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Scalability and replicability analysis of large-scale smart grid implementations: Approaches and proposals in Europe

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ABSTRACT

Smart grid solutions offer great potential for achieving more efficient integration of renewable energy in the distribution network. Numerous pilot projects have been launched to test smart grid solutions in real-life systems. However, the results observed are subject to the specific context of the demonstrators. Therefore, the conclusions drawn may not be directly applicable to the implementation of the same solutions in different locations or at a larger scale. The scalability and replicability analysis (SRA) of smart grid implementations aims to understand the effect of the context and to infer the impacts that may be expected from smart grid solutions. SRA is a very valuable tool to support policy-makers and the industry in shaping the strategy for sustainability and smart grid deployment. This paper reviews existing approaches and proposals for the SRA of smart grid solutions, and describes European research and demonstration projects that have dealt with SRA from various perspectives. Subsequently, a comprehensive methodology for the SRA of smart grid solutions is described in detail. The core of the SRA methodology is technical analysis based on simulation that lets the impact of smart grid implementations be quantified under different conditions. Additionally, the methodology incorporates the analysis of economic, regulatory and social aspects to identify drivers and barriers for scaling-up and replication of smart grid implementations. Furthermore, the proposed methodology is illustrated through its application to the case of medium voltage automation to improve the continuity of supply.

1. Introduction

In order to face upcoming challenges and successfully provide for 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 in recent years, covering a wide range of solutions aimed at achieving the much needed upgrade of the distribution grid [46,5,74] under energy policies based on sustainability and efficiency [50]. Much work is currently being carried out to determine the potential costs and benefits that can be expected from the implementation of such solutions [22,26]. Nevertheless, due to the lack of practical experience, the outcome of actually executing the smart grid on a large scale is still uncertain. It becomes necessary to determine the impacts of the different smart grid solutions available on current networks. Indeed, numerous demonstrators and pilot projects have been launched across the world to test different smart grid solutions in real-life systems [14,70]. These initiatives provide very valuable information [25], however, the results observed are subject to the specific context where the tests are conducted. 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 scalability and replicability analysis (SRA).

This type of analysis is particularly relevant given that substantial investment has already been made in smart grid demonstration projects across the world: up to 2015, over €3.15 billion and $9.7 billion have been invested in the European Union (EU) and the USA respectively [18,69]. SRA maximizes the learning potential from these pilot projects, helping translate the observed results into clear expectations for the large-scale deployment of smart grids. SRA results can indicate the most promising functionalities and contexts. Moreover, SRA results can be of assistance in policy-making to remove the identified barriers to smart grid implementations. Furthermore, SRA results help quantify the estimated impact of smart grid solutions and serve as a valuable input for cost-benefit analyses. The EU has explicitly stressed the need for SRA in its strategic guidelines [24] and has launched research projects GRID+,

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Nomenclature

BA	Benefit Analysis
CA	Cost Analysis
CEER	Council of European Energy Regulators
DER	Distributed Energy Resources
DFACTS	Distributed Flexible AC Transmission Systems
DG	Distributed generation
DSO	Distribution System Operator
EEGI	European Electricity Grids Initiative
EV	Electric vehicle
HP	Heat pump
ICTs	Information and Communications Technologies
JRC	Joint Research Centre
KPI	Key Performance Indicator
LCT	Low Carbon Technologies
LV	Low Voltage
MV	Medium Voltage
NIEPI	Equivalent Number of Interruptions Related to the Installed Capacity (in Spanish)
OLTC	On-Line Tap Changer
RES	Renewable Energy Sources
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
STATCOM	Static Synchronous Compensator
SRA	Scalability and Replicability Analysis
TIEPI	Equivalent interruption time related to the installed capacity (in Spanish)
TSO	Transmission System Operator

GRID4EU, iGREENGrid, SINGULAR, SuSTAINABLE and evolvDSO for the 2011–2016 period to test and analyse the scalability and replicability of smart grid solutions.

