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Scalability and Replicability Analysis in Smart Grid Demonstration Projects: Lessons Learned and Future Needs

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Abstract: This paper compares various approaches to the scalability and replicability analysis (SRA) of smart grid pilot projects, highlighting the need for a comprehensive SRA methodology as called for by the European Commission and International Energy Agency. This study addresses the need for a standardized SRA methodology and explores how three EU-funded projects—Platone, EUniversal, and IElectrix—adapted the general guidelines developed by the BRIDGE initiative. These guidelines provide recommendations for developing a comprehensive large-scale deployment analysis. The results show that while the guidelines are usable and flexible, project-specific conditions and data availability limitations—particularly in regulatory and technical analysis—can pose challenges. Some key recommendations to overcome these and facilitate future applications are identified. These include defining SRA methodologies and securing data-sharing agreements early. The lack of standardized approaches for presenting SRA results hampers cross-project comparison. Thus, creating an open-use case repository and updating the BRIDGE guidelines with more detailed examples, benchmarks, and reference networks is recommended. Additionally, linking SRA with cost–benefit analysis (CBA) is suggested in order to evaluate the commercial viability of smart grid solutions. The paper concludes that while the BRIDGE guidelines have proven to be fit for purpose, further developments are needed to facilitate their practical application in real-world projects.

Keywords: scalability and replicability analysis; smart grid projects; congestion management; distribution grid flexibility

1. Introduction: Why Is the Scalability and Replicability Analysis Needed?

The present paper provides an overview of the state-of-the-art approaches for performing a scalability and replicability analysis (SRA), identifies existing gaps and proposes some recommendations to support future SRA studies.

The SRA aims to assess the applicability of the proposed solutions when deployed in various regions, under different conditions, densities, and sizes with respect to the demonstration project activities. Thus, scalability and replicability in the context of smart grid projects may be defined as follows:

- Scalability: The ability of a system, network, or process to expand in size, scope, or range to adequately meet growing demand;
- Replicability: The ability of a system, network, or process to be duplicated in another location or time [1].

The need for a general methodology to support the development of a tailored SRA approach for smart grid pilot projects was acknowledged in the European Commission (EC) Communication 202/2011 [2]. In this document, the EC highlighted that "There is a considerable gap between current and optimal investment in Europe [in smart grids], which can only partly be explained by the current economic downturn".

This "financing gap" is illustrated in Figure 1, which shows that many projects that successfully complete the R&D prototype phase fail to reach large-scale deployment. During the "industrial development stage," many projects fall into the "technology death risk" area. This failure is primarily due to a lack of adequate studies on their large-scale impact on existing infrastructures, as well as their dependency on regulatory frameworks and stakeholder acceptance. Inadequate assessments increase uncertainty regarding the potential economic and technical benefits of these technologies, leading to a lack of investment from private investors [3,4].
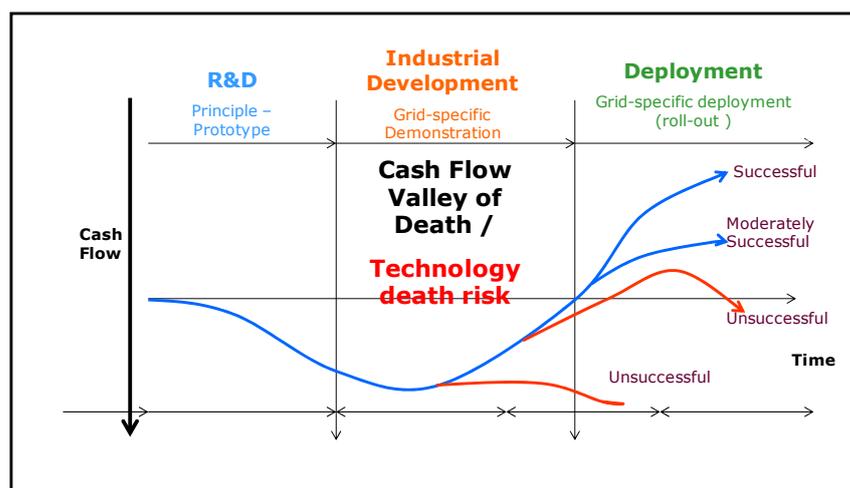

Figure 1. Smart grids: the financing gap for R&I (source: [3]).

In 2023, the International Energy Agency (IEA) [5] stated that "annual investment in grids will need to more than double from around USD 330 billion per year to USD 750 billion by 2030, with around 75% of the investments allocated to the distribution grids to expand, strengthen, and digitalise technologies. There is great potential for raising ambitions; however, many challenges to ramp up investment remain[...] To bridge the investment gap and drive investments towards modernizing grids, policymakers could consider actions to leverage the full range of potential investors and develop models that adequately value broader benefits" [5].

The European Commission, in the European Technology & Innovation Platforms (ETIPs) Smart Networks for Energy Transition (SNET) VISION 2050 [6], established the need for technology R&D initiatives and prompted small-scale pilot projects to verify and demonstrate the functioning and benefits of smart grids. According to the EC recommendations, "projects and investments must now aim for 'real life' demonstration and validation, solving system integration issues and demonstrating the business cases. They must also demonstrate how consumers can benefit most from the introduction of these systems" [6]. The integrated ETIP SNET Roadmap 2020–2030 [7] recommended that, in order to expedite the transition from industrial research to the commercialization of innovative solutions, pilot project outcomes should be supported by detailed analyses to confirm the scalability and replicability of the demonstrated solutions. These analyses should also consider non-technical factors, including public acceptance of grid infrastructure, the development of new market models and products, stakeholder acceptance for innovative solutions, and the alignment of regulations and legal frameworks. Such analyses could help develop solid business cases, supporting private investors' decisions to invest in innovative smart grid technologies, as suggested in the EC document. Finally, the Horizon Europe work program for the years 2025–2027 acknowledged the importance of scalability and replicability analysis and included in several calls the requirement to develop a "plan for the exploitation and dissemination of results that includes a strong business case and sound exploitation strategy [...]. The exploitation plans should include preliminary plans for scalability, commercialization, and deployment (feasibility study, business plan)" [8].

Regulatory Agencies have also provided recommendations that highlight the importance of scalability and replicability analysis. In particular, the European Regulatory Group for Energy and Gas (ERGEG) in [9] provided general guidelines that shall be followed in the development of pilot projects:

- Defining the boundaries between research, development, demonstration, and deployment;
- Evaluating both the anticipated and realized benefits before and after project execution;
- Ensuring the engagement of market participants to interface with customers, guaranteeing the involvement of independent market operators in assessing project advantages;
- Assessing the projects' replicability and openness;
- Establishing transparent validation procedures;
- Implementing clear and transparent criteria for monitoring demonstration projects;
- Evaluating project-specific indicators to measure outcomes;
- Coordinating research projects effectively to prevent overlap and duplication [9].

The Council for European Energy Regulators (CEER) report [10] also suggests that, to address the underinvestment gap and drive investments towards grid infrastructures, solutions such as regulatory sandbox environments can enable network operators to test digital technologies in energy infrastructure at scale while gathering the necessary information to validate the business cases for these digital solutions. Regulatory sandbox tests offer valuable insights into managing digital technologies on a larger scale and highlighting the value they generate. However, these findings and lessons are not always broadly disseminated. To address this limitation, pilot project outcomes should be accompanied by further studies that assess the potential for scaling and replication, thereby encouraging more investment in smart grid initiatives.

This exercise aims to contribute to the creation of a "use case library" that will aid future project consortia that commit to perform these analyses. The expected outcomes include identifying successful qualitative and quantitative examples for new projects, gathering feedback on the implementation of general SRA guidelines and highlighting gaps, good practices, and recommendations for future works.

This introductory section (Section 1) presents the rationale for the development of a comprehensive SRA methodology to be implemented by smart grid pilot projects. Section 2 identifies and analyzes previous work in this field. Section 3 examines how three significant EU-funded projects (Platone, EUniversal, and IElectrix) adapted existing SRA guidelines to develop project-specific methodologies. Section 4 compares the three previous approaches to identify similarities and lessons learned. Lastly, Section 5 presents the conclusions of this comparison, highlighting suggestions and further developments that should be addressed by international task forces of experts developing the common guidelines for SRA.

2. State of the Art of the Existing Literature

The first attempt to provide definitions of scalability and replicability in the context of smart grids was performed in the GRID+ project. The participating partners examined various industrial sectors (such as telecommunications, sensor networks, and distributed computing systems) to identify the factors influencing the scalability and replicability of prototypes. Their goal was to determine which of these factors could also be applied to smart grids [11]. These insights were used to develop a questionnaire designed for an ex-ante evaluation, assessing the extent to which projects were considering these factors and, consequently, whether the solutions tested were truly scalable and replicable. The questionnaire was circulated among a selected group of smart grid projects spanning both transmission and distribution sectors. From the survey results, a set of common barriers hindering the scalability and replicability of innovative smart grid projects was identified (see Tables 1 and 2).

Table 1. Limitation and challenges for scalability factors (source: [11]).

Nature of Limitation	Factor	Issues
Technical	Modularity	Communication capabilities Computing memory
	Software integration	Big data
	Existing infrastructure	Existence of weak components Physical dimensions
	Interface design	Varies based on the project's nature and focus (no definitive judgment)
	Technology evolution	• Anticipated equipment expenses • IT/data security concerns • Lack of standardization in control signals and information flow to/from distributed generation (DG) • Management of big data
Economic	Economy of scale	• Uncertainty in remuneration • Emphasis on feasibility
	Profitability	• Absence of a detailed cost–benefit analysis
Regulatory	Regulation	• Data privacy issues • Insufficient regulations for service provision • Lack of guidelines for interaction
Acceptance	Acceptance	• Changes in customer behavior • Resistance or hesitation from stakeholders

Table 2. Limitation and challenges for replicability factors (source: [11]).

