbon gas divided by total volumes of gas delivered through the grid in one calendar year *[%]*

The indicators for **flexibility and DER integration** are meant to capture the new role of DSOs in a system characterized by more decentralization and intermittency. For electricity, the DSO needs to become more of a system operator rather than a distribution operator, and thus manage an increasing number of DERs, including through demand response and other optimization measures. Again, the number of DERs connected would only partially indicate the level of activity, as merely connecting them is part of the traditional DSO role. The extent to which new tasks are performed to manage the connected DERs is what determines the level of activity. Hence, the existence of digital systems to manage smart meters and their real time information and control capabilities, the procurement of constraint management and reactive power at DSO level, demand response and smart tariffs, and non-wire alternatives (Menonna and Holden, 2002) are all part of the portfolio of the active DSO. In the case of the gas grids, the contribution to flexibility can be in the form of power-to-gas facilities that serve as energy storage. For example, there are pilot projects connecting small scale electrolyzers at the user level, producing hydrogen for longer term storage and transforming it back to power through fuel cells (SoCalGas, 2021). Similar to non-wire alternatives, several DSOs, particularly in the US are also running non-pipeline alternatives, using various interventions to increase flexibility and delay and/or permanently avoid investments in expanding grid capacity (ConEd, 2022). These would qualify as an active role of the gas DSO in promoting flexibility and storage.

[11] Dual energy systems allow the switching between power and gas to optimize energy use in heating.

The indicators included for electricity are:

- Integration of smart meter functionalities for flexibility purposes including real time information on power flows and location dynamic tariffs *[Yes/No & Yes/No]*
- Platform for smart meter data sharing with third parties (e.g. suppliers, aggregators), to ensure interoperability of customers' data *[Yes/No]*
- Demand response and flexibility services at DSO level [Yes/No + MW auctioned/contracted]
- The procurement of constraint management and reactive power at DSO level *[Yes/No + MVAr auctioned/contracted]*
- Reverse flow points between DSO and TSO *[Number]*
- Non-wire alternatives *[Yes/No]*

The indicators included for gas are:

- DSO level power to gas projects for flexibility *[Number]*
- Non-pipeline alternatives *[Yes/No]*

The active electricity DSO needs to update its **adaptive indicative planning** process to serve the decarbonization process. It should take into account the increased penetration of DERs, with its potential impacts on voltage, reverse flows, congestion, but also the availability of local level real time data and thus optimize the planning process, beyond static grid reinforcements.

The active gas DSO needs to include gas decarbonization, low carbon gas injections and electrification in its indicative planning process. The presence of integrated planning with an aim for jointly optimizing capital expenditure (CAPEX) and operational expenditure (OPEX) between electricity and gas for efficient decarbonization is an indication of an active DSO. While strictly conditional on policy and regulation, integrated planning, particularly in jurisdictions with significant penetration of gas, represents a clear sign of DSOs adapting to a new role for decarbonization.

The indicators included for electricity are:

- Updated indicative planning process taking into account the increased penetration of DERs and their potential contribution to system optimization *[Yes/No]*

The indicators included for gas are:

- Updated indicative planning process taking into account injections of low-carbon gases and electrification with a view for optimizing CAPEX between electricity and gas for system decarbonization *[Yes/No]*

Finally, **innovation** has been an objective for DSOs even before the process of decarbonization gained significance. Incentivizing innovation in a regulated business while maintaining prudent costs has been a challenge for regulators (see for example discussion in Pollitt (2008)). However, pursuing or integrating innovative technologies or management models at the DSO level is crucial for the new role in a decarbonized system to become reality. In the absence of indicators that can capture the performance of innovation activity, the percentage of OPEX dedicated to innovation represents an imperfect estimation. What qualifies as innovation may differ from one jurisdiction to another, which may further complicate comparisons.

The indicators included for electricity and gas are:

- Percentage of Revenue dedicated to decarbonization relevant innovation activities *[%]*
- Decarbonization relevant innovation activities that have become business-as-usual *[Number]*

Discussion

After elaborating the definition and methodology for measurement, a number of implications are worth highlighting.

First, the active DSO may generate some *changes in the risk-return profile of the distribution business*. An active DSO will need to pursue additional activities and investments and engage with more actors. Particularly at the beginning, the lack of track record will mean DSOs will need to experiment and innovate with different technologies and business models. Some of these technologies and models may not lead to the desired outcomes, implying that the DSO will need to be comfortable with taking on new types of risks. To generate the incentives for this process to happen, the regulator will need to take these new activities into account and change its regulated revenue model. Higher risk is associated with higher returns, which may increase the total cost of the active distribution system.