Implicitly, scaling-up and replication are performed whenever the potential impact of any solution, technology or policy is assessed, since conclusions are drawn from experimental data by extrapolating and performing sensitivity analyses assuming certain hypothesis. However, scaling-up and replication have not yet been addressed and performed in an explicit and systematic manner. For instance, the benefits of smart grids are quantified in [22]. The observed impact of smart grids is assumed to be directly applicable to all distribution grids in the US, which implies a linear scaling-up, where the different conditions across the country have not been considered.

The objective of this paper is to provide the theoretical and methodological framework to assess the scalability and replicability of smart grid implementations. This analysis is necessary for regulators and policy-makers, in order to identify the funding required for further demonstration projects, to shape a desirable roadmap for smart grid deployment and to establish an adequate regulatory framework with the right incentives. Moreover, the proposed SRA also serves the purpose of distribution companies and the smart grid industry to guide investment and development towards specific smart grid solutions. The main contributions of the work presented in this article are listed below.

Discussion of the main concepts involved in scalability and replicability, which have not yet been formalised in the context of the smart grid

Review of methodological approaches for SRA of smart grid solutions in European research projects and detailed description of an exhaustive methodology to perform SRA for any smart grid project, incorporating the technical, economic, regulatory and social aspects involved

The application of the proposed methodology to a realistic smart grid use case to illustrate the process and showcase the results that can be obtained from SRA

Accordingly, the remainder of the paper is structured as follows: Section 2 focuses on the theoretical framework for SRA, defining the main concepts. Then, Section 3 reviews the methodological developments in Europe through proposals for research and demonstration projects, and Section 4 describes in detail a complete methodology for SRA. Following, Section 5 presents the application of SRA to the case of MV automation for continuity of supply. Finally, Section 6 concludes with the final remarks.

2. 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, while the *replicability* of a system refers to the ability to be duplicated in another location or time. Thus, 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, at a different time and location.

The concepts of scalability and replicability have already been applied in other fields of knowledge, such as environmental governance [54], universal access to energy [71], and information and communications technologies (ICTs) [6]. 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 technologies involved. In order to enable large-scale deployment, smart grid solutions must be able to cope with increasing volumes of information and interacting agents. Therefore, the scalability of solutions is analysed in terms of the capability of information technologies, algorithms, communications and systems to exchange, analyse and store large volumes of data and perform large-scale computations [4]. For instance, the work presented in [72] and [47] aims to overcome the problem of existing demand response approaches that cannot cope with large numbers of electric vehicles and consumers, respectively. Yet another example may be found in [48], where a mechanism is proposed to enable the scaling up of automatic meter reading.

In the context of smart grid projects, the terms ‘use case’, ‘KPIs’ and ‘boundary conditions’ are frequently used and must be clarified for a correct understanding. Smart grid demonstration projects consist of the implementation of smart grid solutions organised into use cases. In line with the Unified Modelling Language definition, a *use case* represents a set of functional requirements that must be performed by the smart grid solution in pursuit of different objectives. For instance, automation systems may increase monitoring of the grid and improve fault management in distribution networks so that continuity of supply is improved, where the use case would be MV automation for reliability improvement.

The impacts observed in the demonstrator are quantified by means of different metrics called *Key Performance Indicators* (KPIs). The concept of Key Performance Indicators (KPI), commonly used in management science [55], has been widely adopted in smart grid research activities. In Europe, the EEGI has provided reference guidelines for smart grids KPIs [28]. A more detailed proposal is provided in [21], where the authors have adapted the proposal of the US Department of Energy (DOE) to the European context [68]. The KPIs selected for each use case must be able to assess the extent to which the objectives of the use case have been fulfilled by the smart grid solution. KPIs should follow SMART criteria as proposed by [62], which state that KPIs must be specific, measurable, attainable, relevant and timely. In the previous example, appropriate KPIs could include improvement of reliability indices such as SAIDI and SAIFI [42].

The impact of any smart grid implementation on the system is