Area	Factor	Issue
Technical	Standardization	• New, non-standardized services • Proprietary standards • Capability for standard-compliant implementation
	Interoperability	• Customized implementation based on project or equipment • Provider-specific applications • New, non-standardized services
	Network configuration	• Focus or dependency on resources • Load and generation mix and conditions • Infrastructure requirements • Demographic factors
Economic	Business models	• Uncertainty in remuneration • Absence of regulations for service provision
	Macro-economic factors	• Lack of analysis on macroeconomic factors • Absence of plans for exporting solutions
	Market design	• Dependency on market structure • Uncertainty in remuneration • Lack of corresponding analyses
Regulatory	Regulation	Non-existent, unclear, or highly variable regulatory and legal frameworks
Acceptance	Acceptance	Change customer and operator behavior

The survey results highlighted that regulatory and stakeholder-related issues were prioritized for replicability, while economic concerns received less attention. Key factors such as standardization, market design, and existing infrastructure were identified as potential risks, with barriers often depending on external actors outside the project's control [11].

The structure of the GRID+ survey has since been adopted as a blueprint by subsequent studies and projects to develop their own methodologies for evaluating the scalability, replicability, and adaptability potential of specific technological solutions. For example, ref. [12] assessed the SRA potential of a smart infrastructure system integrating smart electricity, smart information, and smart communication, while other papers applied GRID+ survey outcomes to assess SRA potential for specific use cases, such as medium-voltage network automation to improve supply continuity [13], or to evaluate SRA potential in European pilot projects like IGREENgrid, GRID4EU, and SUSTAINABLE. These projects have developed both qualitative approaches (that are based on the analysis of the physical architecture of the systems and the specific characteristics of the different components of the demos) and quantitative approaches, which require developing analytical frameworks for different functionalities tested in the demos, under the same general methodological framework. This exercise includes, for example, the selection of the proper simulation tools, the identification of the data needed to build the simulation models, which must describe the key features of the distribution grids that host the demos, etc. [1]. Although the need for SRA has been widely recognized by various smart grid stakeholders and several methodologies elaborated, the approaches proposed are often project-specific, reflecting the unique characteristics of each initiative. This has led to a lack of consensus on a standardized methodology for conducting such studies [12]. Consequently, experts within the smart grid community called for general guidelines applicable to any project. In response, the BRIDGE (BRIDGE is a European Commission initiative which unites Horizon 2020 and Horizon Europe Smart Grid, Energy Storage, Islands, and Digitalisation Projects to create a structured view of cross-cutting issues which are encountered in the demonstration projects and may constitute an obstacle to innovation (source: [12])) community established an ad hoc task force to create recommendations that all pilot projects should follow in conducting SRA, as outlined in Figure 2 [12]. These guidelines incorporated the recommendations discussed above.

The first release of the BRIDGE guidelines has been implemented in several European projects like WiseGRID [14] and GOFLEX [15]. This exercise allowed the BRIDGE TF to conclude that the proposed methodology is flexible enough to consider all the particularities of the different projects, but at the same time structures the analysis in several mandatory steps [12]. Several projects have since implemented the BRIDGE guidelines to elaborate their SRA approaches:

- InteGrid developed a methodology for the scalability analysis of ICT infrastructures for smart grids, using the Smart Grid Architecture Model (SGAM) for a standardized, replicable approach. It consists of two steps: a qualitative analysis to identify potential bottlenecks and a quantitative analysis that simulates critical links under stress conditions to evaluate their operational limits. This methodology was applied for the analysis of the large Customer Commercial Virtual Power Plant (VPP) that provides flexibility in medium voltage for tertiary reserve flexibility offers. The scalability analysis shows no major constraints. Future work will apply the methodology to other scenarios with different architectures and technologies, (i.e., replicability aspects) to enhance the impact of the analysis [16];
- The Crossbow project adopted the BRIDGE guidelines to elaborate a simplified methodology for scalability and replicability factor identification and quantification. The SRA demonstrated that the solutions tested in the project have high scalability and replicability potential for technical aspects. Economically, some products are moderately scalable and replicable, while others show low scalability and replicability. Regulatory and acceptance factors currently exhibit low scalability and replicability;

the uncertainty of the regulatory framework, which is neither stable nor unified across Europe, contributes to economic uncertainty for certain solutions and products. This immature regulatory landscape affects the confidence in the economic viability of these solutions [17];
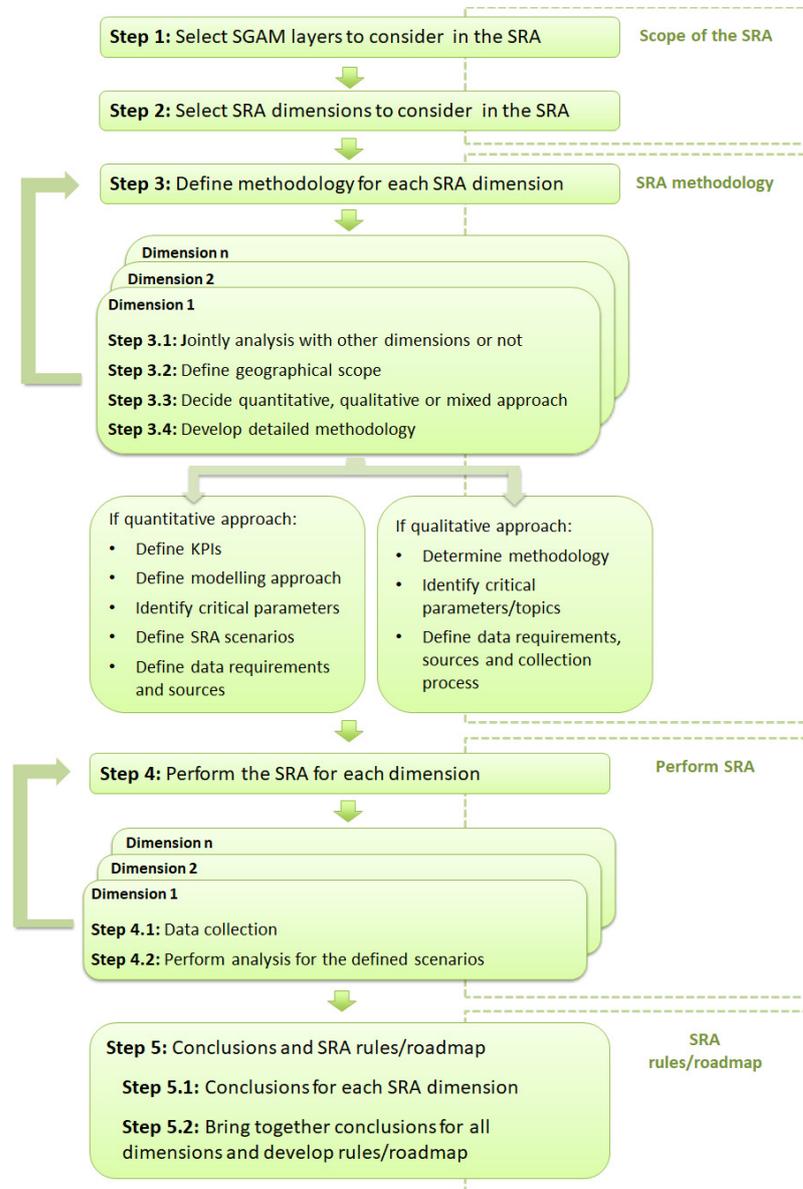

Figure 2. SRA guidelines (source: [12]).

- The RESPONSE project used a SGAM-based quantitative method to perform an ICT SRA. This approach is flexible, not dependent on the use case, communication technology, or analysis method (simulations or experiments). To validate the methodology, it was applied to two case studies from RESPONSE: Case A assessed a Modbus TCP system for DER control and monitoring, while Case B evaluated a wireless M-Bus system for smart metering and sensing. The methodology was successfully applied to the analysis of the selected use cases. The results showed the guidelines' versatility. However, the authors suggested that future work could focus on expanding the methodology by developing simple numeric scalability and replicability indicators for easier comparison of different ICT alternatives. Additionally, complementing the approach with a qualitative evaluation of factors like interoperability and standardization was deemed potentially valuable [18];

- The FLEXITRANSTORE project developed hardware and software solutions for transmission systems and wholesale markets, which were tested in several pilots. A qualitative SRA was conducted to identify the technical, economic, regulatory, and stakeholder acceptance factors that influence the scalability and replicability potential. Two sets of questionnaires, one for scalability and one for replicability, were developed and distributed among project participants, following guidelines from GRID+ and BRIDGE TF. The survey results allowed demo leaders to assess technical variables to determine if a project's solution was naturally scalable or replicable. Economic factors were considered to evaluate whether scaling up or replication was economically viable. Additionally, regulation and stakeholder acceptability factors helped determine whether the current environment was suitable for scaling up the project or if a new environment would be better for adopting the solution [19].

The work presented in these papers proved the adaptability and flexibility of the BRIDGE guidelines for the development of a project-specific approach. However further efforts are still needed to elaborate a comprehensive methodology that can be easily adapted for the analysis of different use cases and to enhance the comparability of the results obtained by different projects.

In 2021 and 2022, the BRIDGE TF on SRA released two updated versions of the SRA guidelines [20,21] that included the recommendations from the aforementioned projects. These updates aimed at addressing the highlighted challenges and introduced further improvements and recommendations with respect to the first release of the BRIDGE guidelines. In particular:

- The BRIDGE TF members shall work on the definition/specification of a common repository with useful information for helping projects in implementing the guidelines;
- The repository shall include information regarding Tools from existing projects, best practices and lessons learned from SRAs. The project developers will be requested to map the objectives of their projects in the SGAM environment. In the second step, a use case library shall be created and constantly updated to help new project consortia align their objectives and maximize the benefits of the SGAM process. The repository shall include the adapted mapping along with a detailed description of each use case, emphasizing what distinguishes it from other related cases already archived in the system [21].