Second, the *active DSO may not be equally desirable in every jurisdiction* at the same time. Since activation is likely to be costly, it may be optimal for these costs to be borne first by systems where decarbonization is more advanced and, importantly, where other basic DSO functions are adequately met – network development, remote control, reduced losses, SAIDI and SAIFI[12]. The active DSO tasks come on top of the traditional ones, which may be prerequisites for activation. A differentiated strategy for activation, one that takes into account the state of the system in a given jurisdiction, may be preferred.

Third, the *incentive for activation may be fundamentally different between electricity and gas*. For gas, activation may be the solution to an existential threat. Without activation, it may be difficult to picture a role for a traditional gas DSO under net zero. The reaction to this existential threat may be binary. Some DSOs may realise that total electrification is likely and choose to scale down their operations. Others may embrace a new role of an active gas DSO that coordinates with predominantly electric systems and integrates low-carbon gases, which can be a solution in the transition phase or even beyond it. At the same time, electricity DSOs face less of an existential threat. Under most realistic scenarios, the relevance of the electricity DSO is expected to grow with increased electrification of transport and heating/cooling, even if the DSO does not become active. In addition, the activation in electricity is of a higher complexity due to the intermittency and decentralization introduced to the system by the higher penetration of DERs. Hence, different incentives may be required for the activation of the electricity DSO in order for it to take the additional roles of facilitators and optimizers of the system.

Fourth, *the extent to which activation is possible may differ between larger or smaller DSOs*. For smaller DSOs, especially in the gas sector, activation may not even be an option. The requirements and scale needed for activation in gas may prevent smaller DSOs from taking this step. The possibility to integrate new functions, pursue innovation and engage with different actors may be greater in DSOs that have certain size, in terms of revenue, points of connection and staff. It may be the case that fragmented systems with more and smaller DSOs will need different models for activation, including the centralization and sharing of certain functions. The prominence of UK, US and Australian DSOs as leaders in DSO level innovation (SPGroup, 2023), is an indication that medium sized private firms that are under supportive incentive regulation may be more likely to become active.

[12] SAIFI and SAIDI are indicators of service continuity. SAIFI measures the frequency of interruptions, while SAIDI measures the duration of interruptions.

4. An application of the methodology electricity and gas DSOs in the UK

We apply the methodology for measuring the active DSO to UK DSOs in electricity and gas by collecting data for the indicators identified in the previous section, under our five issue areas. We rely on public information available on the websites of DSOs, the regulator or utility associations. This data collection took place between February and March 2023. We examine 7 electricity DSOs and information from 8 gas DSOs.[13] The DSOs in Great Britain are regulated by Ofgem, while those in Northern Ireland are regulated by UREGNI. The summary results for each measure are presented in Table 1, which indicates the availability of information of each of the indicators we identified in Section 3. The full results at the company level and the sources of data are presented in a separate Excel File (Annex 1), where the different findings are presented for each DSO.

Electricity DSOs

The research for consistent details on the analysed dimensions revelead different levels of data availability on both the electricity operators' website or reports, as well as on platforms of third parties/authorities. Data availability has been scored in Figure 2, and clustered in three categories: i) no data available (RED), ii) low/medium data availability (ORANGE), iii) high data availability (GREEN).

[13] In the separate data Annex we report the information for the three Northern Ireland gas companies as one, due to their small size relative to the five Great Britain gas companies.

Figure 2.0 Data availability for applying the methodology for Electricity DSOs (percentage of all sample DSOs)

On the **transport** dimension, an increased and consistent focus on electric mobility can be noticed across all electricity DSOs, with different online solutions for customers to both understand their EV charging needs and submit documentation for these connections. However, no dedicated tariffs for EV charging are visible at DSO level. Two DSOs mentioned their involvement in several vehicle to grid (V2G) trials/pilot projects both for domestic and commercial electric vehicles. Additionally, one DSO company mentions that V2G-ready charging points can be connected as part of their grid strategy. Despite these efforts, no specific mentions on active EV load management and optimization can be traced across the DSOs' websites and public documents.

For **heating**, similar to gas operators, electricity DSOs provide no provisions on dual energy systems or the grid level facilitation for these hybrid solutions, confirming once again that these solutions are offered by suppliers (if they are offered at all).

