

Understanding the Impacts of Smart Grid Solutions: A Methodology Proposal to Perform a Scalability and Replicability Analysis (SRA)

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Abstract—Smart grid solutions offer a great potential to improve the operation of the distribution system. Numerous pilot projects have been launched to test smart grid solutions in real-life systems. However, the results observed will be subject to the specific context of the demonstrators. Therefore, conclusions drawn may not be directly applicable to the implementation of the same solutions in different locations or at a larger scale. The objective of this paper is to provide an insight into the scalability and replicability analysis (SRA) of smart grid implementations to understand the effect of the context and infer the impacts that may be expected from smart grid applications. A methodology for SRA of smart grid solutions is proposed with a special focus on a technical analysis based on simulation that allows quantifying the impact of smart grid implementations under different conditions. Additionally, the methodology incorporates the analysis of the economic, regulatory and social aspects to identify drivers and barriers for scaling-up and replication of smart grid implementations. The proposed methodology is illustrated through its application to the case of medium voltage automation for the improvement of continuity of supply.

Index Terms—Power distribution, replicability, scalability, smart grids.

I. INTRODUCTION

IN order to face the upcoming challenges and successfully allow the integration of renewable energies and active demand response, the distribution system needs to become more flexible. The concept of smart grid has become very relevant over the past years, covering a wide range of solutions aimed at achieving the necessary upgrade of the distribution grid [1], [2]. Much work is currently being carried out concerning the analysis of such solutions to determine the potential costs and benefits that can be expected from their implementation [3], [4]. Nevertheless, due to the lack of practical experience, the outcome of actually realizing the

smart grid at a large scale is still uncertain. It becomes necessary to determine the impacts of the different smart grid solutions available on actual networks.

Indeed, numerous demonstrators and pilot projects have been launched across the world to test different smart grid solutions in real-life systems [5] and [6]. These initiatives provide very valuable information on the effects of smart grid solutions on real-life systems [7]. However, the results observed are subject to the specific context where the tests are carried out. Therefore, the conclusions drawn from testing may not be directly applicable to the implementation of the same solutions at a larger scale or in other regions. A thorough analysis must be performed to understand the effect of the context on the results of implementing a smart grid solution. The relevant factors must be identified and the implications of their variation investigated in order to determine how to infer the outcomes that may be expected in different contexts. This is precisely the main goal of the scalability and replicability analysis (SRA) as proposed in this paper.

This type of analysis is particularly relevant considering that substantial investment has already been made in smart grid R&D activities and demonstration projects across the world: up to 2015, over €3.15 billion and \$9.6 billion have been invested in smart grid demonstration projects in the European Union (EU) and in the USA respectively [5], [8]. SRA maximizes the learning potential from these pilot projects, helping translate the results observed in these into clear expectations for the large scale deployment of smart grids. In this regard, the EU has stressed the need for SRA in all research and innovation activities [9] and has launched for the period 2011-2015 research projects GRID4EU, GRID+, iGREENGrid, SUSTAINABLE and SINGULAR¹ based on the demonstration of smart grid solutions with specific focus on scalability and replicability.

The SRA of the impact of smart grid solutions aims to determine the effects of implementing the solution at a larger scale, at a different time or location. SRA can be used to establish the situations where different smart grid solutions can be implemented and the conditions where smart grid functionalities can have a deeper impact on the system. Therefore, SRA results can indicate the most promising functionalities and contexts for future research and testing. Moreover, SRA results can be of assistance in policy-making to remove the identified barriers to smart grid

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¹ http://cordis.europa.eu/fp7/home_en.html

implementations. Furthermore, SRA results help quantify the estimated impact of smart grid solutions and can thus contribute in the quantification of certain benefits of smart grid solutions. Consequently, SRA can be regarded as a valuable input for cost-benefit analyses.

The concepts of scalability and replicability have been applied in other fields of knowledge, such as environmental governance [10] and universal access to energy [11], or with a more technological scope, for issues such as sensors, information and communications technologies (ICTs) [12] and air transportation [13]. However, the application of these concepts within the electric power sector is still incipient. In the context of the smart grid, so far scalability has only been addressed from the perspective of the involved technologies. In order to enable the large-scale deployment of the smart grid, smart grid solutions must be able to cope with an increasing volume of information and rising number of interacting agents. Therefore, scalability of these solutions is analyzed in terms of capability of smart grid information technologies, algorithms, communications and systems to exchange, analyze and store large volumes of data and perform large-scale computations [14]. For instance, the work presented in [15] and [16] aims to overcome the problem of existing demand response approaches, that are very intensive in computation and cannot cope with large numbers of electric vehicles (EVs) and consumers respectively. The authors of [15] propose a method to design EV charging strategies based on aggregation processes. Meanwhile, the authors of [16] propose the use of a Lagrange relaxation approach for mixed-integer programming for the formulation of demand response algorithms. Yet another example related to the architecture of communication networks may be found in [17], where the authors propose a meshed communication network based on concentrators and smart meters with a self-organizing mechanism so that automatic meter reading can be scaled up to include new smart meters when the system is already implemented. Within the GRID+ project the prerequisites for smart grid solutions to be scalable and replicable have been studied. The authors of [18] list technological characteristics of the developed solutions, such as modularity or interoperability, and aspects of the implementation context including for instance profitability or regulatory consent. These factors have been assessed for different demonstration projects through the use of questionnaires addressed at the participants of the projects and other stakeholders.

