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Measuring the digitalisation of electricity distribution systems in Europe: Towards the smart grid

Nestor Rodriguez-Perez *, Javier Matanza, Gregorio Lopez, Rafael Cossent, Jose Pablo Chaves Avila, Carlos Mateo, Tomas Gomez San Roman, Miguel Angel Sanchez Fornie

Institute for Research in Technology, Comillas Pontifical University, C/Santa Cruz de Marcenado 26, Madrid, 28015, Spain

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A B S T R A C T

This paper proposes a set of digitalisation indicators focused on measuring the different digital capabilities and infrastructure of electricity distribution systems, as opposed to previous indicators which have mainly focused on performance and quality of service aspects.

The indicators are classified according to the pillars of digitalisation: sensor and actuator, connectivity, data processing, and digital culture. They are use-case-agnostic and do not require a huge amount of information. In addition to this, three possible new applications of these indicators for distribution system operators and regulatory authorities are identified and discussed.

The extensive use of these indicators in Europe could allow the development of fruitful collaborations between distribution system operators, allow the identification of cause–effect relations between grid performance and digital infrastructure, and improve the replicability of innovative smart grid solutions. However, this will only be possible if regulators promote the adoption of the proposed indicators and the dissemination of their results.

1. Introduction

The Energy Transition is requiring, among other measures, the decarbonisation of the energy sector (generation and demand). This is leading to a massive electrification in the energy system and an increase in the use of renewable sources. In electricity distribution networks, this is translating into an increase in the number of distributed energy resources (DER), Electric Vehicle (EV) charging points, and active participation of demand (e.g., prosumers, demand response), that pose challenges for the operation of the network, which is required to be more dynamic. To cope with those challenges, the development of smart grids is key.

The smart grid can be defined as the application of information and communication technologies (ICT) to the electricity grid (and, therefore, the deployment of monitoring and control devices), so that real time changes in the network (consumption, failures, overload of power lines, etc.) can be remotely detected, processed, and managed. From an infrastructure point of view, a smart grid can be understood as the digitalisation of the electricity grid infrastructure to achieve a better performance.

In Europe, the distribution of electricity is regulated: a National Regulatory Authority (NRA) defines the remuneration scheme for Distribution System Operators (DSOs), including incentives and penalties, based on aspects such as quality of service, CAPEX, OPEX, etc. However, the increasing digitalisation of the distribution grids towards the development of a smarter electricity grid, together with the objectives of higher energy efficiency and penetration of renewables, are requiring the evaluation of how "smart" the grid is becoming, or needs to become, for the ultimate achievement of these objectives.

In the last decade, there has been an increasing interest in defining key performance indicators (KPIs) to be used in the evaluation of the "smartness" of the grid [1,2], its reliability [3], its continuity of supply [4], the performance of smart grid projects [5–7], the situational awareness effects [8], and the evaluation of flexibility markets in distribution systems [9].

At a European level, this interest is reflected in Directive 2019/944 of the European Parliament [10], which sets in its article 59.1 that the national regulatory authorities (NRAs) shall evaluate how DSOs perform regarding the development of a smart grid that enables higher

* Corresponding author.
E-mail address: nestor.rodriguez@iit.comillas.edu (N. Rodriguez-Perez).

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levels of energy efficiency and renewable energy; this evaluation should be based on a set of indicators, and published in a periodical report with some recommendations. In this sense, the EU Action Plan "Digitalising the energy system" [11] set the intention of the European Commission to ensure an appropriate regulatory framework by 2023 and to support the work of defining common smart grid indicators so that NRAs can monitor smart and digital investments. The indicators have to be defined by NRAs in a consultation process with the DSOs to check the feasibility of the implementation and reduce the regulatory risk of lack of data to compute them.

To address this Directive, European System Operators (SOs) associations proposed a set of up to 58 key indicators that can be calculated to monitor the smartness of grid operation and its evolution [12]. The KPIs are related to system observability, system controllability, active system management, smart grid planning, transparency in data access, local flexibility markets and customer inclusion, smart asset management, and TSO–DSO coordination capabilities.

Prior to this joint effort from SOs, in [1] a set of KPIs were proposed to measure the six main characteristics that a smart grid should present: enable informed participation by customers; accommodate generation and storage options; additional services; power quality; optimisation of assets and efficient operation; and resilient operation.

The Smart Grid Index in [2] tries to benchmark different DSOs regarding how smart is their grid based on publicly available information and according to seven dimensions: monitoring and control, data analytics, supply reliability, DER integration, green energy, security, and customer empowerment and satisfaction.

Authors in [4] assess the efficiency in the continuity of electricity of supply in Brazil by benchmarking the continuity indicators of electric utilities.

Ref. [5] provides an extensive review on what KPIs are used by smart grid projects and recommends a set of KPIs in six categories: metering, asset management, quality of supply and distributed generation (DG), sustainable communities, flexibility and network balance, and digitalisation. In [6,7], authors propose a multi-criteria fuzzy analytical hierarchy process methodology to assess smart grid performance in projects, showing that this is mainly determined by efficiency, security and quality of supply.