As for the facilitation of heat pumps in the grid, two operators are providing technical assistance to customers interested in installing these alternative solutions in their buildings, especially for larger heat pumps for multiple proprieties. One of these DSOs is working with academic institutions to understand the impact of heat pump operation on the distribution network. A third DSO has issued a dedicated guide on heat pumps and the engagement of the operators with local authorities and building owners on this topic.

On the **flexibility and DER integration** dimension, a number of solutions are already in use, while others are tested and considered for larger scale application. On the smart meters side, their utilization and capabilities, few details are provided, despite the acknowledgement of all electricity DSOs of their importance in building the energy systems of the future. One explanation may be that in the UK suppliers own and manage smart meters, being also responsible for the customers' consumption data.

Although all DSOs are participating in flexibility tenders – for dynamic, restore, secure, or sustain services, as well as for reactive power options – not all of them are including specific details on their websites and reports. Moreover, According to the Energy Networks Association (ENA) and its latest report, aggregating results at July 2022 level, network companies have tendered 3.7GW flexibility, with almost 2GW being contracted, in the previous 12-month monitoring period (Energy Networks Association, 2022).

While the mention of non-wire alternatives is not obviously available on DSOs' websites and public documents, the operators extensively mention – both in their short and long-term plans – the use of decentalized solutions, storage, or the above-mentioned flexibility options to decrease the increasing pressure on the existing infrastructure, in the light of higher electricity volumes distributed in the grids.

No information provided on the existence of reverse flow points between DSOs and TSOs.

In terms of **adaptive indicative planning**, all DSOs submit five-year investment plans for regulatory approval. On medium and long-term planning, as in the case of gas operators, electricity DSOs have different vision documents or long-term strategies for supporting decarbonization targets. The documents refer to all technologies, underlining the need for anaccelerated electrification, brought by a better cooperation among stakeholders.

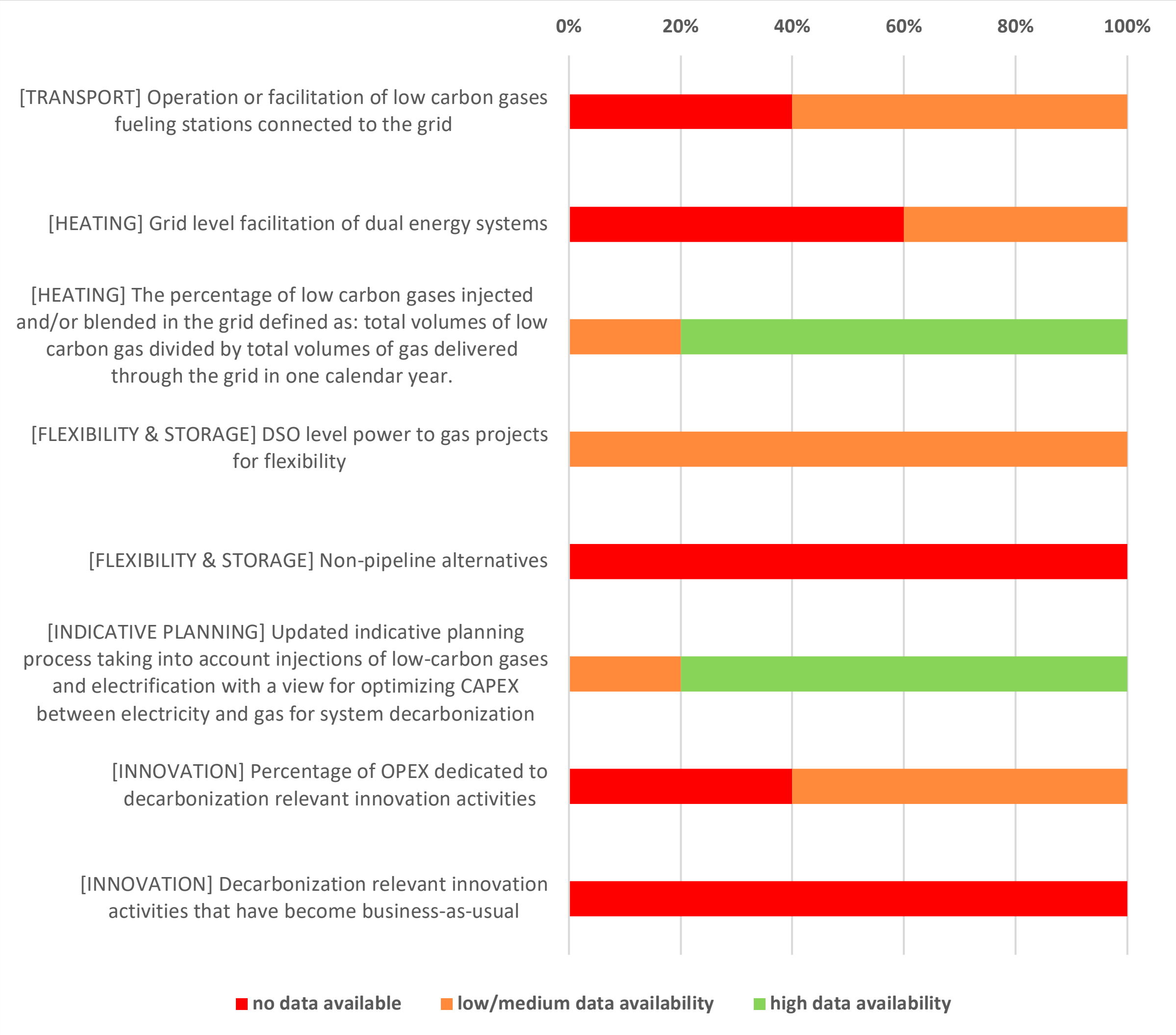
On the **innovation** dimension, electricity DSOs seem to focus their efforts on finding alternative sollutions to current challenges, leveraging on the available opportunities provided by their regulatory-approved plans. One DSO states that, since the beginning of the RIIO-ED1 price control period (2015-23), it adopted 50 innovative solutions into everyday business, solutions which represent almost £283.6 million in savings. However, the definition for innovation varies significantly from one operator to the other, making the relative assessment of innovative solutions difficult to perform.