3. Implementation of BRIDGE SRA Guidelines in New Smart Grid Projects

The following key criteria have been used to select the projects included in this analysis:

- Diversity of use cases: Projects that have compared pilots with at least two distinct use cases within the SRA framework, conducted under varying boundary conditions. This allows for the comparison of results across different demonstration environments, assessing the potential for internal replicability based on the specific conditions characterizing each demo;
- Use of different alternatives for distribution grid modeling: Network and user data gathering is usually a major challenge for SRA studies. Thus, this research assesses projects that use different alternatives such as (i) test networks, i.e., recognized benchmarks within the international modeling community (e.g., JRC networks), (ii) real network data provided by the corresponding DSO (subject to confidentiality), and (iii) custom-made network models combining actual data and synthetic data. This provides a wider picture of possibilities to overcome this particular barrier;
- Commitment to quantitative SRA: Selected projects must demonstrate a strong commitment to performing quantitative SRA, involving the development of simulations to rigorously assess scalability and replicability;
- Public and recent data: Projects must provide publicly available and up-to-date data to ensure transparency and relevance in the analysis;
- Representation of innovative solutions: The selected projects should represent use cases related to innovative solutions aimed at enhancing grid flexibility, aligned with

the functional goals outlined in the ETIP SNET Roadmap Functionality 10 (F10), integrating flexibility in generation, demand, conversion, and storage technologies [7];
- The results of the SRA were not yet published in a peer review journal;
- This approach ensures that the analysis is grounded in robust, comparable data, while also reflecting the latest developments in smart grid research. The findings from these case studies will offer valuable insights for future projects and contribute to refining the existing SRA guidelines.

The adoption of these criteria led to the selection of the following European projects: Platone [22], IElectrix [23], and EUniversal [24].

3.1. Platone Experience: Examples of Results

The Platone (Platform for Operation of distribution Network) project [12], funded by Horizon 2020, focused on enhancing observability of renewable energy and unpredictable loads. A consortium of 12 partners from Belgium, Germany, Greece, and Italy developed management platforms to unlock grid flexibility and promote an open market. The project aimed to develop and test advanced management platforms to unlock grid flexibility and to realize an open and non-discriminatory market, linking users, aggregators, and operators. The solutions developed in the project were tested in three European pilot projects. Each pilot tested different use cases (UCs). The project performed both a quantitative assessment to evaluate the scalability and replicability potential of the solutions tested in the demos in the European context and a qualitative assessment to perform the replicability analysis of the Platone solutions in the Canadian energy system [17]. To perform the quantitative assessment, the steps suggested in Figure 2 were followed.

3.1.1. Step 1: Select Smart Grid Architecture Model Layers

As a tool to analyze the scalability and replicability of projects, the Platone methodology uses the Smart Grid Architecture Model (SGAM) [25] to identify the applied aspects of a smart grid system or project. In particular, the Platone approaches considers the following SGAM layers:
- Business layer;
- Function layer;
- Communication layer;
- Component layer.

The detailed descriptions in the SGAM layers of the use cases implemented in the Platone demos are reported in Platone D.1.1 [19].

3.1.2. Step 2: Select SRA Dimensions to Consider in the SRA

In D 1.1 [26], the Platone consortium identified in which dimensions the project would have an impact to consider them in the replicability and scalability task. These dimensions include technical and economic analysis, regulatory framework, and stakeholder acceptance. The geographic selection for these analyses was influenced by data availability, regulatory information, and grid characteristics.

Technical Analysis
- Focused on the function, component, and communication layers.
- Two use cases (UCs) were analyzed:
  - UC1: Desired curtailment, where demos enable the grid manager to reduce grid imports, maximizing local self-consumption. KPIs include reducing grid energy exchange, peak load, and increasing self-consumption;
  - UC2: Zero power exchange, which simulates zero power exchange between LV/MV and MV/HV grids using local flexibility sources. Scalability and replicability are assessed across demos in Germany, Italy, and Greece;

- The project avoided confidentiality issues by using representative networks from the DSO Observatory project, representing typical European networks for large-scale analysis.

Regulatory Analysis

Two qualitative regulatory analyses were performed:

- Replicability of solutions within the European Energy Markets, considering EU regulations;
- Assessing the deployment of solutions in the Canadian energy system by reviewing European projects and consulting Canadian experts on regulatory and stakeholder issues. Information needed for this task was collected with a tailored questionnaire distributed among Canadian experts identified by the Northern Alberta Institute of Technology. The aim of the exercise was to identify potential barriers and enabling factors as described in D7.5 [27].

Business Layer Analysis

The consortium adopted a hybrid multi-criteria cost–benefit analysis (MC-CBA) method to assess the economic, social, and environmental benefits of large-scale project deployment using KPIs developed from the demos. This method is based on the MC-CBA approach developed by ISGAN (International Smart Grid Action Network) [28].

Stakeholder Acceptance

Workshops were conducted to gather feedback from pilot project customers, addressing obstacles and benefits observed in the demos, especially for congestion management with local prosumers. Feedback is summarized in D8.10 [29].

3.1.3. Step 3: Develop Detailed Methodology

The Platone consortium decided to perform both a quantitative SRA of the solutions tested in the pilot projects in the European context and a qualitative assessment of the replicability solutions in the Canadian energy system. For both the analyses, the Platone partners developed ad hoc methodologies. The quantitative methodology was described in D7.2 [30] and D7.6 [31] and is reported in Figure 3.
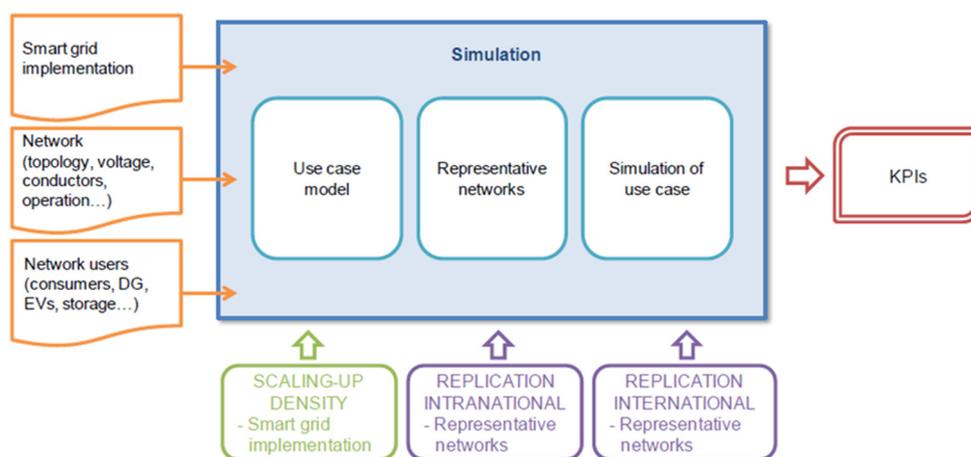

Figure 3. Methodology for the quantitative SRA developed by Platone consortium (source: [30]).

Quantitative Methodology

The Platone methodology for assessing scalability and replicability analysis (SRA) is structured around guidelines from the BRIDGE initiative and follows several key steps:
Scalability Analysis:

- Scalability in density: Assesses the impact of increasing the penetration of a solution (e.g., higher distributed generation or consumer flexibility) within a specific area;

- Scalability in size: Evaluates the effects of deploying a solution over a larger geographic area, while maintaining the same technical, economic, and regulatory conditions.

  Replicability Analysis:

- Intranational replication: Replicates a solution within the same country, considering different technical conditions but similar economic and regulatory frameworks;
- International replication: Replicates a solution in different countries, considering varying technical, economic, regulatory, and stakeholder conditions.

To simulate the selected demo use cases (UCs) within the SRA, the Platone project partners (WP7) developed specialized tools and algorithms to optimize the operation of distribution grids. These tools help distribution system operators (DSOs) leverage flexibility services from distributed resources to address local grid congestion. The software architecture for these simulations is illustrated in Figure 4 and detailed in D7.6 [31].
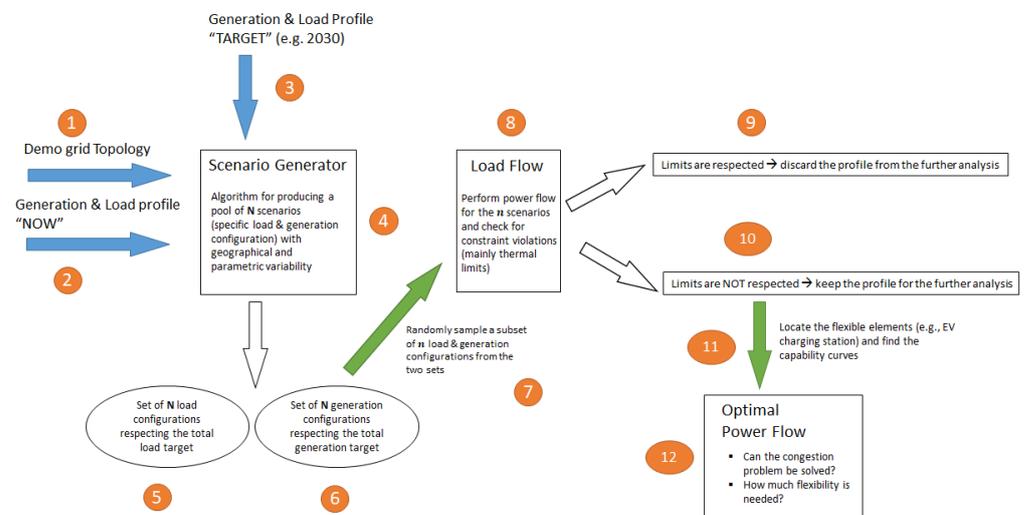

Figure 4. Software architecture developed by Platone for the technical SRA (source: [31]).

These advanced algorithms and tools have been employed to reproduce the control strategies showcased in the project demonstrations. In the context of the SRA, two control strategies have been modeled:

- Desired power exchange: This approach simulates a strategy that enables distribution system operators (DSOs) to limit a designated amount of energy imported from or exported to the main grid. This limitation is balanced by utilizing flexibility services from local sources. Furthermore, the SRA-UC can model situations in which the DSO requests operators of distributed flexibility sources to adjust their production and consumption patterns to alleviate potential congestion on peak days;
- Zero power exchange: This approach simulates a strategy that allows the DSO to set the power exchange value between low-voltage (LV) and medium-voltage (MV) grids, or between MV and high-voltage (HV) grids, to zero during specified time intervals.

These strategies will be referred to as "SRA-UCs" throughout the rest of the paper. They represent mathematical models that reflect the unit commitment (UC) implemented in the field by one or more pilot initiatives, as previously described. Table 3 describes how the SRA-UC has been used in the different steps of the Platone SRA.