Covatariu et al. [13] aim to measure to what extent a DSO (both in the electricity and gas sector) is active in decarbonisation, proposing indicators in five dimensions: transport, heating, flexibility and DER integration, adaptive indicative planning, and innovation.

Fotopoulou et al. [14] proposes 23 indicators for system operators to assess the performance of smart grids, categorising them in five main categories (technical, environmental, economic, social, and platform engineering).

As presented, the existing literature about smart grid KPIs covers almost all the aspects that can be expected in a smart grid. However, most of them focus on the performance of the grid (i.e., output) and not on the evaluation of the means and infrastructure implemented (i.e., input) that drive that performance. They neither offer a comprehensive perspective on the extent of digitalisation in DSOs nor facilitate a fair comparison in this regard. A more digitalised grid does not necessarily mean a better or "smarter" grid. Apart from performance indicators, indicators that are exclusively focused on the digitalisation of electricity distribution grids are needed to be able to draw solid conclusions about the impact of digitalisation in distribution grids, to assess the cause–effect relation between digitalisation investments (digitalisation indicators) and grid performance (performance indicators), to improve the ability to integrate new resources, and to measure and compare the digitalisation efforts of DSOs in a clear and objective way, regardless of their size.

This paper aims at proposing a set of indicators specifically oriented to measure the digitalisation of distribution systems to assess the digital capabilities and infrastructure put in place to achieve the grid performance levels. The digitalisation indicators in this paper have been proposed by a interdisciplinary group of experts (i.e., the authors) with wide experience working with different DSOs and the DSO Observatory of the EU Joint Research Center; from energy regulation experts to ICT and sensors experts, thus including all the areas of expertise required by smart grids. Furthermore, these indicators have been reviewed in terms of feasibility and potential available data by three subject-matter experts from three Spanish DSOs, in their personal capacity (not as DSO representatives).

Since this work is the result of collaboration with EU DSOs, and the EU Directive 2019/944 has created the need for smart grid indicators in Europe, the target area of this paper is Europe, although all the proposed indicators would be applicable to a non-European distribution utility, as they are use case and regulatory agnostic.

Instead of using categories related to the operation of smart grids, the indicators in this paper are categorised according to the pillars of digitalisation of distribution grids: sensors and actuators, connectivity, and data processing indicators. Furthermore, this paper contributes with an additional fourth pillar, the DSO's digital culture, which is proposed together with its corresponding indicators. The main novel characteristic of the indicators proposed is that, in contrast to most KPIs in the literature, they are aimed at evaluating the digitalisation measures and infrastructures that can be implemented by DSOs, and not the resulting performance of smart grids and demonstrations' success. In addition, this paper discusses three possible applications extremely useful for DSOs and NRAs that will be more difficult to achieve with the sole use of performance indicators. The scope of the paper is therefore to propose a set of digitalisation indicators (input indicators) and discuss their potential applications when measured.

The rest of the paper is organised as follows. First, a benchmark of the indicators proposed in the literature is provided. The pillars for the digitalisation of power distribution grids are presented in Section 3. Section 4 describes the key indicators proposed for the measurement of digitalisation of power grids. These indicators are classified based on the pillars for digitalisation, including the digital culture of DSOs. Section 5 discusses the usefulness and advantages of these indicators for DSOs and NRAs. Finally, conclusions are drawn in Section 6.

2. Benchmark of state-of-the-art smart grid indicators

There are several proposals of indicators to measure different aspects of electricity distribution networks. In addition to academia [1], great efforts have been made by institutions such as the Joint Research Center (JRC) of the European Commission through its DSO Observatory [15,16], DSO associations [12], EU-funded projects [14] and, outside Europe, by the U.S. Department of Energy [17,18] and SP Group [2]. This section provides a benchmark of these references, which correspond to different points in time, and highlights the motivation behind the digitalisation indicators proposed in this paper.

Table 1 quantitatively compares how many indicators are proposed by the main references, and how many categories or dimensions are used by these to organise the indicators. It shows that the number of categories is approximately the same, in the range of 6–8, whereas the number of indicators significantly varies. On the other hand, the 18 digitalisation indicators proposed in this paper are organised in just four categories that match the pillars of digitalisation.

Since the purpose of this paper is not to review each of the 300 indicators proposed in the cited literature, Table 2 maps the high-level categories that have been used by the literature, summarising their scope. With respect to these categories, digitalisation is a cross-cutting issue.

Starting with the one that defines the lowest number of indicators, SP Group [2] provides a unique "Smart Grid index" to measure the "smartness" of distribution grids that is calculated based on seven "dimensions" or categories. Although it can be assumed that these dimensions are assessed based on multiple indicators, [2] does not enumerate them and just presents the final index. Despite authors in [2]

Table 1
Number of indicators and categories per reference.