It can be concluded that the literature has dealt with the scalability of specific technological solutions themselves, but not with the scalability and replicability of the outcomes expected. For example, communication technologies must be analyzed to assess how smart metering is enabled, but it is the interest of this article to evaluate whether different types of consumers with smart meters would react to price signals, whether demand shifting would reduce losses at different voltage levels, whether network constraints would be avoided in different types of networks, or whether regulation would be able to promote active participation of consumers.

Scaling-up and replication are implicitly performed whenever the impact of any situation, solution, technology, policy, etc. on a system is assessed, since conclusions are drawn from experimental data by extrapolating and

performing sensitivity analysis considering certain assumptions and hypothesis. For instance, the IPCC analyzed in [19] the environmental, economic and social impacts of different renewable energy source (RES) technologies. A wide range of scenarios were considered to assess the effect of aspects such as the different energy sources displaced by RES or diverse climate change scenarios. Furthermore, several environmental policies and targets were also analyzed. A different example may be found in [3], where the benefits of smart grids are quantified based on a linear scaling-up of the impacts of smart grid solutions, assuming that results are directly applicable for all distribution grids across the US, which means that different conditions and contexts have not been considered. However, scaling-up and replication have not been yet addressed and performed in an explicit and systematic manner in the context of the smart grid. There is therefore a lack of a common framework to perform SRA for smart grid demonstration projects.

The objective of this paper is to give an insight into the concepts of scalability and replicability and to propose a methodology for the SRA of smart grid implementations tested in demonstration projects, with a specific focus on the technical analysis.

The paper is structured as follows: after this introduction, section II presents the main concepts within the framework of SRA. Afterwards, section III describes the proposed methodology for SRA in detail, and the methodology for the technical analysis within SRA is further developed in section IV. Then, section V illustrates the application of the methodology proposed for technical SRA to the automation in the MV network for the improvement of continuity of supply. Finally, section VI concludes with the final remarks.

II. IMPORTANT CONCEPTS RELATED TO SCALABILITY AND REPLICABILITY

The scalability of a system may be defined as its ability to increase in size, scope or range. On the other hand, the replicability of a system refers to the ability to be duplicated in another location or time. Then, the scalability and replicability analysis (SRA) of a smart grid solution aims to determine the effect that may be expected from the implementation of the solution at a larger scale, in a different time and location.

The SRA of smart grid solutions presented in this paper is focused mainly on the technical, economic, social and regulatory aspects of the implementation of the smart grid. Under this approach, the objective of the SRA is to assess the effect of the context on the results from implementing smart grid solutions, rather than the technological scalability and replicability of the solutions themselves or how to implement them. Thus, the SRA will be more general and open, since conclusions drawn from the SRA of a certain smart grid implementation will be applicable to other smart grid implementations with similar functionalities and objectives but different technologies in place. This feature is particularly interesting given that the technological solutions implemented may be experimental or conditioned by external factors (historical reasons, industrial partnership, etc.). Technological aspects and related issues, such as modularization, standardization and interoperability of smart grid solutions are

out of scope of the proposed SRA. The SRA of smart grid solutions aims to extract general conclusions beyond the scope of the demonstration projects. The Smart Grid Architecture Model (SGAM) [20] includes different interoperability layers to represent the different entities and their relationships in the context of smart grid domains. The proposed SRA focuses on the functional layer, to analyze the impact of implementing smart grid functionalities in the domain of the distribution system. It also includes the business layer to examine the effect of the regulatory framework, economic aspects and the perspectives of the different stakeholders involved. All of these aspects are interconnected, and the SRA aims to study the relationship among all the parameters.

In the context of smart grid pilot projects and demonstrators, the terms ‘use case’, ‘KPIs’ and ‘boundary conditions’ are frequently-used and must be clarified for a correct understanding. Smart grid demonstration projects consist on the implementation of smart grid solutions organized into use cases. In line with the UML² definition, a use case represents a set of functional requirements that must be performed by the smart grid solution in pursue of different objectives. For instance, automation systems may increase monitoring of the grid and improve fault management in the distribution network so that continuity of supply is improved for network users - this implementation could be regarded as the use case of MV automation for reliability improvement.

The impacts observed in the demonstrator are quantified by means of different metrics called Key Performance Indicators (KPIs). The KPIs selected for each use case must be able to assess to what extent the objectives of the use case have been fulfilled by implementing the smart grid solution. Usually, a reference value is defined for a KPI so that the success of the smart grid solution can be measured. In the previous example, appropriate KPIs could include improvement of reliability indices such as SAIDI and SAIFI [21].

The impact of any smart grid implementation on the system, represented by the values registered for the corresponding KPIs, is subject to the technical specificities, the regulatory framework and the environmental and social context of the system itself and the location and time where the implementation is carried out. These aspects are comprised within the so called boundary conditions of the implementation. Taking the previous example, relevant technical boundary conditions include for instance network topology and how meshed the networks are, which may vary for different locations, areas of different load density, networks designed and built by different distribution companies, etc. Regarding regulatory boundary conditions, incentives for continuity of supply, which may vary across countries, for instance, will have a direct impact on the motivation of distribution companies to implement the use case of MV automation for reliability improvement. Relevant stakeholders may include for instance operators in the control centers of the DSOs who will have to process new data and potentially supervise autonomous systems. Depending on the existing control systems and operation protocols, centralized supervision could for instance hinder local automation.