The "zero power exchange" SRA-UC was implemented exclusively in the German demo due to specific regulatory conditions. The "scalability in density" analysis simulates a scenario where a larger share of customers participates in providing flexibility services than in the original demo. In this SRA -UC the DSO is allowed to operate the demo network in the "zero power exchange" operational conditions (i.e., to set the power exchange between the LV and MV grid equal to 0 during the entire trial). However, this SRA-UC was not implemented in the Greek or Italian demos because it was not permitted

under their national regulatory frameworks or tested in the fields. As a result, the SRA-UC "zero power exchange" was applied only to the "scalability in density" stage of the German demo. The "zero power exchange" SRA-UC was applied to subsequent stages of the SRA for the other two pilots, specifically during the "international replicability" analysis. This step simulates demo performance under different regulatory conditions, with a focus on exploring how distributed resources could provide flexibility services in regulatory environments (for example in a regulatory framework that allows the "zero power exchange" operational conditions). The results of these analyses, along with other SRA simulations, are documented in D7.6 [31].

Table 3. Application of the demo SRA-UC to the Platone SRA (source: [31]).

Use Case	Italian Demo	Greek Demo	German Demo
Desired power exchange	• Scalability in density • Intranational replicability	• Scalability in density • Intranational replicability	• Scalability in density • Intranational replicability
Zero power exchange:	• International replicability	• International replicability	• Scalability in density • Intranational replicability

The software architecture for these simulations (illustrated in Figure 4) incorporates several components, including a "scenario generator" developed using Python. 3.12 This tool creates random scenarios based on variations in loads and generation growth, considering geographic and parametric uncertainties. The Optimal Power Flow (OPF) formulation was modified to include flexible loads and new variables that represent flexible load power values, simulating scenarios of zero power exchange and desired power injection to the external grid. Flexibility is modeled by defining load units with a range of potential values, and cost factors are applied to influence curtailment [31].

3.1.4. Step 4.1: Data Collection

The information needed to perform the simulation described in Figure 4 has been obtained by looking at the DSOs grid development plans, and with interviews with the demos. The input data are summarized in Table 4. The table also reports an example of data provided by the Italian partner of the Platone project for the application of the "scalability in density" study. In this case, the desired power exchange OPF is used for the simulations. The objective function selected by the OPF is the minimization of the system costs.

Table 4. Input data requested by the Platone software architecture (source: [31]).

Variable	Value	Unit	Description
n_nodes	13	Number	Number of nodes situated below the substation
Cosφ	0.9		Power factor
perc_increase_load	55.08	[%]	Anticipated increase in load compared to the baseline scenario
uncertain_load	10.00	[%]	Error margin associated with the forecasted increase in load
perc_increase_gen	41.96	[%]	Anticipated increase in generation compared to the baseline scenario
uncertain_gen	10.00	[%]	Error margin associated with the forecasted increase in generation
perc_nodes_gen	30.0	[%]	Percentage of nodes equipped with generators in the target scenario
gen_types	10.00	labels	Types of generators connected to the grid in the target scenario (default: PV; PV and storage)
gen_percs	90.00	[%]	Percentage of each type of generator (total must equal 100%)
load_types		labels	Types of loads connected to the grid in the target scenario (default: residential; EV; fixed; storage)

Table 4. *Cont.*

Variable	Value	Unit	Description
load_percs	30.00%	[%]	Percentage of each type of load (total must equal 100%)
min_contracted_power	3	[kW]	Minimum contracted power in the target network scenario
med_contracted_power	6	[kW]	Average contracted power in the target network scenario
max_contracted_power	9	[kW]	Maximum contracted power in the target network scenario
perc_min	60	[%]	Percentage of loads equipped with meters reflecting the minimum contracted power in the target scenario
perc_med	35	[%]	Percentage of loads equipped with meters reflecting the average contracted power in the target scenario
perc_max	5	[%]	Percentage of loads equipped with meters reflecting the maximum contracted power in the target scenario
Load flexibility curtailment	50	[%]	Percentage of individual flexible loads that can be curtailed compared to the baseline profile

3.1.5. Step 4.2: Perform the Simulations for the Selected Scenarios

This paragraph provides an example of results from the scalability in density analysis of the Italian demo in the Platone project, specifically focused on congestion management in a low-voltage (LV) distribution network in 2030. The analysis used the "desired power exchange" Optimal Power Flow (OPF) model on 2200 scenarios generated by the scenario generator tool, simulating different distributions of loads and generators across 22 time slices affected by grid congestion. In this simulation, the power injected from the medium voltage (MV) to the LV grid was reduced by 10% from the baseline for each time slice, with the aim of assessing whether local flexibility sources could resolve the resulting grid congestion. Key findings showed that certain slack nodes (nodes 13 in urban and 115 in semi-urban networks) had significantly higher negative values of active ($P_{\_gen}$) and reactive ($Q_{\_gen}$) power, indicating that these nodes imported more energy from the MV grid in the baseline scenarios. To manage the curtailment, local generators and flexible loads compensated for the power reduction. The required flexibility was calculated as the difference between the baseline scenario and the values generated by the OPF tool across all 2200 scenarios. The analysis also presented graphs illustrating the mean, minimum, and maximum values for active and reactive power in both generators ($P_{\_gen}$, $Q_{\_gen}$) and loads ($P_{\_load}$, $Q_{\_load}$). Figures 5 and 6 summarize these simulation results, showing that a 10% curtailment in power injected from the MV grid simulated congestion, with local flexibility required to address it.

Figures 7 and 8 show simulations for "replicability intranational" SRA-UC, applying the same method to the JRC semi-urban LV network (115 nodes).

As shown in Figures 5 and 6, to alleviate local congestion resulting from the desired power exchange, each generator connected to the grid must increase its output to 0.015 MW and 0.008 MVAR. These findings indicate that the ratio of flexible load to the total load served in the analyzed network is 52.46% for active power and 22.20% for reactive power. Each load must provide a maximum flexibility value of 0.00860 MW and 0.00569 MVAR. It is noteworthy that, according to the results published in D2.16 [32] regarding the technical SRA of the Platone platform in the Italian demonstration, the platform can ensure the effective execution of the entire process with a projected penetration of flexibility sources equal to 30% of the total customers served within the geographical area of the Italian demonstrator. Figures 7 and 8 present the outcomes of applying the same SRA-UC in a rural network. These results confirm that the "desired power exchange" SRA-UC can be effectively implemented during summer peak days in urban distribution grids, even under future scenarios with significant distributed generation penetration. Indeed, the previous section's findings and relevant simulations demonstrated that local congestion could be

resolved by utilizing contributions from local flexibility sources across the 2200 scenarios analyzed in each simulation.
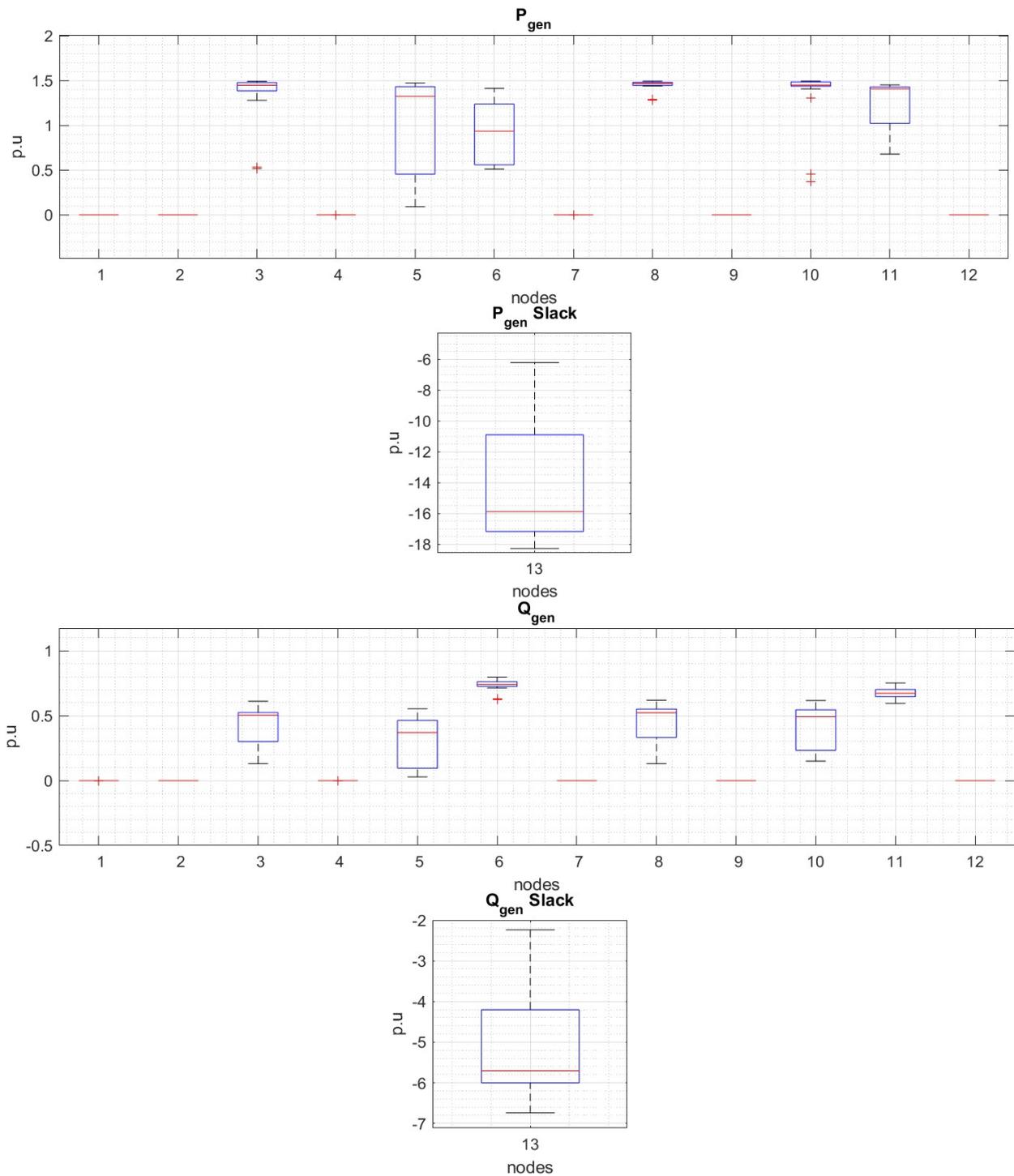

Figure 5. Flexibility (in terms of active and reactive power) of the generators in the scenario "scalability in density, demo network, desired power exchange" (source: [31]).