Reference	No. of categories	No. of indicators	Objective
Dupont et al. [1]	6	59	Evaluate the "smartness" of the grid, including some indicators related to information exchange, advanced sensors, and other digital infrastructure.
SP Group [2]	7	1	Measure the "smartness" of distribution grids with a single index.
DSO associations [12]	8	58	Assess the performance of smart grids through 8 KPIs and 58 indicators.
Fotopoulou et al. [14]	4	23	Performance assessment of smart grids.
EU JRC DSO Observatory [15,16]	6	48	Technical characteristics and performance of European DSOs.
U.S. Department of Energy [17]	7	134	Measure the progress towards the smart grid considering different stakeholders in the electric sector.
U.S. Department of Energy [18]	21	38	Measure the progress towards the smart grid.
This paper	4	18	Measure the digitalisation level of electricity distribution grids, supporting EU Directive 2019/944

Table 2
Benchmarking of main smart grid indicators in the literature.

	[15]	[2]	[1]	[17]	[12]	[14]	[18]
DER penetration and integration	X	X	X	X	–	–	X
Additional products, services, and markets	X	–	X	X	X	–	X
DSO–TSO coordination	X	–	–	–	X	–	X
Monitoring and control	X	X	–	–	X	–	X
Grid management tools	X	–	–	–	X	–	–
System reliability	X	X	X	X	–	–	X
Data analytics	–	X	–	–	–	–	–
Security	–	X	–	X	–	–	X
Customer empowerment	–	X	X	X	–	–	X
Asset optimisation	–	–	X	X	X	–	X
Quality of Service	–	–	X	X	–	X	X
Grid planning	–	–	–	–	X	–	–
Data access	–	–	–	–	X	–	–
Environment	–	–	–	–	–	X	–
Economic	–	–	–	–	–	X	X

state that all the information used to calculate the index was extracted from public sources, it lacks transparency on how the different dimensions are measured, how the final index is calculated based on these, and which public sources of information were used. In addition to this, one single index may be useful to benchmark DSOs at a high level, but it does not provide enough information on what can be specifically improved by DSOs, which are the differences between them, or if they need further investments on digital technologies. This can also be misleading; as this "smartness" is expressed as a percentage, it would be difficult to interpret a 100% score and if that would mean that there would not be margin to improve.

The report of the Office of Electricity Delivery and Energy Reliability of the U.S Department of Energy [17] presents 134 metrics to measure the implementation progress of the Smart Grid from an industry perspective. These metrics were identified, discussed, and assessed in terms of relevance by more than 140 experts in the field. The metrics in [17] are not exclusively focused on DSOs; they also consider other stakeholders in the electricity distribution field (e.g., smart grid startup companies, customers, etc.). The application of these metrics would present some issues: first, many of the metrics present significant uncertainties regarding data availability, how they would be measured, and their usefulness to the analysis, such as *Number of products with end-to-end interoperability certification*, *# of new standards*, or *Number of households with home area network*; second, the number of metrics is very high, they involve different stakeholders, and many of them are difficult to measure. The data collection process from all the stakeholders would require a very significant effort, which would have to be considered when defining a final set of KPIs.

As a continuation of the previous report, the Pacific Northwest National Laboratory elaborated the Smart Grid Status and Metrics Report [18] for the U.S. Department of Energy. It makes the distinction between "build metrics", that describe attributes that support the smart grid, and "value metrics", that describes the value of an outcome of a smart grid. It considers 21 metrics with a total of 38 sub-metrics, discussing deployment trends, projections, and recommendations for the future. Despite some of these indicators evaluate digitalisation as an input (e.g., *Percentage of substations with automation*), the majority aim to assess performance (output) and many of them are based on absolute numbers and not percentages, making it difficult to compare DSOs of different sizes.

The DSO Observatory of the EU JRC [15,16] measures 48 indicators that provide a very detailed view on the technical characteristics and performance of DSOs in Europe, but without focusing on the digital capabilities and infrastructure. It shows the great amount of technical information that can be provided by DSOs. However, most of these indicators only provide a general view of the characteristics of the distribution network and are dependent on the size of the DSO. Indicators such as the *total km of network lines per voltage level*, the *total number of connection points*, or the *percentage of PV installations connected per voltage level* provide information on the electrical infrastructure but they cannot be used to objectively compare DSOs of different sizes between them. For example, a large distribution network would have more kilometers of lines, more connection points and, probably, more distributed PVs per voltage level than a small one and, despite this, it would not necessarily mean that the larger distribution network is "smarter".

Dupont et al. [1] propose 59 key performance indicators to assess the "smartness" of a smart grid, including some indicators related to information exchange, advanced sensors and other digital infrastructure. Some of these indicators also involve other stakeholders apart from DSOs (e.g., *Number of customers served by ESCO's*, *Flexibility that aggregators can offer to other market players*, etc.) and, as in [15], others would not provide an objective comparison of DSOs (e.g., *Number of microgrids in operation*, *Number of EV charging points*, etc.).