For an aggregated effort on innovation, OFGEM's reports give a clear indication on the level of these investments. Accorrding to the regulator, in 2020-2021, distribution network operators spent £25.2 millions on 168 innovative projects, which represents 83% of their yearly allowances. For reference, that represents 0.11% of total expenditures (TOTEX) (see OFGEM, 2022).

Gas DSOs

The research for consistent details on the analysed dimensions revealed different levels of data availability on both the gas operators' website or reports, as well as on platforms of third parties/authorities. Data availability has been scored in Figure 3, and clustered in three categories: i) no data available (RED), ii) low/medium data availability (ORANGE), iii) high data availability (GREEN).

Figure 3.0 Data availability for applying the methodology for Gas DSOs (percentage of all sample DSOs)



On the **transport** dimension, there do not seem to be any operational low carbon gas filling stations. One DSO mentions the aspiration for its grid to serve as the backbone of a network of biomethane filling stations in the near future. Another DSO conducts a pilot project (HyPark) using fuel cells connected to the gas grid to charge EVs when the power network is constrained. All DSOs discuss the potential of hydrogen for transport in their gas visions, but do not specify their role in that sector.

For the **heating** dimension, dual energy systems are mentioned by one DSO – as smart hybrid systems of heat pumps and gas boilers with automatic switching. They are in the trial phase. It may be the case that in the UK, the dual system offer is more within the mandate of the suppliers rather than DSOs, which can explain why they are not discussed more in the DSO gas visions.

Low carbon gas injections are piloted or operational for almost all DSOs. The larger DSOs have already connected between 17 and 42 biomethane sites that deliver significant quantities every year. On hydrogen, the large DSOs are involved in pilot projects for blending in various ratios and locations, with some also piloting 100% hydrogen grids. All DSOs present hydrogen as a major use case for the gas grid in the future – responding to the UK policy aiming to have grids ready for 20% hydrogen blending already in 2023.

On **flexibility and DER integration**, two DSOs are implementing pilot projects for power to gas. One DSO is connecting a green hydrogen facility using power from a nearby offshore wind park and transporting it through a 100% hydrogen mini network to 300 homes. Another DSO is trialing 100% hydrogen grids in unoccupied parts of its network. All DSOs mention green hydrogen as part of their plans.

At the same time, the non-pipelines alternative approach does not appear on the websites or in the planning documents of UK gas DSOs. This may imply that the focus continues to be on reinforcing grids. Alternatively, It may be the case that the process of searching for non-pipeline alternatives is internal and does not involve third parties, which may explain why public information is scarce.