The SRA performed within the Platone project indicates that future distribution network congestion, particularly on summer peak days, can be managed through distributed flexibility resources and extensive deployment of the Platone architecture. The quantitative results presented in Figures 5–8 confirm that the "desired curtailment" SRA-UC can be scaled effectively, allowing up to 30% of grid customers to participate, aligning with

utility development strategies. Furthermore, the analysis indicates that this SRA-UC can be successfully replicated across various network configurations, including rural networks, in addition to the urban networks used in the pilot.
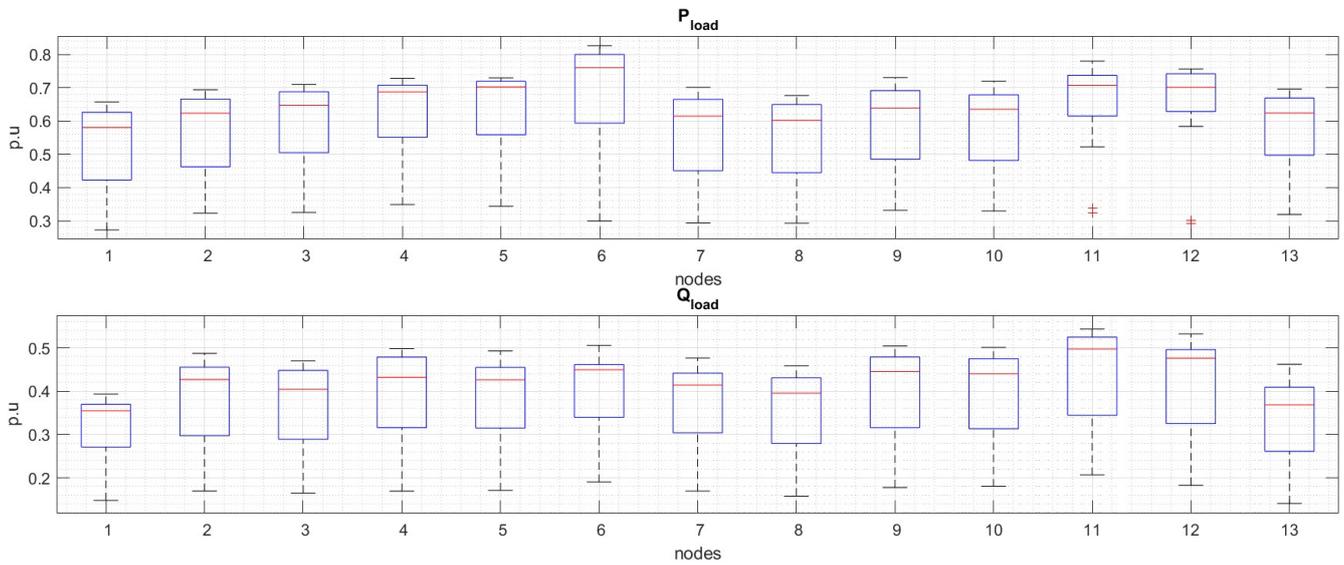

Figure 6. Flexibility (in terms of active and reactive power) of the loads in the scenario "scalability in density, demo network, desired power exchange" (source: [31]).

In addition to these technical findings, a qualitative assessment identifies potential barriers to large-scale implementation in the demo countries:

- Regulatory barriers: The necessity of establishing optimal regulatory frameworks to support the deployment of the tested solutions;
- Stakeholder engagement: Recommendations for enhancing stakeholder involvement in the management of the tested SRA-UCs.
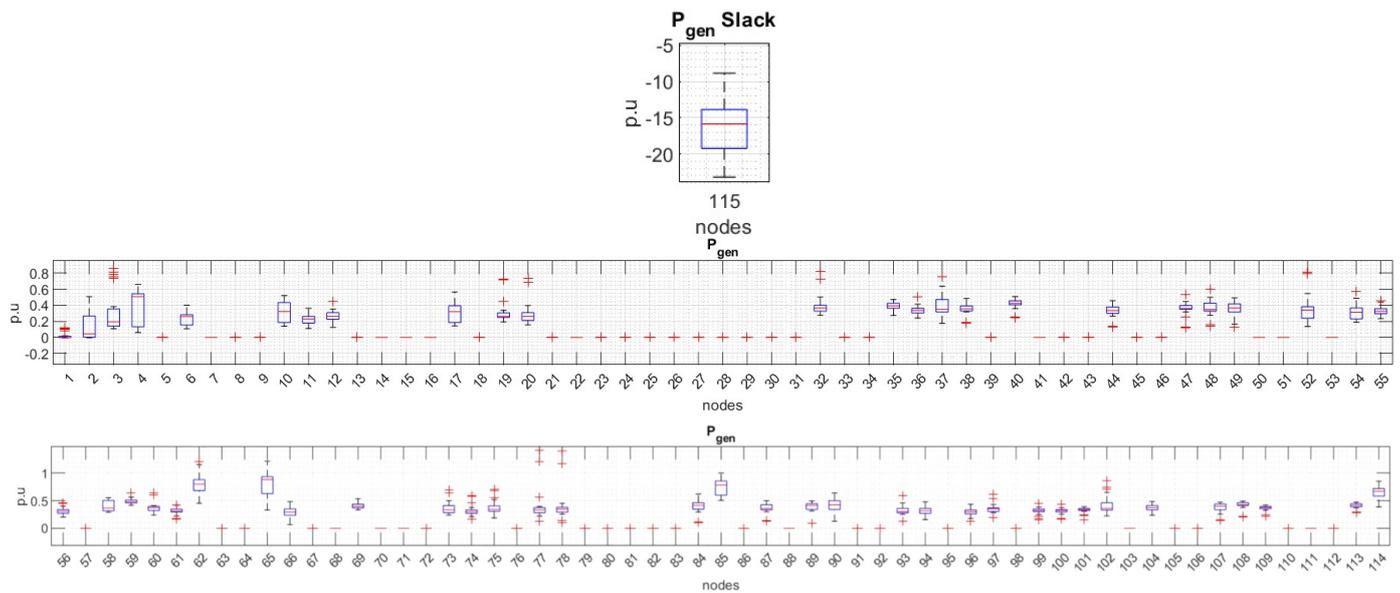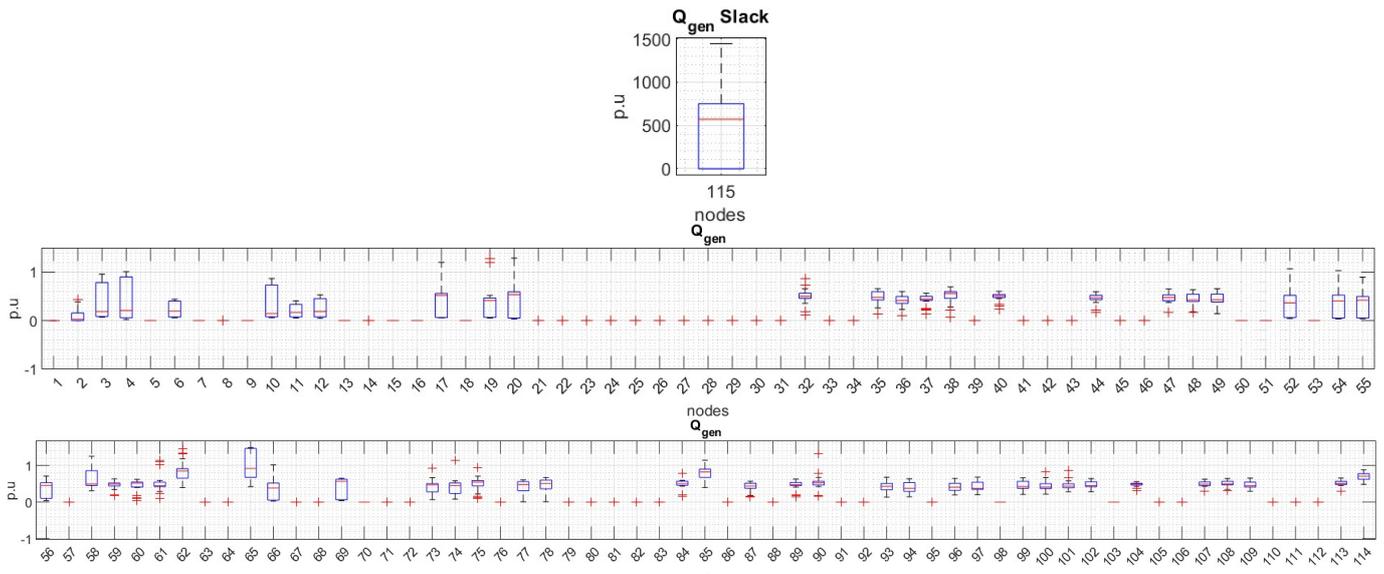