Increasing the scale of the implementation, or implementing the smart grid solution to fulfill the same functionalities at a different location involves changes in the boundary conditions. The new implementation with its particular set of boundary conditions may result in different technical, economic and social impacts on the distribution system. Therefore, the SRA will necessarily be strongly linked to the exhaustive analysis of the parameters that constitute the boundary conditions. As a result, the scaling-up and replication rules are determined and the domain validity of these conclusions is defined, which is the range or spread around the boundary conditions that ensures the applicability of the scaling-up and replication of the results.

Furthermore, scalability and replicability have different dimensions that can be considered for SRA. Scalability may be regarded from these two different perspectives:

- **Scalability in density:** the implementation of the use case is considered in the same location of the demonstrator, but the scope of the use case is widened in terms of variation of parameters such as the number of consumers involved, the volume of participating distributed energy resources (DER) or the penetration degree of the smart grid solution.
- **Scalability in size:** the implementation of the use case is assessed for a larger area. For instance, at a regional level, boundary conditions related to regulation and stakeholders will be the same or very similar, but widening the scope may involve different types of distribution networks, sub-areas of different load density, etc.

In relation to the scope of replication, two different dimensions may also be identified:

- **Intranational replicability:** the implementation of the use case is analyzed for different distribution areas in the country of the demonstrator. Similar boundary conditions may be expected regarding regulation, perspectives of stakeholders, or technical aspects such as voltage levels. However, different locations may involve different network architecture, different reliability levels, etc.
- **International replicability:** the implementation of the use case is analyzed for areas in different countries. The boundary conditions may differ widely, including for instance different regulation schemes, network characteristics, economic conditions or perspectives from stakeholders.

III. GENERAL SRA METHODOLOGY

The objective of the SRA of a smart grid solution is to assess the impact of the use case and to provide the guidelines to infer the results that may be expected from the implementation of the smart grid use case in a different context, either at a larger scale or in a different location. The approach proposed in this paper for SRA is strongly linked to the boundary conditions, to identify the key parameters that may have an impact on the results achieved with the smart grid solutions. The methodology developed for the SRA of a smart grid use case is presented in Fig. 1.

The work stream of SRA comprises two main stages: a first step of quantitative and detailed **technical analysis** (1); and a second stage of **general analysis**, more qualitative, to include a wider range of dimensions such as economic, social and

² Unified Modeling Language, <http://www.uml.org/>

regulatory aspects (2). Both steps aim to determine the effect of changes in the boundary conditions for the elaboration of the **scaling-up and replication rules** (3).

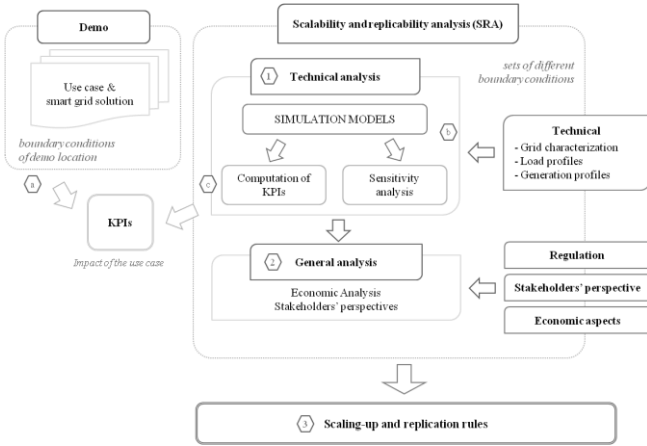


Fig. 1. Methodology for SRA of a smart grid use case.

1. Technical analysis

First, the use case is subject to a technical analysis to compute the values of the KPIs that would correspond to different boundary conditions. For this purpose, simulation tools are used to assess performance of the smart grid solution. The behaviour of the system will be described both before and after the implementation of the smart grid use case in terms of the corresponding KPIs. The simulation tool will require technical input data including the necessary information to characterize the distribution network and the network users, including consumers, DG units and any other DER connected to the grid. Depending on the use case and the pursued objectives, the simulation tool will have to compute different KPIs. Furthermore, different boundary conditions will be relevant and will have an effect on the impact of the resulting KPIs for different types of use cases. For instance, in the case of MV automation for reliability improvement, network topology, fault rates and protection elements in the network will be key parameters to assess the process of fault management. By contrast, in the case of voltage control through DER management, the protection elements will not be important, but instead generation and load profiles will be key parameters, and load flow analysis will have to be performed.

- Initially, the use case is modelled for the boundary conditions of the demonstrator and the values of the KPIs are computed. The values obtained with the simulation tool will be compared to those registered in the actual implementation of the demonstrator to ensure consistency and coherence of the results of the technical SRA.
- Variations of these boundary conditions are translated into changes in the values used for the technical parameters of the model. Thus, in order to quantify the effect of the boundary conditions on the impact of the implementation of the smart grid solutions, sensitivity analyses will be performed for the KPIs to the technical parameters.

- The new values of the KPIs will be computed for a range of different values of the technical parameters to represent different contexts. For example, the values of the KPIs will be computed increasing the length of the modeled distribution network to represent the impact of implementing the solution in an area where consumers are more dispersed.

2. General analysis

Once the effect of the relevant technical parameters has been assessed and quantified, the scope of the analysis will be widened to include economic and regulatory aspects, as well as the perspectives of the different stakeholders involved in the smart grid. These interconnected aspects will be studied to understand their effect on the outcome of the implementation of the smart grid use case. The objective is to identify barriers, facilitators and drivers for its large-scale implementation. Coming back to the example of automation for reliability improvement, regulation concerning continuity of supply and investments will be essential for distribution companies.