Fotopoulou et al. [14] propose 23 indicators for system operators to assess the performance of smart grids. These indicators are divided into four categories: technical, environmental, social, and platform engineering indicators. Technical indicators comprise mainly quality of service indicators, such as *Technical losses, Voltage deviation*, or *Harmonic distortion*; Environmental indicators focus on indicators such as *Direct CO2 emissions*; The social indicator proposed aims to measure the *Adoption/acceptance of proposed strategies*; and the last category, the platform engineering indicators, aims to evaluate the performance of the software and algorithms implemented based on different aspects, such as *Average CPU usage*, *User interface friendliness*, or *Tool accuracy*. The indicators in this last category, although strongly related to digitalisation, are mainly focused on the performance (output) of implemented digital elements (software, algorithms) and not the degree of implementation of such elements (input). In addition to this, it would be difficult to measure this category for all the processes of a DSO.

Finally, DSO associations [12] propose 58 indicators that are involved in the calculation of eight key performance indicators. The descriptions of the indicators are not very detailed, just providing some high-level examples on how they could be measured. An indicator that exemplifies this well is indicator 3.2 *Grid Reconfiguration*, where the following example to measure it was given: "*Effectiveness in fault prevention (in respect to a baseline) weighted according to the relevance of the area*". This definition poses multiple questions that should be addressed: Who defines the baseline? Is it the same for every DSO? What method is used to assign weights? Is there a standard methodology to assess the relevance of an area? In addition to this, the weights applied to each indicator for the calculation of the eight KPIs are not specified, so their adequacy and interpretation once calculated is unknown.

As Table 2 shows, literature mainly focuses on the performance and expected outcomes of a smart grid; aspects such as DER penetration and integration, system reliability, and additional products, services, and markets, are considered by most references. What all the categories or dimensions have in common is that they are being currently addressed through the digitalisation of the network but they do not provide simple and specific indicators to measure this digitalisation. They may provide an overview on how much a distribution network resembles a smart grid but lack of detailed information on how this performance or "smartness" is achieved. Not all the indicators may be used to effectively and objectively compare different distribution networks between them and, when it is possible, the comparison would just provide a benchmark of distribution networks and the objectives to achieve, but without really assessing what infrastructure would be needed. With the high investment in digitalisation of distribution networks that is taking place in recent years, this becomes essential to efficiently achieve a smart grid; it would not make sense to increase the deployment of technologies at the electricity distribution level if it would not improve the performance, resilience, or reliability of the grid.

The digitalisation process of electricity distribution grids resembles the deployment of broadband communications in Europe some years ago: first, different technologies were demonstrated; then, the infrastructure was built; and finally the applications were developed.

Therefore, a set of indicators that allow the assessment of the level of digitalisation of distribution networks is needed to complement the indicators proposed in the literature, fill the information gap, and expand their potential usefulness for both the DSOs and NRAs. The indicators proposed in this paper would contribute to this by:

- Focusing on measuring the digital infrastructure and capabilities of a DSO (input), at different levels, that may have an impact on performance metrics (output) such as quality of service, reliability, energy equity indicators, etc. Therefore, these indicators are conceived to be analysed together with performance indicators. This way, NRAs would find it easier to provide elaborated recommendations to comply with article 59.1 of EU Directive 2019/944.
- Being independent of the size of the DSO evaluated, so they would allow a more objective comparison between networks.
- Being simple and clearly defined, most of them as percentages, without involving complex formulas or weight assignment methods.
- Including 12 new indicators (out of 18) that have not been defined previously in the literature or whose scope is more specific than existing ones.
- Considering indicators related to the digital culture of the DSO, which is essential to fully leverage smart grid solutions.

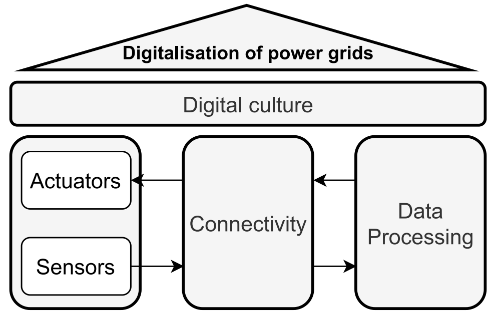

Fig. 1. Pillars of digitalisation of power distribution grids.

- Being "affordable", in terms of effort, for DSOs. The indicators in this paper have been qualitatively validated by three experts from Spanish DSOs. As mentioned above, [15] also shows that a significant amount of information can be provided by DSOs.

3. Pillars for the digitalisation of power distribution grids

In the last few years, the digitalisation of the electricity sector has taken a significant step with the massive deployment of smart meters in many countries: more than 1.2 billion smart meters have been installed worldwide (Europe accounting for more than 123 million smart meters) [19]. Thanks to this deployment, many DSOs have already started using big data techniques and machine learning algorithms to extract valuable information from smart metering data [20], and consumers can access their consumption data more easily.

Apart from smart metering, many DSOs are currently deploying advanced supervision sensors in low voltage feeders [21], improving the detection of technical and commercial abnormalities, and Phasor Measurement Units (PMUs), which improve system control and monitoring [22,23]. However, in general, distribution networks are not sufficiently digitalised yet to cope with the massive integration of DER that is expected.

Digitalisation of power distribution grids is mainly based on three pillars [24]: sensors and actuators, which are necessary to monitor and control the grid; connectivity, related to the ICT implemented for the communications of sensors and actuators with other systems; and data processing, related to the exploitation of the data collected. One could think of them as the *muscles* and *senses*, the *nervous systems*, and the *brain*, respectively.