Figure 7. *Cont.*

Figure 7. Flexibility (in terms of active and reactive power) of the generators in the scenario "replicability intranational, semi-urban network, desired power exchange" (source: [31]).
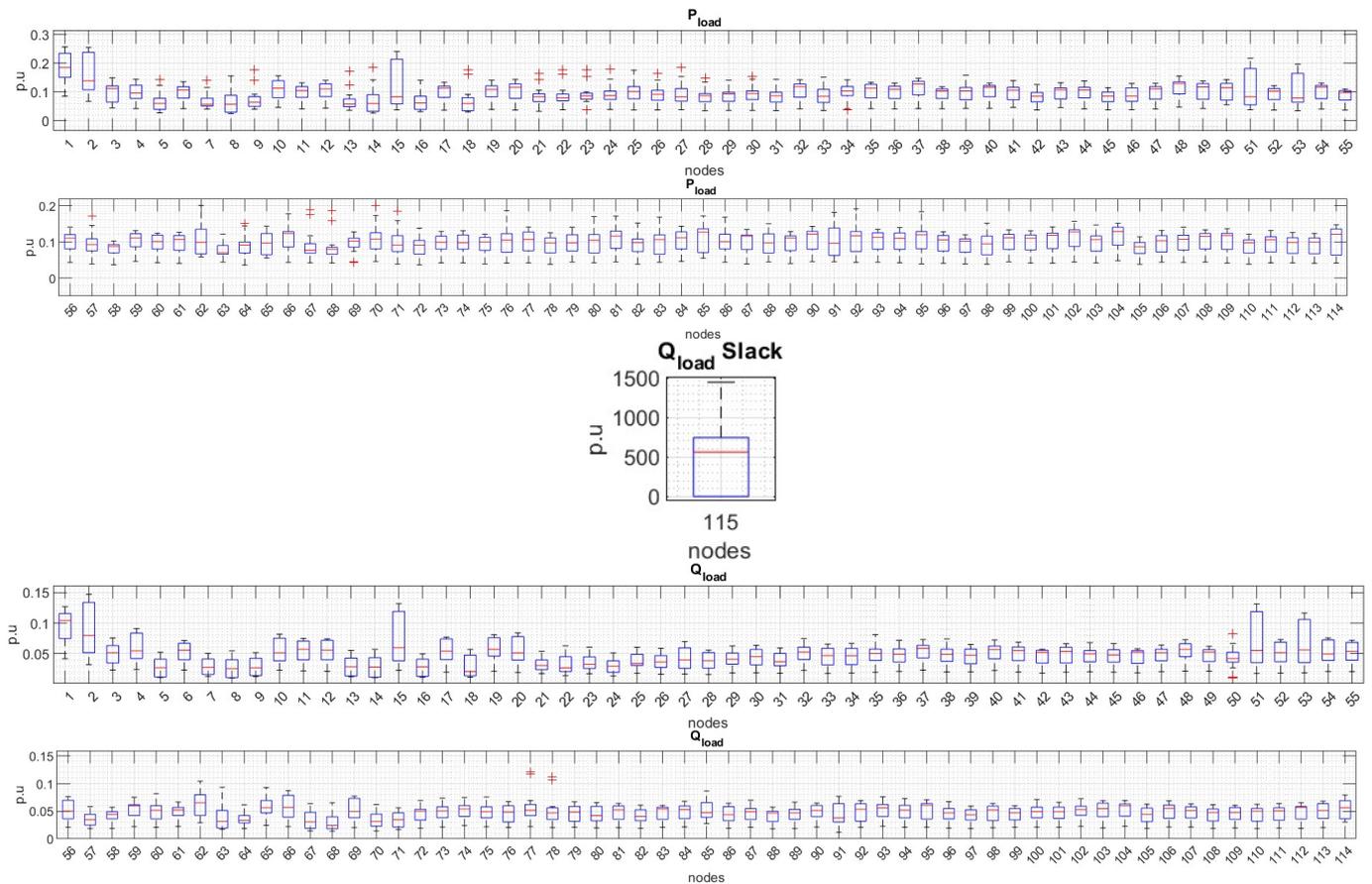
Figure 8. Flexibility (in terms of active and reactive power) of the loads in the scenario "replicability intranational, semi-urban network, desired power exchange" (source: [31]).

In D7.6 the results of all the simulations performed in the SRA are reported (replicability intranational, replicability international and scalability in size. In these simulations the SRA-UCs were simulated using different representative networks to capture different boundary conditions). The specific results of each step are reported in the deliverable;

however, the comparison of the results of each step of the quantitative SRA allows for drawing the following conclusions:

- The results demonstrate that the "desired power exchange" use case, simulating a 10% curtailment in power imported from the MV grid, successfully resolved local congestion through the activation of flexibility services from local distributed generators and flexible loads. In the Italian demo, the Platone platform effectively handled flexibility provision from 30% of customers, with future scenarios exploring higher penetration rates. However, challenges were observed in rural networks where the system needed to exploit a large amount of reactive power to solve local congestion, highlighting the necessity of compensating for voltage drops in areas with longer lines and significant distributed generation;
- For the effective deployment of "zero power exchange" use cases, particularly in semi-rural networks, the provision of flexibility services may need to be supported by the installation of distributed devices like inverters or distribution static compensators (D-STATCOMs) to address reactive power demands. The simulations underscore the feasibility of integrating flexibility services into both urban and rural networks but also identify the technical limitations and potential solutions required for more complex grid configurations [31].

3.1.6. Step 5: Conclusions and Elaborations of SRA Rules

The outcomes of step 4 allow to elaborate the following conclusions:

- The SRA proves that future network congestion, such as those during summer peak days, can be addressed by leveraging distributed flexibility sources and large-scale deployment of the Platone architecture.
- The quantitative results (Figures 5–8) confirm that:
  ○ The "desired curtailment" SRA UC" can be scaled in density, allowing the involvement of 30% of grid customers as planned in utility development strategies.
  ○ The UC can also be replicated in different network configurations, such as rural networks, beyond the original urban pilot.
- Qualitative assessment identifies key barriers to large-scale implementation:
  ○ Regulatory barriers: The need for optimal regulatory schemes to support tested solutions.
  ○ Stakeholder engagement: Recommendations to enhance stakeholder participation in managing the SRA UCs [31].

3.2. The IElectrix Experience: Using Battery Storage Systems and Demand Response to Alleviate Grid Constraints and Enhance Local Energy Self-Generation

The IElectrix project [15] aimed to develop and demonstrate solutions to facilitate and promote the development of local energy communities (LECs). Within IElectrix, LECs were used as a mechanism to speed up the integration of renewable generation, particularly at the lower voltage levels, and enhance end-user awareness and active participation of consumers. Demonstration activities were carried out in four countries, namely Germany, Hungary, Austria and India. These combined smart grid functionalities with end-user and active DER participation, with a strong focus on battery storage systems. The goals of the use cases included the maximization of the consumption of locally produced renewable electricity or the deferral of reinforcements, in both cases using demand response and storage systems, as well as testing the islanded operation of a LEC grid. IElectrix also performed an SRA combining quantitative and qualitative analyses as described below.

3.2.1. Step 1: Select Smart Grid Architecture Model Layers

The IElectrix project followed the BRIDGE guidelines and structured its SRA according to the SGAM. As reported in the deliverable D4.1 [33], up to five SGAM layers were addressed [26]:

- Business layer: the development of LECs is contingent to the transposition and development of certain dispositions in the electricity market directive [34] and the renewable energy directive [35]. Moreover, since the project use cases required the active participation of grid users and innovative approaches by DSOs, a stakeholder analysis was deemed necessary.
- Function layer: the impact of several use cases, particularly those aiming at alleviating grid constraints or islanded operation, strongly depend on the technical characteristics of the grid and its users. Hence, its evaluation requires addressing the function layer.
- Information, communication and component: testing the use cases required the deployment of complex communication, control and information systems. Thus, this layer was included in the SRA to understand to what extent the selected architecture was replicable and scalable.

3.2.2. Step 2: Select SRA Dimensions to Consider in the SRA

Next, the scope and dimensions for the previous five SGAM layers were defined. Concerning the business layer, the focus was placed, on the one hand, on regulation about DSO regulation, demand response, energy communities and self-generation. On the other hand, the stakeholders' viewpoints on LECs were addressed. The functional SRA encompassed the use case replicability and scalability through simulations for 11 distribution networks, 7 MV and 4 LV, in 7 countries: 4 demo countries (Germany, Hungary, Austria and India) and 3 replication countries (Sweden, Greece and France). Further information can be found in Deliverable D4.2 [36]. Lastly, the information, communication and component layers were jointly analyzed through a qualitative approach addressing both the replicability barriers posed by the use of non-standard proprietary solutions or vulnerability to cybersecurity threats and the replicability of the selected ICT architecture as more devices are connected and controlled.

3.2.3. Step 3: Define Methodology for Each Dimension

The methodology developed for each layer and dimension described in detail below.

Functional SRA

A quantitative simulation-based approach was selected to assess the impact of the use cases (D4.1 [33] and D4.2 [36].), measured through a set of use-case-specific KPIs. The seven high-level use cases (HLUC) selected were sorted into four groups, each aggregating HLUCs with similar objectives and assessed through a distinct simulation approach. Table 2 describes the groups that were defined.

For illustrative purposes, the simulation approach used to evaluate the use cases in group 2 is presented. Group 2 comprehends a German and Hungarian demo use cases related to the deployment and optimal operation of a mobile battery to solve voltage violations and congestion in MV networks. These were simulated for the German and Hungarian demo networks and replicated for the Greek, Swedish and Austrian MV networks. The methodology consisted in six main steps displayed in Figure 9:

As shown above several scenarios with different levels of DG penetration and/or peak demand were defined for each grid. Grid constraint violations were identified through hourly power flow analyses and the location of the Battery Energy Storage System (BESS) system was determined considering these constraints and the nodal sensitivity factors, i.e., searching the location where the BESS would have the strongest impact to solve the identified grid issues. Lastly, the hourly BESS charge and discharge profile required to address grid issues throughout the year was determined. This was repeated for several combinations of the BESS power (kW) and capacity (kWh).
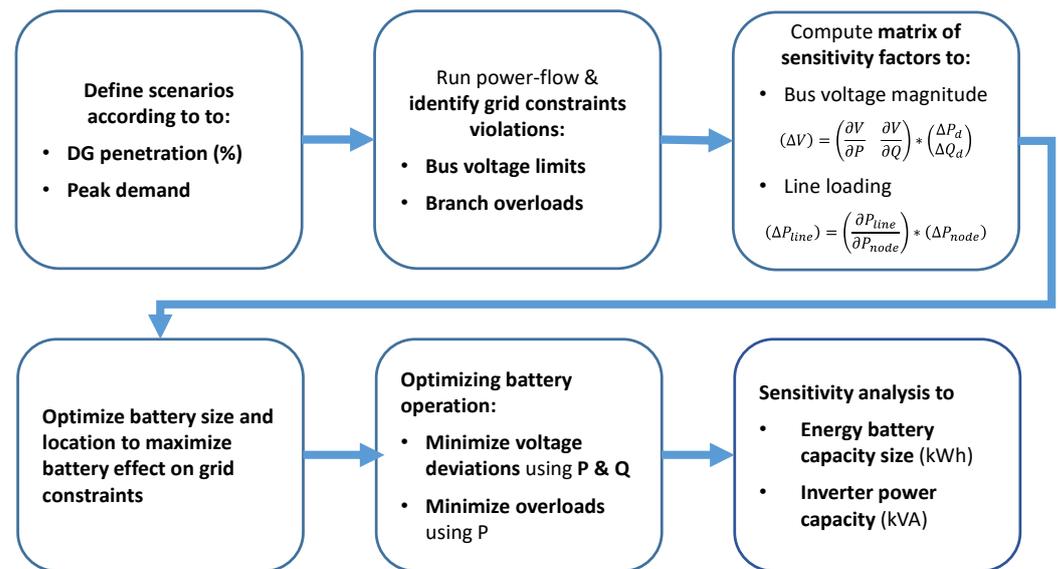
Figure 9. IElectrix simulation approach to perform the functional SRA in HLUC group 2 (source: [33]).