For the **adaptive indicative planning** dimension, all DSOs have a ten years vision for their grid, that includes ample references to decarbonization activities, integration with the electrification process and others. However, they are visions rather than plans. The plans with activities, targets and capital allocations, where available, have fewer references to such new tasks. This may indicate that the process of turning the visions into plans may be itself in the beginning, or it may indicate the high degree of uncertainty (from modest reduction to shutdown) in terms of the potential pathways for the methane sector noted earlier.

Finally, on the **innovation** dimension, company Network Innovation Account (NIA) reports mention the spending on innovation activities (Energy Networks Association, 2022). Some DSOs publish a breakdown by innovation theme, others do not. The data is presented by year by some DSOs and cumulatively by others. The heterogeneity in reporting makes comparison difficult, but may be indicative of the innovation process itself, which may not easily fit into predetermined categories. There is little public information on the innovation processes that graduated into business as usual practices, illustrating that many of them have not yet become market ready.

Overall, the process of measuring the active DSO for gas based only on public information illustrates the points discussed in this paper. Many of the dimensions of the active DSO are just about to begin, included in discussions and visions, but not part of the day-to-day reality. However, biomethane sites are already operational, hydrogen pilots are being implemented and the innovation activity is intense. An attempt to measure the active DSO using the proposed methodology may generate more significant results in the years to come.

Observations on the United Kingdom case

An examination of the available of measures of the active DSO for the leading jurisdiction of the United Kingdom illustrates that the active DSO is at an early stage for both electricity and gas even where it is being strongly promoted by the energy regulator. The exercise also illustrates the need for clearer and better measurement. Information on the degree of activation of the DSO is fragmented and patchy at best.

5. Conclusion

System decarbonization requires an active DSO. However, a working definition of the active DSO is missing. Defining the active DSO is complicated by a number of factors. Firstly, DSOs are regulated businesses and their decisions are in response to regulatory incentives. These are in turn based on wider policy choices at country level. Secondly, identifying the enabling role of the DSO may be difficult. For example, a DSO that serves EV chargers, heat pumps or various DERs is performing its traditional role. To be considered active, it needs to manage and optimize the additional resources in the grid. To overcome these conceptual difficulties, we propose a neutral definition of the active DSO that will examine its roles and activities, without discerning the various factors that may explain them, such as the decarbonization path chosen at policy level, the type of regulation or the quality of its management. We also attempt to capture the enabling, management and optimization dimensions for new technologies and business models, not just their presence in the grid.

We define **the active DSO as one that, in addition to its traditional roles, performs new tasks and engages with new actors to contribute to the decarbonization of the system. The active DSO goes beyond its core functions of developing and maintaining the grid and connecting customers, and takes an additional role as the facilitator of new processes, technologies and business models required for decarbonization.** We group these new tasks along five dimensions: transport, heating, flexibility and DER integration, adaptive indicative planning, and innovation. We propose a methodology for measuring the extent to which a DSO is active by looking at indicators along the five dimensions.

Measurement is important because it allows DSOs and their regulators to quantify and compare the extent to which a given DSO is 'active'. This could be useful for setting corporate strategic goals and for setting regulatory targets under incentive regulation. The indicators of activity we suggest include the presence of management and enabling activities for EVs, biomethane and hydrogen, demand management, non wires or non pipeline alternatives, dynamic planning, and innovation adoption. We apply the methodology to electricity and gas DSOs in the United Kingdom. Based on this initial attempt at measurement, a number of conclusions emerge. First, many of the new tasks of the active DSO are still in their infancy, which makes measurement less relevant at this stage. Second, there seem to be more opportunities for becoming active for electricity DSOs, given the challenges of intermittaency, storage and decentralizations, which create opportunities to use digitalization. Third, for gas DSOs, becoming active may be a response to an existential threat, the efforts around hydrogen, biomethane and coupling with electrification are telling and are becoming significant. Fourth, DSO and regulatory disclosure and reporting may need to include standardized information on the new tasks of the active DSO to enable incentives and oversight.

References

Anaya, K., Pollitt, M., 2021. How to Procure Flexibility Services within the Electricity Distribution System: Lessons from an International Review of Innovation Projects. Energies 14, 4475. https://doi.org/10.3390/en14154475

CEER, 2015. The Future Role of DSOs - A CEER Conclusions Paper. Council of European Energy Regulators, Brussels.