Together with these, a fourth pillar for the digitalisation of distribution grids is here proposed: the digital culture of the DSO. The development and testing of new digital solutions in the grid, and the adoption of cybersecurity measures in all the DSO's activities, are things that could be facilitated by a DSO that, apart from hiring new digital talents, trains its personnel in digital capabilities, provides them with the appropriate digital tools, and that makes it possible to customers to interact through digital means. DSO's digital culture can become a facilitator or a barrier when implementing most technical solutions.

These pillars of digitalisation show a high level of interdependence, as shown by Fig. 1; a significant development of one pillar usually requires an equivalent development of one of the others, increasing the number of use cases and applications of digitalisation. For example, the deployment of a great number of sensors, on new or existing assets, may require to adapt the communications infrastructure needed to collect the data, and to increase the computing and storage capacity of the servers in charge of processing and analysing such data. Regarding the digital culture, the DSO must ensure that the personnel involved have the adequate tools and training to fully and properly leverage and maintain the new infrastructure.

Table 3
Indicators to evaluate the digitalisation of power distribution grids.

Category	Indicator
A. Sensors and actuators	A1. % of nominal consumption power with smart meters deployed A2. % of primary substations with automation and remote control A3. % of secondary substations with automation and remote control A4. % of remote control devices outside primary and secondary substations per voltage level (MV and LV) A5. % of nominal power corresponding to LV feeders that are monitored online A6. % of transformers that are remotely monitored
B. Connectivity	B1. % of primary substations with broadband communications and % of nominal power that they represent B2. % of secondary substations with broadband communications and % of nominal power that they represent B3. % of DER that establish communications with the distribution network and % of nominal power that they represent
C. Data processing	C1. % of network observable per voltage level (MV and LV) C2. % of information that is available in real-time/semi-real-time C3. % of network assets with digital twins
D. Digital culture	D1. Existence of a digitalisation plan and responsible people D2. % of employees and field workers currently enrolled in internal training courses in digital technologies and cybersecurity. D3. % of field workers with access to documentation through connected devices D4. % of the distribution network documentation that is accessible digitally D5. Availability of a digital platform for consulting and carrying out procedures for users D6. % of network users registered in the metering data app and, with respect to this, % that are active users per month

4. Key indicators of digitalisation

Given the four key pillars of digitalisation in Section 3, the proposed KPIs, which would have to be measured by the DSO, are categorised based on these:

- Sensor and actuator indicators.
- Connectivity indicators.
- Data processing indicators.
- Indicators of digital culture.

Indicators for each group are presented in Table 3 and briefly described and discussed in the following section. In order to offer a fair comparison between DSOs of different sizes, most indicators are expressed as a percentage. It is highlighted that, as the purpose of these indicators is to measure digitalisation, and not directly performance, high percentages would not necessarily mean high performance nor cost effectiveness. Further analysis could study how different levels of digitalisation measured through the proposed digitalisation indicators correlate or explain the improvements on utility's performance measured through performance indicators.

To be effectively interpreted, these digitalisation indicators will need a prior characterisation of the distribution network (type of area, voltage levels...). For example, the requirements and connectivity necessities for a rural electricity network and for a urban one would not be the same, so they cannot be directly compared. It must be also remarked that these terms may have a different meaning depending on the sector (ICT or electricity), DSO, or country. In Europe, a common nomenclature is still needed for the electricity and ICT sectors.

4.1. Sensors and actuators indicators

The indicators in this group aim to measure the digitalisation of the distribution system in terms of the deployment of sensors and actuators. These devices allow a faster, more automated, and more sustainable operation of the network.

4.1.1. % of nominal consumption power with smart meters deployed

The deployment of smart meters allow users to measure their consumption accurately and remotely, and to modify their consumption and contracted power (if applicable) to adapt it to prices and actual use of the network. At the same time, smart meters also protect users against overloads. In addition to this, the DSO can use smart meter data to quickly and easily detect and locate supply interruptions, considerably improving the quality of service. This indicator can be divided into two parts: % of residential power with smart meters, and % of commercial and industrial power with smart meters.

4.1.2. % of primary substations with automation and remote control

The number of operators in charge of a power distribution area is limited and a maintenance crew is not always close to the location of the breakdown. This indicator, together with the following one, measures if, and to what extent, the DSO is able to remotely reconfigure the network and restore the service, by acting automatically or manually on the devices deployed from the control centre.

4.1.3. % of secondary substations with automation and remote control

As mentioned above, this indicator is similar to the previous one.

4.1.4. % of remote control devices outside primary and secondary substations per voltage level (MV and LV)

To operate the network safely, it is necessary to install devices (e.g., switches and voltage control devices) at certain points of the network and not only in the primary and secondary substations. These devices enable the DSO to carry out actions remotely and reduce supply downtime.

4.1.5. % Of nominal power corresponding to LV feeders that are monitored online

The monitoring of LV distribution power lines can be key to improve network operation and reliability.