3. Scaling-up and replication rules

Finally, the results obtained throughout the two-step analysis are gathered to draw conclusions on the most important aspects that must be considered for SRA, scaling-up factors, validity domain for replication, drivers and barriers that may be encountered for scaling-up, under what circumstances a smart grid implementation may be more advisable, etc. These conclusions are put into the form of general premises to formulate the so-called scaling-up and replication rules. Considering the example of automation, scaling-up and replication rules may describe that the trend of the improvement of continuity of supply achieved by increasing levels of implementation of automation has a saturation effect, so that for different circumstances it may be advisable to implement this solution up to a certain degree. Section V presents the application of the SRA methodology hereby proposed to the use case of MV automation for reliability improvement.

IV. TECHNICAL SRA METHODOLOGY

The technical analysis is essential for the SRA and provides the quantitative basis for the resulting scaling-up and replication rules. Therefore, the methodology to perform the technical SRA deserves further attention. The range of objectives aimed at by different smart grid use cases is very wide. Consequently, the impacts and corresponding KPIs may differ significantly among use cases. Likewise, the simulation tools used for the technical SRA will have to be adapted for the quantification of the appropriate KPIs and sensitivity analyses may focus on different sets of input data. Notwithstanding, the methodology presented in this paper can be applied in principle to any smart grid use case, provided that adaptations are made.

The distribution system will be modeled through representative networks. Distribution networks in each country may be classified into a reduced number of categories, according to the type of areas and consumers served (typical categories include industrial, urban, sub-urban and rural

networks). Each of these categories may be represented by a representative network, consisting in a few feeders with the same grid architecture as actual networks and the same network characteristics, given by a range of values for the technical parameters of real networks (e.g.: feeder length, amount and rated power of MV/LV substations, undergrounding ratio, etc.). The use of representative or reference grids has been common in the field of regulation, serving for instance as a benchmarking tool for regulation of distribution investments for quality of service [22] or to estimate overall distribution costs in Brazil [23], and in research to characterize the Italian distribution system [24] for simulation or to assess the impact of DG integration on distribution planning, expansion and operation [25].

Similarly, different generation and demand scenarios will be defined to represent the range of potential conditions of distribution systems. For this purpose, network users of the different representative networks will be characterized, considering characteristics such as for instance density of demand, types of consumers, or size and technology of DG units and other DER. Publicly available statistics and aggregated data published by some National Regulatory Authorities, state-owned agencies for the promotion of renewable energy or Transmission System Operators can be used to build standard generation and demand profiles, such as for instance the Photovoltaic Geographical Information System (PVGIS) developed by the Joint Research Centre [26], the interactive maps for photovoltaic and wind generation in Italy, Atlasole³ and Atlavento⁴ by the Italian agency GSE or the statistics provided by the Spanish TSO [27]. This kind of reference scenarios has also been used in research [28].

Once the distribution network and its users have been adequately characterized, the steps described below have been defined. Note that the process for technical SRA has been designed according to the different dimensions of scalability and replicability described in section II.

1. Selection of simulation tool and relevant KPIs

The objectives pursued by different smart grid use cases vary and these will determine the type of impacts to study for SRA. Simulation tools and KPIs must be selected accordingly, so that all relevant aspects of the system are integrated and the performance of the smart grid solution is emulated. The impact of implementing the use case must be quantified through adequate KPIs, so that situations with different boundary conditions can be compared.

For instance, automation aims to improve continuity of supply, so the impact of implementing such solution is mainly observed on the reach of faults in the network and the process of service restoration. Solutions involving DER management for voltage control pursue efficiency improvements and will affect voltage profiles, demand and generation peaks and energy losses. In the first case, reliability analysis will be needed to assess the outcomes of the use case, while in the second case, simulation would have to focus on loadflow analyses.

The timeframe of simulations must also be adapted to the nature of the smart grid use case, ranging from

milliseconds to analyze the dynamic behaviour of the system for instance when analyzing islanding, up to hours to evaluate the process of service restoration for automation use cases, or days to schedule the charge and discharge of storage according to demand and generation forecasts.

2. KPI computation of demo conditions

As previously mentioned, the use case is modelled under the boundary conditions of the demo. A representative network will be built with the characteristics of the actual grid where the solution is tested, and generation and demand scenarios will be representative of load and feed-in patterns corresponding to the location of the demonstrator. The technical analysis of such model will provide the baseline of the parameters required for the computation of the KPIs of the demo. Then, the implemented smart grid solution will be modelled too so that the new values of the corresponding parameters are obtained. The KPIs will be computed according to their definition, comparing the baseline values to the values obtained when the use case is considered.

3. Scalability in density

In order to analyze scalability in terms of density, the parameters that will be subject to variation at this stage will be related to the volumes of demand, DER and smart grid solutions, depending on the use case. For instance, these parameters will include the number of consumers involved, the degree of engagement of the consumers and volume of shiftable or sheddable load for demand response use cases. Meanwhile, in other use cases the penetration degree of the smart grid solution itself will be assessed, such as the degree of automation, the number of telecontrolled switches or the number of monitored elements in the grid for automation use cases.