Chyong, K., Pollitt, M., Reiner, D., Li, C., Aggarwal, D., Ly, R., 2021. Electricity and gas coupling in a decarbonised economy. Centre on Regulation in Europe, Brussels.

ConEd, 2022. Non-Pipeline Alternatives for Natural Gas Customers | Con Edison [WWW Document]. URL https://www.coned.com/en/business-partners/business-opportunities/non-pipeline-solutions (accessed 2.17.23).

Cretì, A., Fontini, F. (Eds.), 2019. Some Principles of Electricity Sector Regulation, in: Economics of Electricity: Markets, Competition and Rules. Cambridge University Press, Cambridge, pp. 72–80. https://doi.org/10.1017/9781316884614.007

Dougherty, S., Nigro, N., 2014. Alternative Fuel Vehicle & Fueling Infrastructure Deployment Barriers & the Potential Role of Private Sector Financial Solutions. Center for Climate and Energy Solutions. URL https://www.c2es.org/document/alternative-fuel-vehicle-fueling-infrastructure-deployment-barriers-the-potential-role-of-private-sector-financial-solutions/ (accessed 2.16.23).

Dudjak, V., Neves, D., Alskaif, T., Khadem, S., Pena-Bello, A., Saggese, P., Bowler, B., Andoni, M., Bertolini, M., Zhou, Y., Lormeteau, B., Mustafa, M.A., Wang, Y., Francis, C., Zobiri, F., Parra, D., Papaemmanouil, A., 2021. Impact of local energy markets integration in power systems layer: A comprehensive review. Applied Energy 301, 117434. https://doi.org/10.1016/j.apenergy.2021.117434

Energy Networks Association, 2022. Annual Innovation Summary [WWW Document]. ENA Innovation Portal. URL https://smarter.energynetworks.org/annual-innovation-summary/ (accessed 2.23.23).

Eurelectric, 2020. Distribution Grids in Europe: Facts and Figures, Euroelectric, Brussels.

Fischer, D., Madani, H., 2017. On heat pumps in smart grids: A review. Renewable and Sustainable Energy Reviews 70, 342–357.

Gjorgievski, V.Z., Markovska, N., Abazi, A., Duić, N., 2021. The potential of power-to-heat demand response to improve the flexibility of the energy system: An empirical review. Renewable and Sustainable Energy Reviews 138, 110489. https://doi.org/10.1016/j.rser.2020.110489

Henni, S., Staudt, P., Kandiah, B., Weinhardt, C., 2021. Infrastructural coupling of the electricity and gas distribution grid to reduce renewable energy curtailment. Applied Energy 288, 116597. https://doi.org/10.1016/j.apenergy.2021.116597

IEA, 2022. Smart Grids, Paris: IEA, www.iea.org/reports/smart-grids

IRENA, 2019. Future role of distribution system operators – Innovation Landscape Brief. International Renewable Energy, Abu Dhabi.

Karagiannopoulos, S., Aristidou, P., Hug, G., 2017. Hybrid approach for planning and operating active distribution grids. IET Generation, Transmission & Distribution 11, 685–695. https://doi.org/10.1049/iet-gtd.2016.0642

Klyapovskiy, S., You, S., Cai, H., Bindner, H.W., 2019. Incorporate flexibility in distribution grid planning through a framework solution. International Journal of Electrical Power & Energy Systems 111, 66–78. https://doi.org/10.1016/j.ijepes.2019.03.069

Knezović, K., Marinelli, M., Zecchino, A., Andersen, P.B., Traeholt, C., 2017. Supporting involvement of electric vehicles in distribution grids: Lowering the barriers for a proactive integration. Energy 134, 458–468. https://doi.org/10.1016/j.energy.2017.06.075

LaMonaca, S., Ryan, L., 2022. The state of play in electric vehicle charging services – A review of infrastructure provision, players, and policies. Renewable and Sustainable Energy Reviews 154, 111733. https://doi.org/10.1016/j.rser.2021.111733

Lode, M.L., Heuninckx, S., te Boveldt, G., Macharis, C., Coosemans, T., 2022. Designing successful energy communities: A comparison of seven pilots in Europe applying the Multi-Actor Multi-Criteria Analysis. Energy Research & Social Science 90, 102671. https://doi.org/10.1016/j.erss.2022.102671

Maleki Delarestaghi, J., Arefi, A., Ledwich, G., Borghetti, A., 2021. A distribution network planning model considering neighborhood energy trading. Electric Power Systems Research 191, 106894. https://doi.org/10.1016/j.epsr.2020.106894

Menonna, F., Holden, C., 2002. Where Are All the Non-Wires Alternatives? [WWW Document]. URL https://www.greentechmedia.com/articles/read/where-are-all-the-non-wires-alternatives (accessed 2.17.23).