4.1.6. % of transformers that are remotely monitored

Transformers are critical equipment that are in constant operation that require a high initial investment. Having sensors measuring critical parameters of this equipment, such as oil temperature [25] and vibrations [26], can help to predict and, mainly, to prevent failures before they happen through a proper maintenance. In addition to ensuring the security of the distribution network and the electricity supply, this can also lead to an extension of the useful life of the transformers. This indicator could be distinguished between transformers in primary substations and transformers in secondary substations.

4.2. Connectivity indicators

In order to support the deployment of sensors and actuators in the network, the control centres of DSOs must have the necessary communications infrastructure to securely send control commands and receive monitoring data. The faster and more distributed these communications are, the more secure the electricity supply will be.

Therefore, two of the indicators in this section are related to the presence of broadband connectivity. What is considered broadband depends significantly on the technology used. In general, a broadband connection can be considered when the speed offered is higher than the offered by narrowband technologies such as narrowband power line communications (up to 500 kbps) [27].

4.2.1. % of primary substations with broadband communications and % of nominal power that they represent

Although, currently, it is not necessary to have broadband communications in all the substations and distribution transformers, this is something to consider in the coming years. With a broadband communications infrastructure, the DSOs will be able to manage not only the devices deployed by themselves, but also all the energy management and generation/storage devices installed by users in a near future. Communications closer to real-time between control centres and primary substations and secondary substations (next indicator) will allow the DSO to increase its knowledge about the status of its network and will help to increase the number of possible functionalities and services for user participation and consumption.

4.2.2. % of secondary substations with broadband communications and % of nominal power that they represent

As mentioned above, this indicator is similar to the previous one.

4.2.3. % of DER that establish communications with the distribution network and % of nominal power that they represent

This indicator refers to all the DER that establish communication with it in order to coordinate their actions for the safe and efficient operation of the network. For example, Home Energy Management Systems (HEMS), Battery Management Systems (BMS), communications for Electric Vehicle (EV) charging infrastructure, generators or storage for self-consumption, etc. The existence of this communication provides the users the possibility of having an active role in the electricity system if they wish.

4.3. Data processing indicators

These indicators are related to the processing of the data generated by sensors, which were transmitted using connectivity capabilities, and then translated into specific functionalities.

4.3.1. % of network observable per voltage level (MV and LV)

The electrical distribution system is incredibly extensive geographically, so it is not economically or technically feasible to have every point of the system monitored at every voltage level. Observable means that the DSO is able to know the functioning of the grid by analysing the data collected (voltage, current, power, etc.) By optimising the arrangement of sensors [28] and applying mathematical techniques with the available data, the state of the parts of the grid that are not being directly monitored can be estimated (i.e., power system state estimation) with a reduced margin of error [29].

4.3.2. % of information that is available in real-time/semi-real-time

This indicator measures the real-time and semi-real-time data processing capabilities of the DSO: what percentage of information within a day can be generated in less than 15 min from the moment the input data was collected.

4.3.3. % of network assets with digital twins

The prediction on the behaviour of equipment or part of the network allows optimising the operation and making better decisions. This is currently being done through the so-called "digital twins", which can be understood as highly-detailed models that replicate the functioning of physical systems to analyse, optimise, and manage them [30].

Despite some additional indicators related to the amount of data processed (e.g., volume of information processed versus the volume of information collected during a period; number of uses cases based on advanced analytic) could be added, these have eventually been discarded due to the complexity of accurately and fairly measuring them from a practical point of view. It was opted to give more importance to the applicability and measurement potential of the data processing indicators than their completeness.

4.4. Indicators of digital culture

A highly digitalised distribution network cannot be properly leveraged if the people who interact with it (e.g., for planning, operation, or maintenance activities) do not have the necessary training and resources. Consequently, we foresee the following indicators regarding Digital Culture.

4.4.1. Existence of a digitalisation plan and responsible people

The existence of a plan within the DSO to digitalise the distribution network implies that it has not only studied the weak points and aspects to improve the network, but also that the DSO is aware of the potential functionalities and services that users willing to participate actively could demand.

4.4.2. % of employees and field workers currently enrolled in internal training courses in digital technologies and cybersecurity

A DSO that cares about the continuous training and learning of its employees means that it values its human resources and that knows that they constitute the basis of an efficient and safe operation of the network. This remains essential even though new personnel with digital skills is hired, as new technologies and cyber threats are continuously emerging.

4.4.3. % of field workers with access to documentation through connected devices

If technicians and maintenance crews can access all the information needed through a laptop, tablet, or mobile phone, they will be much more agile and efficient in performing tasks than if they instead have to carry up-to-date papers and notebooks with the technical specifications of devices and equipment. Furthermore, it should also be possible for the field workers not only to access this documentation, but to be able to edit it when finding inconsistencies with respect to reality.

4.4.4. % of the distribution network documentation that is accessible digitally

In relation to the previous indicator, it is important that, apart from the operators deploying connected devices, the information needs to be available in digital format. This could be an indicator difficult to measure in certain cases. Alternatively, it could be estimated by consulting field workers about their use of documentation in digital format in their tasks.