Business Layer—Regulatory Analysis

This SRA dimension aimed to identify potential regulatory barriers to replication or upscaling. The methodology comprised four steps (D4.1 [33] and D4.3 [37]):

I. Identify key regulatory topics.
II. Map regulatory topics to use cases assessing the relevance of each topic for each use cases through a semi-quantitative scale.
III. Characterize national regulation in the seven target countries through questionnaires filled-in by national partners as well as publications by national regulators, other organizations, or academic papers.
IV. Identify barriers and drivers to replication and upscaling through a comparative analysis across countries. A semi-quantitative index named regulatory compatibility was obtained for each use case, combining the relevance of each topic and the regulatory maturity per topic and country.

Business Layer—Stakeholder Analysis

The goal was to characterize the perspectives of stakeholders and end-users in order to deduce how their behavior can affect the deployment and performance of LECs. This was done through a survey-based approach (D4.1 [33], D4.2 [36] and D4.3 [37]). Ad hoc on-line questionnaires were developed separately for end-users and others including: regulators, retailers, IT firms, grid operators, manufacturers, etc. These mostly comprised multiple choice questions where respondents can select multiple preferred options and rank them, to create a user-friendly environment.

Information, Communication and Component Layers—ICT Scalability and Replicability Analysis

A qualitative approach to assess individually the scalability and replicability of the demos ICT architecture was developed (D4.1 [33] and D4.3 [37]) so as to identify possible bottlenecks in the communication system as mapped on the SGAM. First, relevant attributes of the components and communication links were defined and sorted into three categories: reliability, computational resources and manageability.

Through questionnaires adapted to the ICT architecture of each demo, the corresponding partners were asked to fill-in a questionnaire to rate in terms of importance each scalability and replicability attribute on a scale of 1 to 3, as well as to rate the performance through a scale between 1 to 5. Combining both ratings and applying graph theory rules, ICT bottlenecks were identified.

3.2.4. Steps 4 and 5: Perform SRA for Each Dimension and Draw SRA Conclusions and Rules

Some illustrative results are presented below. It is relevant to note that data collection for the simulations in the functional SRA was a time-consuming activity. Further details on these results can be found in D4.2 [36] and D4.3 [37].

Functional SRA

The simulation approach differed for each of the four use case groups described above. Group 2 has been selected to illustrate the results and conclusions drawn. It aimed at testing the effectiveness of a mobile BESS in MV networks to minimize grid constraints. Simulations were performed for seven MV networks for present and future scenarios which present either high level of DG penetration or high peak demand, which cause either voltage violations or congestion problems.

Figure 10 shows the results obtained for a Hungarian MV as the share of remaining hourly over voltages as compared to the scenario with no storage system (base case). Results for this grid, characterized by over voltages and relatively low R/X ratio, show that inverter size is more relevant than the storage capacity. This can be seen in the red dotted box in the table at the bottom of Figure 10, which shows that for a given inverter capacity of 500 kVA, increasing the BESS capacity (kWh) does not significantly reduce grid constraints in this network. The reason is that the reactive power control capability of the inverter is used to control the bus voltages.
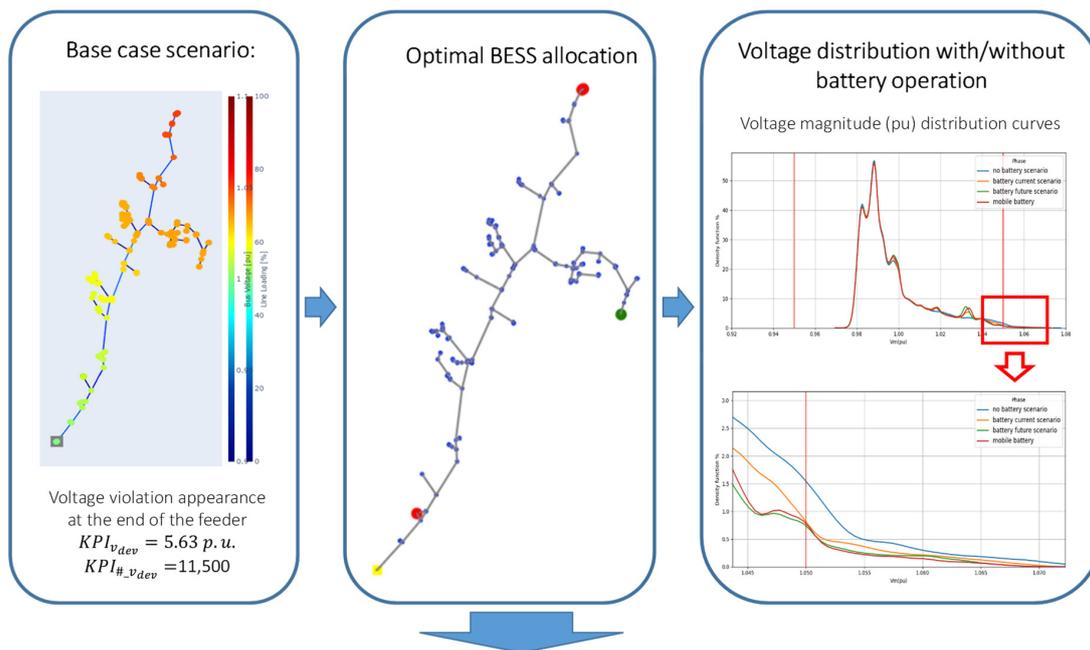
KPI: % number of nodes and hours with problems compared to the initial case without applying the battery							
		Inverter Capacity (kVA)					
		250	500	750	1000	1250	1500
BESS capacity (kWh)	500	40%	19%				
	750	40%	17%	6%			
	1000	40%	16%	5%	1%		
	1250		16%	4%	0%	0%	
	1500		16%	3%	0%	0%	0%
	1750		16%	3%	0%	0%	0%

Figure 10. Overall methodology for the IElectrix functional SRA (source: [36]). Red dots show the location of solar PV units. Green dots the location of BESS. Yellow rectangle shows the primary substation (used as slack bus).

The simulations outcomes highlighted how in networks characterized by voltage violations problems BESS should have high inverter power rather than energy capacity and should be placed towards the end of the feeder. On the other hand, in MV networks characterized by overloads the optimal siting of BESS is downstream the overloaded component. Furthermore, MV grids with multiple consecutive hours with congestion, a high energy capacity (at least 3 h) is preferred. In most cases, BESS sizes of at least 1 MW and/or 1 MWh were required to tackle the network constraints.

Business Layer—Regulatory Analysis

A regulatory compatibility index was obtained for each BUC and target country, combining an estimation of the relevance of the different barriers and a maturity rating of current regulation per topic and country. This index is a compact qualitative evaluation of the extent to which current regulation may facilitate or hamper the implementation of certain BUCs. Figure 11 presents an example of the compatibility index obtained for two use cases: DE-1 (mobile BESS to solve MV grid constraints) and IN-2 (maximize consumption of locally produced energy through demand response). These results show that national regulation still creates relevant barriers to the upscaling and replication of these use cases, and that regulation is generally better adapted to demand response than to the use of BESS for distribution grid support. Nonetheless, the situation differs across countries as some countries such as Sweden or France already have some favorable conditions for demand response and LECs.
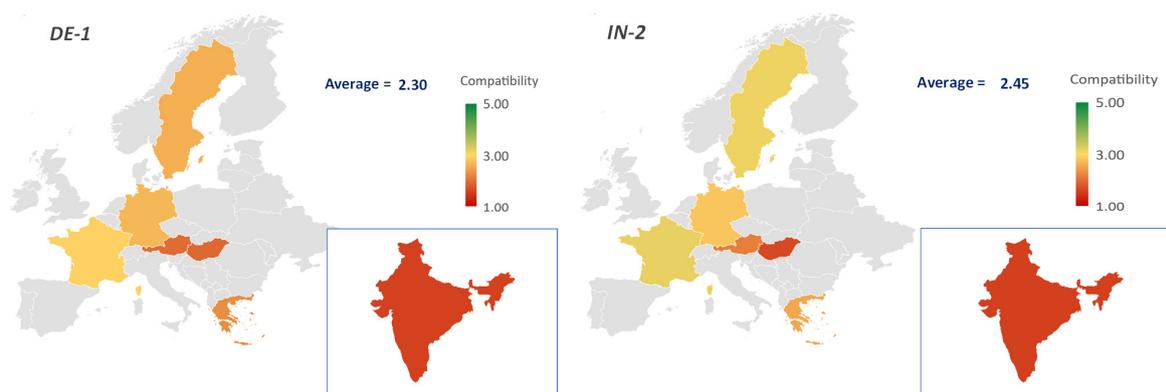

Figure 11. IElectrix regulatory compatibility index obtained for the business use cases DE-1 and IN-2. The higher the value, the higher the regulatory compatibility (source: [37]).

Overall, the most critical regulatory topics identified were:
- DSO revenue regulation fails to place flexible solutions on a level playing field with grid reinforcement;
- Flexible solutions are hampered by one or more of the following: (i) unclear framework for BESS ownership, (ii) flexible connections are not permitted or only as temporary, (iii) DSOs are unable to procure flexibility services;
- Collective self-generation schemes in many cases are either not allowed or limited to the internal network of a single building, constraining scalability;
- The framework defining the conditions to create, organize and operate an energy community is not in place in most of the target countries.