NG ESO, 2022. Future Energy Scenarios 2022 | ESO [WWW Document]. URL https://www.nationalgrideso.com/future-energy/future-energy-scenarios (accessed 3.28.23).

Ofgem, 2019. Position paper on Distribution System Operation: our approach and regulatory priorities. Office of Gas and Electricity Markets, London.

Pereira, G.I., Pereira da Silva, P., Soule, D., 2020. Assessment of electricity distribution business model and market design alternatives: Evidence for policy design. Energy & Environment 31, 40–59.

Pollitt, M., Giulietti, M., Anaya, K., 2021. Optimal regulation for European DSOs to 2025 and beyond. CERRE. URL https://cerre.eu/publications/optimal-regulation-european-dsos-energy-transition/ (accessed 2.16.23).

Pollitt, M., Giulietti, M., Covatariu, A., Duma, D., 2022. The Active Distribution System Operator: An International Study. Centre on Regulation in Europe, Brussels.

Pollitt, M.G., 2008. The Future of Electricity (and Gas) Regulation in a Low-carbon Policy World. The Energy Journal Volume 29, 63–94.

Proka, A., Hisschemöller, M., Loorbach, D., 2020. When top-down meets bottom-up: Is there a collaborative business model for local energy storage? Energy Research & Social Science 69, 101606. https://doi.org/10.1016/j.erss.2020.101606

Psara, K., Papadimitriou, C., Efstratiadi, M., Tsakanikas, S., Papadopoulos, P., Tobin, P., 2022. European Energy Regulatory, Socioeconomic, and Organizational Aspects: An Analysis of Barriers Related to Data-Driven Services across Electricity Sectors. Energies 15, 2197. https://doi.org/10.3390/en15062197

Quarton, C.J., Samsatli, S., 2020. Should we inject hydrogen into gas grids? Practicalities and whole-system value chain optimisation. Applied Energy 275, 115172. https://doi.org/10.1016/j.apenergy.2020.115172

Schittekatte, T., Meeus, L., Jamasb, T., Llorca, M., 2021. Regulatory experimentation in energy: Three pioneer countries and lessons for the green transition. Energy Policy 156, 112382. https://doi.org/10.1016/j.enpol.2021.112382

SoCalGas, 2021. SoCalGas and Bloom Energy Showcase Technology to Power Hydrogen Economy with Gas Blending Project | SoCalGas Newsroom [WWW Document]. URL https://newsroom.socalgas.com/press-release/socalgas-and-bloom-energy-showcase-technology-to-power-hydrogen-economy-with-gas (accessed 2.17.23).

SPGroup, 2023. Smart Grid Index [WWW Document]. URL https://www.spgroup.com.sg/sp-powergrid/overview/smart-grid-index (accessed 3.28.23).

Statista, 2023. Number of electric passenger vehicles in use globally 2022-2025 [WWW Document]. Statista. URL https://www.statista.com/statistics/970958/worldwide-number-of-electric-vehicles/ (accessed 3.28.23).

Sulewski, P., Ignaciuk, W., Szymańska, M., Wąs, A., 2023. Development of the Biomethane Market in Europe. Energies 16, 2001. https://doi.org/10.3390/en16042001

Thomas, S., 2018. Evolution of the Distribution System & the Potential for Distribution-level Markets: A Primer for State Utility Regulators. National Association of Regulatory Utility Commissioners, Washington DC.
Valarezo, O., Gómez, T., Chaves-Avila, J.P., Lind, L., Correa, M., Ziegler, D.U., Escobar, R., 2021. Analysis of New Flexibility Market Models in Europe. Energies 14, 1–24.
van der Waal, E.C., Das, A.M., van der Schoor, T., 2020. Participatory Experimentation with Energy Law: Digging in a 'Regulatory Sandbox' for Local Energy Initiatives in the Netherlands. Energies 13, 458. https://doi.org/10.3390/en13020458
Wargers, A., Kula, J., Ortiz De Obregon, F., Rubio, D., 2018. Smart charging: integrating a large widespread of electric cars in electricity distribution grids. EDSO for Smart Grids.