4. Intra-national replication

In a subsequent step, the characteristics of the network and generation and demand scenarios will be modified to consider replication within the country of the demonstrator. The objective is to analyze the different situations that are representative of the country, considering the typical types of network that correspond to different types of distribution areas (e.g.: urban, sub-urban, industrial and rural areas). For this purpose, a set of representative networks is developed for the country. Simulation is carried out to compute the values of the KPIs in the different areas. The parameters that will experiment variations may include network characteristics such as architecture, feeder length and types of conductors, reliability levels and the characteristics of consumers, DG and other DER owners, such as their size and type of technology.

5. International replication

International replication is carried out by defining representative networks and generation and demand scenarios for the new country or region, which should account for its specific boundary conditions reflected by different technical parameters, such as standard voltage levels or DG technologies installed. Then, the same simulation tools would be used to compute the new values of the KPIs, and sensitivity analyses would be performed

³ <http://atlasole.gse.it/atlasole/>

⁴ <http://atlaimpianti.gse.it/atlavento/>

to assess the range of technical boundary conditions that correspond to the new country or region, for those parameters where the new country differs from previously analyzed countries.

6. Scaling-up in size

Scaling-up a use case in size means considering a larger area, which implicitly involves replication, as the technical parameters may vary across the region considered. Therefore, scalability is addressed determining scaling-up factors for the results expected in each type of representative network for a given country or region. No further simulation is needed at this step, but rather a good characterization of the area in terms of the share of the distribution system that can be represented by each representative network. This way, the results obtained from simulation for replicability using the representative networks may be weighted.

V. CASE STUDY: AUTOMATING SECONDARY SUBSTATIONS TO IMPROVE CONTINUITY OF SUPPLY

In order to illustrate the proposed SRA methodology, this section presents its application to the use case of MV network automation to improve continuity of supply. Due to space restrictions, a simplified case study is presented, while a more thorough SRA will be developed in future work.

This case study is based on a hypothetical demonstrator project to test MV automation in an urban network. MV automation consists in equipping secondary (MV/LV) substations with fault detectors and remotely controlled switches, thus allowing automatic grid reconfiguration to reduce both the size of the areas affected by sustained MV faults and the number of manual operation actions required to detect the fault, isolate the faulty section and restore electricity supply [29]. Consequently, the impact of this use case must be assessed in terms of improvement of reliability indices.

A. First stage: technical SRA

As previously stated, the technical SRA is the core of the proposed approach and provides the basis to infer the scaling-up and replication rules. The diagram in Fig. 2 summarizes the process of technical SRA for MV automation, with the corresponding inputs, simulations and main outcome, the KPIs, as will be explained throughout this sub-section. Sensitivity analysis will be performed for the parameters listed in the striped box for scalability and those in checked boxes for replication.

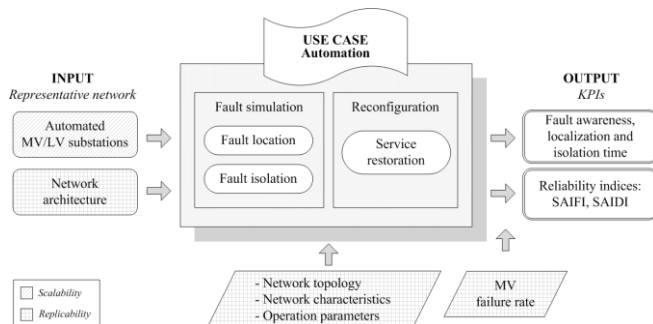


Fig. 2. Technical SRA for the use case of MV automation to improve continuity of supply.

1. Selection of simulation tool and relevant KPIs

Reliability improvement will be assessed using reliability indices SAIFI and SAIDI, evaluating the reduction of these indices per automated secondary substation with respect to the baseline values where there is no automation, i.e. number of interruptions reduced per automated secondary substation (Δ SAIFI) and minutes of interruption reduced per automated secondary substation, respectively (Δ SAIDI).

For technical SRA, reliability analyses must be carried out. The simulation tool must simulate all possible faults in the MV line, i.e., the failure of all elements of the MV line, to identify the affected consumers and the duration of the supply interruptions for each of them caused by each fault. For each fault, the steps of the actual process of fault detection, isolation, reconfiguration and service restoration are considered to compute the time needed to restore service for each consumer. For this purpose, the aspects considered include the distances to travel, the areas to inspect and the operation of elements at each step of the process, according to the formulas in TABLE II. SAIFI and SAIDI are then obtained by weighting the number and duration of supply interruptions with corresponding consumers; and the different simulated faults with the failure rate of the corresponding elements. Simulation has been carried out using MATLAB for the present case study.

Two representative networks have been built for this case study, consisting of a MV feeder for an urban area and a rural area, respectively. The diagrams of these two networks are shown in Fig. 3 and Fig. 4, while their main technical parameters are summarized in TABLE I. The urban MV feeder is part of a meshed network. This feeder is connected at its end to the end of another MV feeder through a normally-open switch, so that there is an alternative path for supply in case of need. Furthermore, secondary substations (MV/LV) are connected to the grid in a so called input-output or lead-through configuration, i.e., in series to the grid, through manually operated protection elements at both sides. The rural network has a more radial structure, with ramifications and no connection to other feeders for reconfiguration. Secondary substations are connected to the MV network in an antenna configuration through manually operated load switches.