4.4.5. Availability of a digital platform for consulting and carrying out procedures for users

When users have the possibility to interact with the DSOs easily and online, the barriers to their active participation are significantly reduced. It also contributes to improve DSO's customer service and response time to incidents notified by users. This is a binary indicator: if the DSO does not have said platform, it would be 0, and 1 if it is available.

4.4.6. % of network users who are registered in the metering data application and, with respect to this, % that are active users per month

The first step towards an active participation of users in the distribution network is that they show interest in their own electricity consumption.

5. Applicability

The advantages and applications of the proposed indicators are numerous.

First, these indicators do not require a huge amount of input information and complex calculations in contrast with when measuring smart grid performance indicators because they are related to the digital infrastructure of the grid and not its resulting performance. For example, in [12] KPIs' formulas involve calculating different weights for the addends/summands, whereas the digitalisation indicators presented in this paper are mostly percentages, much easier to calculate. Since the remuneration of DSOs is regulated, they carry out the accountability of network investments and maintain an inventory of the assets installed at primary and secondary substations. Indicators such as *"A5. % of nominal power corresponding to LV feeders that are monitored online"* could be extracted by the DSO from already-available information. Other, such as *"A1. % of nominal consumption power with smart meters deployed"* and *"A2. % of primary substations with automation and remote control"* are already measured [15,31]. Therefore, the process of measuring the proposed indicators would not be very time-consuming.

Second, contrary to performance indicators, the measurement of these digitalisation indicators do not seek the maximisation of digitalisation but the optimisation of digitalisation.

Third, the proposed indicators have been categorised according to the pillars of digitalisation of power distribution grids and they are use-case-agnostic. Any smart grid solution would be related to, at least, one of these pillars. As mentioned in Section 3, a significant development in one indicators category (i.e., pillar of digitalisation) would typically require a similar improvement in at least another category. Therefore, to completely leverage these indicators, every category should be analysed considering the others.

Fourth, the proposed indicators were reviewed by three subject-matter experts and practitioners from three Spanish DSOs who provided feedback in their personal capacity and not as DSO representatives. The consulted experts significantly appreciated the necessity for indicators that measure the digitalisation of DSOs. They considered that data availability, in principle, would not be a problem to implement the proposed indicators, and positively valued their feasibility, highlighting the realism of the outcomes that could be expected from these.

And last but not least, the digitalisation indicators proposed in this paper are in line with the recommendations of the DSO Observatory, an initiative supported by the European Joint Research Center (JRC) that monitors how DSOs are evolving to foster the energy transition [15]. The DSO Observatory recommends to follow an European-wide approach to collect DSO technical data, and to reflect, at a policy level, on the adequacy of grid digitalisation versus grid expansion. The proposed indicators would provide more information on the digitalisation characteristics of DSOs that could be measured with different objectives that can be of great interest for both NRAs and DSOs: (A) to get a overview of the distribution system, (B) to determine the relation between performance and digital infrastructure, (C) to obtain more information for the replicability of solutions. These objectives are discussed below.

5.1. Overview of the distribution grid

By measuring the proposed indicators, the current state of the digital infrastructure of the grid could be summarised.

Sensors and actuators indicators provide information about how large the control and monitoring infrastructure on field is. The larger this infrastructure is, the smarter the grid can become. With the increasing deployment of DG, DER, and new energy services, the distribution grid will require a wider range of action and more information to guarantee grid reliability.

Connectivity indicators show the preparedness level of the grid to communicate in a fast and reliable way not only with the already-deployed sensors and actuators, but with new devices that may be installed in the future either by the DSO or third parties.

Data processing indicators provide an idea of how good the DSO processes data and how sensors and actuators' data are leveraged for an efficient and safe operation of the grid. For this category, it is extremely important to consider the two previous categories (pillars of digitalisation) to obtain relevant good insights. If the scores in sensors and indicators and connectivity are acceptable, but the scores for data processing are low (e.g., low observability of the grid), the DSO should improve its capacity to process grid data, so that the sensors and communication infrastructure can be better leveraged.

Digital culture indicators, despite being related to the corporate level of a DSO, show if the digitalisation of the distribution grid is being accompanied with the development of the digital capabilities of the DSO's personnel and customers. High scores in this category would show that both employees and customers may find less difficulties and resistance to change when implementing new smart grid solutions and services.

5.2. Relation between performance and digital infrastructure

The full digitalisation of the distribution grid may not be necessary to keep an appropriate performance and quality of service. In fact, digitalisation increases the cybersecurity risk and, over certain levels, performance may not improve. For example, the reliability of MV grids, regardless of the topology, does not significantly increase for automation degrees higher than 20%–30% [32]. Whether the added value of a specific digitalisation investment is higher than its benefits and cybersecurity risk is something that should be evaluated case by case (cost–benefit analysis).

By measuring the digitalisation of different distribution grids, the relation between grid performance and digitalisation may be observed and leveraged to keep cost-effectiveness, avoiding over-investments. It would also help to know if the areas that are being digitalised are those which require it the most. Large DSOs could carry out comparisons between their distribution zones with different digitalisation levels and energy services, and determine to what extent the digital infrastructure influences grid performance so that new investments can be better planned.