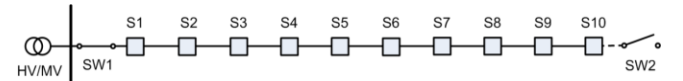


Fig. 3. Urban representative network. HV/MV: primary substation; S1-S10: secondary substations; SW1: normally-closed switch; SW2: normally-open switch for reconfiguration.

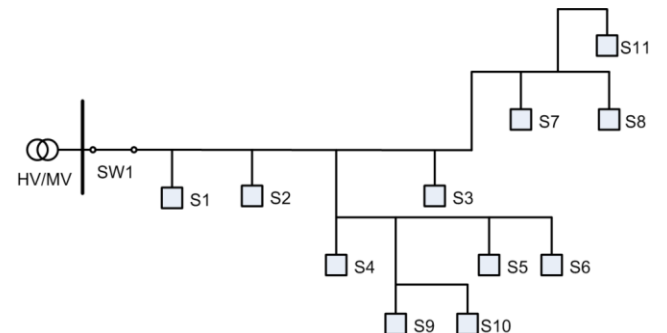


Fig. 4. Rural representative network. HV/MV: primary substation; S1-S11: secondary substations; SW1: normally-closed switch.

TABLE I
TECHNICAL PARAMETERS OF THE REPRESENTATIVE NETWORKS

	Urban network	Rural network
Installed capacity	10 x 630kVA	11 x 150kVA
Feeder length	11km	45km
Number of consumers	1500cons	220cons
Fault rate	0.1 fault/km·year	0.125 fault/km·year

TABLE II
REQUIRED TIME FOR SERVICE RESTORATION IN MV FEEDERS

	Urban network	Rural network
Restoration time [30]	- <i>Fault location, isolation and service restoration:</i> t = 5min+ $\Sigma \text{step}_i (10\text{min} + \text{dist. to switch} \times 60\text{km/h})$	- <i>Fault location:</i> t = 5min + dist. to starting point x 80km/h + dist. to fault x 50km/h - <i>Reparation:</i> t = 60min - <i>Service restoration:</i> t = 5min + 5min/switch + dist. to switch x 80km/h

2. KPI computation of demo conditions

The considered demonstrator consists in the automation of MV/LV substation S5. At this step, this demonstrator is assessed through simulation. The simulation tool selected in the previous step is applied to the urban representative network to obtain the value of reduction of SAIFI and SAIDI achieved by automation. The obtained results can be found in the first row of Table II.

3. Scalability in density

Scalability in terms of density is addressed considering the variation of the automation degree, that is, the share of secondary substations that feature automation. Thus, four scenarios are defined with different degrees of automation: (i) demo conditions, where MV/LV substation S5 is automated, which corresponds to a share of 10% of the MV/LV substations; (ii) S4 and S7 are automated, corresponding to an automation degree of 20%; (iii) S2, S4, S6, S8 and S10 are automated, so that automation degree is 50%; and (iv) where all MV/LV substations are automated, i.e., 100% automation degree.

TABLE II
RESULTING KPIs FOR THE USE CASE OF MV AUTOMATION IN THE URBAN REPRESENTATIVE NETWORK FOR DIFFERENT DEGREES OF AUTOMATION

Automation degree	ΔSAIFI (min/SS)	ΔSAIDI (min/SS)
10%	0.60	21.20
20%	0.40	14.10
50%	0.20	6.83
100%	0.11	3.69

4&5. Intra-national and international replication

In this case study, intra-national and international replicability have been merged in a single section as a simplification. The process of simulations is very similar in both cases, so they can be illustrated together. Nevertheless, in a comprehensive SRA, these two stages should be considered as subsequent steps.

Replicability is addressed through sensitivity analysis for the technical parameters that have an impact on the results achieved by automation. Relevant technical parameters for this use case are those related to the type of network and reliability levels, including grid architecture (how meshed the networks are, configuration of the connection of secondary substations to the MV line), protection elements that allow for switching and reconfiguration (amount, location, accessibility and repairing time, etc.), and distribution of the consumers (number of consumers in each substation and feeder, installed capacity of substations). Moreover, sensitivity to failure rates of MV feeders is studied. This parameter can account for effects such as ageing of the network (typically, older networks will suffer from higher failure rates), or external conditions (typically, poorer reliability levels may be expected under very extreme weather conditions or in areas with street works in progress).

In order to assess replicability at an intra-national level, simulations are carried out for the corresponding set of representative networks developed for the country. Replicability at international level would be addressed in the same manner, using the corresponding set of representative networks for the analyzed country and the range of values of the technical parameters to account for its technical boundary conditions. In some cases, these variations of the regulatory, economic and social context in each country will translate into the variation of specific technical parameters. For instance, regulation with strong incentives for continuity of supply improvement may result in more meshed network topologies.

As already stated, intra-national and international replicability are both illustrated in one single section for this simplified case study to illustrate sensitivity analyses through a reduced set of examples. In this case study, simulation has been performed for different values of network length. Failure rates have been assumed to be proportional to length of conductors, so that faults in the MV network will occur more often for longer feeders. The results show that the reduction of reliability indices is higher for longer networks, and the effect is deeper for SAIDI reduction, as can be seen in Fig. 5. The effect of automation in reducing the number of affected consumers increases in proportion to the length increase. Additionally, the process for fault management will be more time-consuming for longer networks, since distances to cover will be longer, so the reduction of minutes of interruption will also be higher given a certain degree of implementation of MV automation.

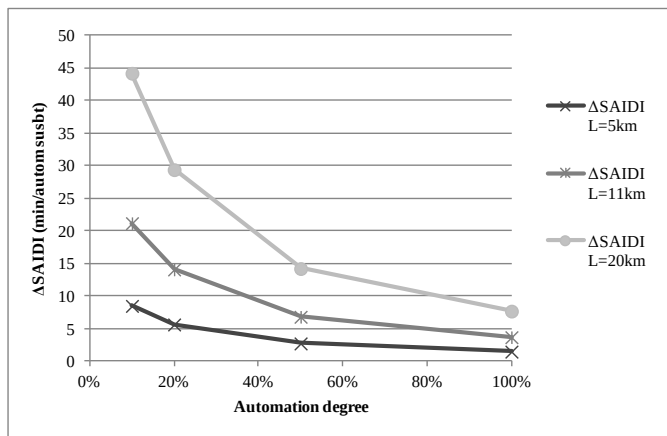


Fig. 5. SAIDI reduction per automated substation for the urban representative networks for different values of network length.

Then, simulations have been carried out for the rural reference network for three scenarios: i) MV/LV substations S2, S4 and S7 are automated, corresponding to an automation degree of 27%, ii) S1, S2, S3, S4, S7, S9 are automated, so that the automation degree is 55%, and iii) all MV/LV substations are automated, automation degree of 100%. The resulting KPIs are presented in TABLE III. In rural areas where no reconfiguration of the grid can provide an alternative path for supply when a non-faulty section of the grid is isolated, the number of interruptions cannot be reduced by automation. The implementation of this use case has only a mild impact on the reduction of duration of interruptions, since protections may be operated remotely during the process of reclosing for service restoration but only once the faulty section has been located, isolated and repaired.

TABLE III
RESULTING KPIs FOR THE USE CASE OF MV AUTOMATION IN THE RURAL REPRESENTATIVE NETWORK FOR DIFFERENT DEGREES OF AUTOMATION

Automation degree	ΔSAIFI (min/SS)	ΔSAIDI (min/SS)
27%	0	2.83
55%	0	3.24
100%	0	2.24

6. Scaling-up in size

The results obtained for the representative networks can be scaled-up considering the weight of each of the representative networks for the considered area. The importance of a good characterization of the distribution system of the considered area and the adequacy of the selected representative networks is crucial at this step.

In some European countries, distribution regulation actually establishes categories to classify the networks based on population density and use of electricity to set standards and requirements for continuity of supply [31] and in some cases, information regarding the characterization of the distribution grid is made available in national statistics and reports. For instance, in the case of Spain, there are four types of zones [32] and the Spanish Ministry of Industry, Energy and Tourism periodically publishes installed capacity, number of consumers and reliability indices per zone for all provinces. The aggregated data for the country is presented in TABLE IV and it shows that urban areas have a much higher amount of

consumers and installed capacity. Almost 50% of the total installed capacity corresponds to urban networks, while rural areas only account for around 15%. Using a set of representative networks containing based on the four zone types, the results obtained from simulation can be weighted and thus scaled-up for the country.

For the present case study and using the data for Spain, a deep impact could be expected from the implementation of MV automation, since urban areas have a high relative importance.

TABLE IV
DISTRIBUTION ZONE TYPES FOR REGULATION OF CONTINUITY OF SUPPLY IN SPAIN (2011)⁵

Automation degree	Urban	Sub-urban	Concentrated Rural	Scattered Rural
Definition	>20,000 & principal towns	2,000 – 20,000	200 – 2,000	<200
Installed capacity (MVA)	73,063	54,976	16,832	7,159
Number of consumers	15,242,473	9,424,968	3,298,946	631,006

B. Second stage: general analysis

At this second stage economic and regulatory aspects are integrated into the SRA. Furthermore, the viewpoints of relevant stakeholders are also studied to determine potential drivers and barriers to the implementation of MV automation.

Regulation of the distribution business must send economic signals for an adequate level of continuity of supply. The most common regulatory approach in Europe is the so called incentive based regulation, with different bonus/penalty mechanisms linked to performance of DSOs regarding certain targets for reliability indices [33]. These mechanisms are designed to ideally drive DSO investment towards the optimal level of quality. Therefore, different regulatory schemes may act as a barrier or enabler for the implementation of MV automation. Distribution companies are incentivized to improve continuity of supply until the point where the improvement of continuity of supply is such that the marginal cost of smart MV/LV substations equals the marginal incentive received [34], [35].

Yet another important aspect to consider is that the use of different reliability indices may lead to slightly different conclusions, which in turn could result in different economic incentives for improvement of continuity of supply for distribution companies. Indices based on the number of consumers place an equal weight on all consumers independent of their size and consumption, while indices based on load place a higher importance on consumers with larger demand. As an example, two cases are compared for the rural network: the previous case with homogeneous demand (20 consumers in each 150kVA substation S1-S11) and a case with a larger consumer located in an area of poorer reliability (20 consumers in each 150kVA substation in S1-S10 and one consumer in 150kVA substation S11, located at the furthest ramification where consequently supply interruptions are more

⁵ <https://oficinavirtual.mityc.es/eee/indiceCalidad/total.aspx>

frequent and service is restored later). The KPIs obtained as improvement of SAIDI and SAIFI have been compared to the improvement of indices based on installed capacity ASIDI and ASIFI [21]. In the case of homogeneous consumers, both sets of indices yield the same results. However, if S11 feeds only one consumer, SAIDI and SAIFI values are lower because the proportion of consumers in S11, where reliability is poorer, is lower as compared to the previous case. By contrast, ASIFI and ASIDI values remain the same because the installed capacity has not been changed. Consequently, in this case, the improvement in continuity of supply observed in respect to SAIDI is slightly weaker than that measured in terms of ASIDI, as can be seen in the results presented in TABLE V.