NRAs could also benefit from this. By measuring the proposed indicators in addition to performance indicators for all the DSOs, the NRA may get a clear view of which digitalisation indicators have to be enhanced in order to improve performance. With these insights, NRAs could identify clusters of DSOs with similar digitalisation conditions and provide ad hoc recommendations or even design new regulatory schemes to promote specific investments that prove to have a positive influence on grid performance.

5.3. Information for replicability of solutions

One of the most important parts of a smart grid solution is the assessment of its scalability and replicability potential. The scalability of a solution can be understood as how well it can increase its size, scope, or range [33]. On the other hand, replicability is related to the ability of the solution to be implemented in a different location or time [33].

The functional scalability and replicability analysis (SRA) in smart grid research and demonstration EU projects are usually based on simulations and KPIs assessment for different scenarios [33,34]. However, once the project is finished, future similar implementations may find some difficulties when trying to extrapolate previous insights for a specific distribution grid. The assessment of the proposed indicators could complement the SRA insights and demonstration's KPIs in order to facilitate the replication analysis of the solution in the future. Given similar digitalisation conditions that are relevant for the solution, similar performance outcomes (either good or bad performance) may be expected.

For example, let us consider a demand response (DR) solution demonstrated within a smart grid project. Together with the SRA and the KPIs that show the performance of the solution, the proposed indicators could be measured for the electricity distribution area where it is being implemented. Some indicators may show a strong influence on performance: smart metering (indicator A1) is essential to know how and which consumers are responding to the DR scheme; the existence of fibre optics communications in primary and secondary substations (indicators B1 and B2) may play a key role in the transmission of all the data involved in the solution; and a high share of consumers with energy consumption awareness (indicator D6) could mean that the interest and participation in DR would be higher and, therefore, have a higher impact on the performance of the DR scheme. Specially in DR demonstrations, as the duration of the pilot is limited, consumer's motivation and participation may be high during the pilot and decrease with time. However, if consumers already presented some energy awareness before, it could be used as a basis for the DR scheme.

Although some other factors may have an impact on performance (e.g., regulation), these indicators would contribute to reduce the uncertainty inherent to the implementation of solutions in other areas and, at the same time, generate knowledge to study to what extent the digitalisation of distribution networks is necessary to increase its "smartness". With this knowledge, future implementations of the solution could evaluate, based on the digitalisation indicators of the grids where they were developed, the digital characteristics of the distribution grid area under consideration, analyse what was the performance in those areas, and take action to maximise the probability of success in the new implementation.

6. Conclusion

The existing list of KPIs to evaluate the performance of smart grids covers almost all the aspects that can be expected in a smart grid. However, most of these KPIs do not provide insights on which digitalisation investments and infrastructure have been carried out to deploy smart grids.

So far, existing KPIs have focused on performance and quality of service aspects. However, nowadays, the main approach followed by DSOs to improve their performance indicators is the digitalisation of the grid and its processes. The set of indicators proposed in this paper, which are specifically focused on digitalisation and not on performance, aims to answer the need of measuring the digitalisation level of distribution grids and to become a mean to determine which digital capabilities are driving the performance levels measured.

The proposed indicators are in consonance with the JRC DSO Observatory's recommendations to measure the digitalisation of DSOs and to facilitate the comparison of international experiences and best practises. They are use-case-agnostic, do not require a huge amount of information, and could be leveraged by both NRAs and DSOs to get a complete view of the digitalisation level of distribution grids, to identify cause–effect relations between performance and digital infrastructure, and to foster the replicability of innovative smart grid solutions. Furthermore, three experts from Spanish DSOs qualitatively validated these indicators in terms of clarity, relevance, and data availability.

The extensive use of these indicators among DSOs and NRAs could open new synergies. DSOs would be able to take advantage of other DSOs' experiences when considering different digitalisation alternatives and when estimating the success and replicability of innovative smart grid solutions. At the same time, NRAs would be in a better position to promote or discourage certain digitalisation investments. Nevertheless, these benefits would only be experienced if regulators promote the adoption of the digitalisation indicators proposed and disseminate their results, so that different experiences and learnings can be shared. Such collaboration between stakeholders could improve the pace at which the challenges of the Energy Transition are addressed.

There are still many research and implementation open questions. For instance, it should be quantified the specific relevance of each proposed indicator for each performance indicator considered (e.g., weight assignment); in the same way, this relevance should also be quantified for the different generic smart grid use cases. In addition to this, DSOs would have to be willing to measure the indicators and, to validate the framework, the correlation between clusters of similar DSOs (from the digitalisation perspective) and performance should be analysed. Finally, apart from digitalisation, the development of cybersecurity indicators could be an interesting but complex future work.

CRediT authorship contribution statement

Nestor Rodriguez-Perez: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Javier Matanza:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Gregorio Lopez:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Rafael Cossent:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Jose Pablo Chaves Avila:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Carlos Mateo:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Tomas Gomez San Roman:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Miguel Angel Sanchez Fornie:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization.

Data availability

No data was used for the research described in the article.

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