TABLE V
RELIABILITY INDICES AND RESULTING KPIs FOR MV AUTOMATION IN THE
RURAL NETWORK WITH A NON-HOMOGENEOUS DEMAND

Automation degree	SAIDI (min)	Δ SAIDI (min/SS)	ASIDI (min)	Δ ASIDI (min/SS)
0%	192.91		195.81	
27%	184.68	2.75	187.32	2.83
55%	173.70	3.20	176.35	3.24
100%	168.65	2.21	171.16	2.24

Stakeholder acceptance is a key issue for the successful implementation of smart grid use cases, especially for those stakeholders whose active participation is required. In the case of MV automation, the most relevant stakeholder is the DSO, and more specifically grid operators in control centers. Operators in distribution control centers supervise available information to control the state of the system and make operation decisions. Automation systems usually involve a higher degree of monitoring, so that the volume of information available to process is much higher. Operators may fear losing control of the system, or even may feel that their job is at risk. Furthermore internal rules may impede the implementation of local or autonomous systems so that operators must supervise and validate operations proposed by the automated system. Such restrictions could harm the potential for fast restoring of the service. It can be expected that the adoption of MV automation can be easier for DSOs with already higher automation degrees.

C. Resulting SRA rules

This case study briefly illustrates the steps of the proposed SRA methodology. Only some preliminary results have been obtained. Naturally, a comprehensive SRA would lead to more categorical and verified conclusions. However, these results already show some interesting trends that can be summarized in the following SRA rules:

- Greater impact on continuity of supply in meshed networks
In radial networks with no interconnections among different feeders, the time required for fault detection can be improved, but there is no possibility to recover non-faulty segments of the network. In meshed networks, typically used for urban areas, both the number of interruptions and their duration may be reduced. Therefore, implementation of automation should focus on urban areas.

For more rural areas, reinforcement of the network should be considered to provide redundancy to the network through interconnections, prior to automation.

- Effect of increasing automation is non-linear; there is a saturation effect
At first, implementing a mild degree of automation achieves a drastic improvement of continuity of supply. Increasing MV automation to a higher degree, by contrast, further improves continuity of supply, but at a much lower degree. Therefore, large-scale adoption of MV automation should be carefully planned to achieve the optimal level of automation.
- Greater impact on networks with poorer reliability
Given a certain network topology, poorer levels of reliability due to higher fault rates or higher feeder lengths leave a greater margin for improvement, so the implementation of automated substations will be more beneficial.
- Deeper SAIDI reduction for longer networks
Since failure rates are assumed to be proportional to length of conductors, faults in the MV network will occur more often, and thus the effect of automation in reducing the number of affected consumers will increase in proportion. Additionally, the process for fault management will be more time-consuming for longer networks, since distances to cover will be longer, so the reduction of minutes of interruption will also be higher given a certain degree of implementation of MV automation.
- Regulation plays an important role in the uptake of MV automation by DSOs
Regulatory reliability requirements and the scheme and volume of regulatory incentives for improvement of continuity of supply and innovation in different countries will drive DSOs towards different investment strategies. Furthermore, the use of indices based on consumers for monitoring continuity of supply may lead to the prioritization of residential areas with numerous domestic consumers. By contrast, the use of indices based on load may incentivize giving precedence to more commercial areas with larger consumers in the implementation of smart grid solutions for reliability improvement.
- The engagement of operators needed for success
Distribution operators will work with a new solution. Proper information and training can help increase their levels of acceptance.

VI. CONCLUSIONS

Implementing smart grid solutions can have very positive effects on the system, but the outcomes that may be expected in actual distribution grids will be conditioned by the technical, economic, regulatory and social boundary conditions of the implementation. Pilot projects across the world are testing different smart grid solutions in real-life systems. However, the results observed may not be directly applicable to the implementation of the same solutions at a larger scale or in other regions.

This paper raises the subject of scaling-up and replication of the impacts of smart grid solution to bridge the existing gap between demonstration projects and widespread adoption of

the smart grid. A methodology for scalability and replicability analysis (SRA) of smart grid use cases has been developed. The SRA aims to provide a set of scaling-up and replication rules, qualitative premises to help infer what results may be expected when implementing the smart grid use case at a larger scale or in different locations.

The proposed methodology is based on simulation to perform technical sensitivity analyses to identify the relevant parameters within the boundary conditions and determine their effect on the impacts of the smart grid use case, quantified by the corresponding Key Performance Indicators (KPIs). Moreover, the proposed SRA analyzes the effect of economic, regulatory and stakeholder-related aspects.

The proposed methodology can be applied for SRA of any smart grid use case. In this paper, the application of the methodology has been illustrated for the case of MV automation for reliability improvement. From this simplified analysis it can be concluded that automation should be prioritized for meshed networks, more frequent in urban areas, up to a certain optimal degree of automation. Regulation for continuity of supply will play a key role to encourage or discourage the adoption of automation in distribution networks.

Future work will focus on performing the comprehensive SRA of different smart grid use cases to learn more about the large-scale adoption of the smart grid.

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