Business Layer—Stakeholder Analysis

The key takeaways from the survey can be summarized as follows:
- Stakeholders associate energy communities with sustainability. Nonetheless, end-users also highlighted concepts such as collectivity or cooperation, whereas stakeholders emphasized energy independence and acceptance;

- Concerning expected benefits of energy communities, consumers selected low emissions, energy independence or lower bills. Institutional stakeholders placed the efficient integration of DG, followed by efficiency in network operation or benefits to end-users (e.g., reduced bills or new services);
- Most consumers stated they were willing to adapt their consumption, whereas, contradictorily, institutional stakeholders mentioned consumers are reluctant to modify their consumption patterns. Both groups agreed on pointing out insufficient economic compensation and regulated tariffs as hindering demand response;
- End consumers declared to be willing to share electricity within the community, and this seems to be a preferred option for people who are already members of an energy communities, indicating that this could be an important driver for consumer involvement;
- Consumers' greatest concerns regarding energy communities was losing control or comfort, data privacy or unclear economic benefits. On the other hand, institutional stakeholders mostly mentioned barriers related to high costs, low perceived benefits or regulatory barriers.

Both stakeholders and end-users viewed energy communities as relevant to facilitate the growth of RES. However, institutional stakeholders seem to regard energy communities as an economic opportunity and a mechanism to increase end-user acceptance, whereas consumers perceive value in the feeling of direct and collective participation in emission reduction. In fact, energy sharing within the community was found to be one of the main drivers for the participation of end consumers.

The survey results pointed out some barriers to the active participation of end users: inappropriate tariff designs, retail market limitations, or lack of trust in the company offering the service by consumers. Results suggest that successful energy communities should focus both on economic benefits and the fact that collective action is being taken to reduce emissions.

Information, Communication and Component Layers—ICT Scalability and Replicability Analysis

Figure 12 shows an example of the aggregate scores obtained for the German demo both for components (left) and communication links (right). The largest the value of the aggregate score, the most suitable for upscaling and replication that particular element of the ICT architecture is and vice versa.

Figure 12. Web diagram with the obtained attribute aggregate scores for components (**left**) and links (**right**) in the German demo—IElectrix ICT SRA (source: [37]).

The results reported in Figure 12 show that the selected ICT architectures do not present unsolvable constraints for upscaling or replication. The main bottleneck detected

is related to the process speed of the component used to communicate between the DSO system and the flexibility service providers (RTUs and BESS controller), which can be easily upgraded either replacing existing devices with higher capabilities or contracting more processing speed from the cloud service provider.

3.3. The EUniversal Experience: Assessing the Performance of Local Flexibility Markets for Different Flexibility Products and Services

The main goal of the EUniversal project [24] was to develop and test a so-called Universal Market Enabling Interface (UMEI). The UMEI is an open, modular, and interoperable API specification enabling the seamless interaction of flexibility service providers (FSPs) and DSOs in different flexibility market platforms. In order to fulfill this goal, EUniversal comprised three different pilots in Germany, Poland, and Portugal, where ten business use cases (BUCs) were tested on actual grids [38]. These BUCs focused on implementing local flexibility markets for DSO flexibility procurement in the short- and long-term, covering congestion management or voltage control services through active and/or reactive power. The EUniversal SRA included a combination of quantitative and qualitative analyses addressing the three previous countries [38].

3.3.1. Step 1: Select Smart Grid Architecture Model Layers

In line with the BRIDGE guidelines (see Figure 2), the SRA methodology was structured according to the SGAM layers. In this case, the layers within the SRA scope were the business, function, and information layers; as described in D10.2 [39] and D10.4 [40]. This selection was based on the following factors:

- Local flexibility markets are meant to be a complement and alternative to conventional grid reinforcements in those areas where this solution is deemed the most suitable from a techno-economic perspective. The outcomes of local flexibility markets are strongly dependent on a number of factors including the distribution grid topology and characteristics (rated voltage, impedances, R/X ratio, etc.) or the local flexibility service providers (FSPs) capabilities. Thus the functional layer was considered central to the SRA;
- The business layer was deemed key to the SRA, as DSOs are regulated entities. Thus, since flexibility markets require fundamental changes in grid planning and operation practices, they also require adapting the regulation as well as to interact with new agents such as flexibility market platforms or FSPs whose business models are still immature;
- Lastly, since the UMEI represents the most important innovation of EUniversal, addressing the information layer was deemed necessary.

3.3.2. Step 2: Select SRA Dimensions to Consider in the SRA

Concerning the function layer, both the use case replicability, considering 4 distribution grids from 3 countries (i.e., international replicability and, in one country, national replicability), and scalability (in density) were carried out. These four distribution networks comprised one MV grid from Poland, two LV grids from Germany, and a distribution grid from Portugal including both MV and LV. Further information on the gris characteristics and the FSPs considered in each case can be found in D10.4 [40].

In the case of the business layer, the focus was placed on the regulatory aspects and stakeholders' perspectives. Lastly, regarding the information layer, the SRA focused on the software replicability. Note that the UMEI, as it consists of an API specification, is scalable by design.

3.3.3. Step 3: Develop Detailed Methodology

The methodology developed for each layer and dimension is described below.

Functional SRA

A quantitative approach was selected for the functional-oriented dimensions. This methodology, illustrated in Figure 13, consisted in simulating the BUCs under different scenarios to assess the effect of changes in the technical boundary conditions, as shown in Figure 13. First, grid models and FSP data are prepared as an input to the simulation models (step 1). Next, the scenarios to evaluate are defined, i.e., what sensitivities in terms of parameters to vary (e.g., DG penetration) and range of variation (e.g., from 0% to 50%) are run (step 2). The third and fourth steps consist of actually running the simulation models, collecting the results, and calculating the KPIs measuring the impact of the uses cases (e.g., grid constraints avoided).
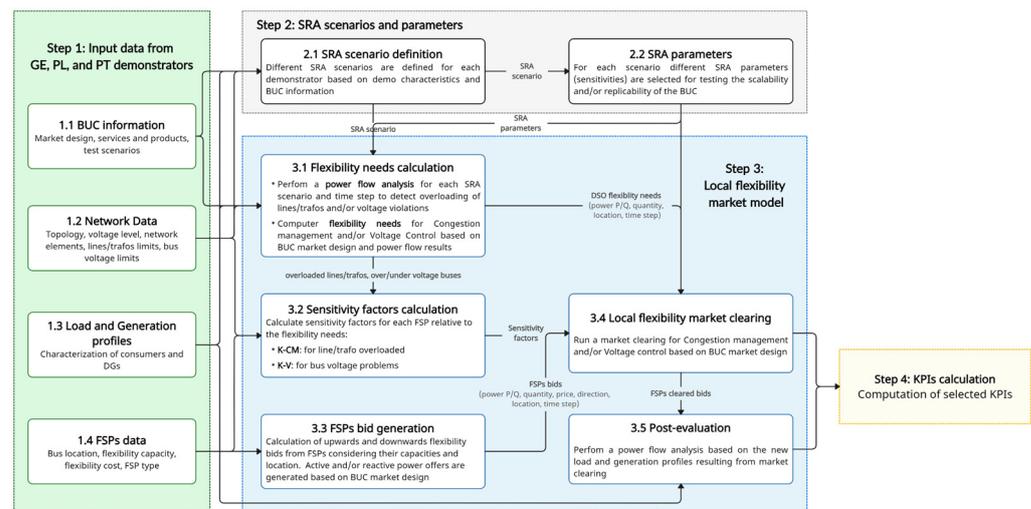

Figure 13. EUniversal functional quantitative modeling and simulation process (source: [40]).

Local flexibility markets (LFMs) are modeled as optimal power flow problems whose decision variables are the flexibility activation from FSPs so that network constraints are solved. The optimization function is the minimization of the flexibility costs plus the cost of the so-called non-served flexibility, which represents a penalty for the grid constraints that cannot be solved. This can happen when all flexibility has been activated or the FSPs are located in an area with no influence over these constraints. The use cases modeled differed according to the flexibility products, i.e., active power only (P), reactive power only (Q), or both (PQ); as well as the service delivered: congestion management (CM), voltage control (VC), or both simultaneously (CM + VC). These resulted in nine different local market specifications (combination of three products and three services).

As shown in Table 4, the German and Polish demos tested BUCs addressing simultaneously congestion and voltage problems using either active power only (CMVC-P) or reactive power only (CMVC-Q). Thus, the additional SRA simulations covered using both active and reactive power flexibility to tackle these problems jointly as well as separately addressing both types of network constraints with the three product specifications (P, Q, and PQ). On the other hand, the Portuguese demo tested congestion management using only active power flexibility (CM-P) and voltage control using both active and reactive power (VC-PQ). Thus, SRA simulations addressed the remaining LFM specifications described above.

Likewise, different scenarios in terms of DER penetration, load increase, or FSP availability and cost were run for the scalability and replicability scenarios. An ex-post evaluation was performed through power flows to compute the relevant KPIs. These KPIs included the avoided restrictions (both congestion and voltage issues), the increase in hosting capacity for DER, the cost of the flexibility procured from the local market, and the avoided CO_2 emissions from the increased grid hosting capacity.

Regulatory and Stakeholder Analysis

A qualitative SRA was selected for the business-oriented dimensions. The aim was to identify key open questions concerning congestion management in European distribution grids through a combination of desk research and stakeholder consultation. As a result, a set of regulatory recommendations to enable the use of flexibility for congestion management were provided. Firstly, a mapping of relevant regulatory topics and stakeholders was carried out [32]. Based on this, the main open questions faced by stakeholders and regulators were identified. The corresponding answers were defined and revised firstly based on desk research and the conclusions were discussed in workshops held with stakeholders both from within the project consortium and external stakeholders such as DSOs, market platform developers, FSPs, or aggregators.

Information Layer—Software Replicability

The UMEI is a set of open APIs that enable seamless interactions among the different actors in local flexibility markets [31]. A quantitative approach to analyze the UMEI API was not deemed appropriate as communications would be made through the internet, not relying on ad hoc communication infrastructures. Additionally, UMEI follows a REST architecture, so it already provides great scalability.

Nonetheless, the adoption of an API can be facilitated or hampered by its design. Thus, if developers find the specification hard to understand, use or update, the possibilities of replicating and scaling-up the UMEI are reduced. Hence, a qualitative SRA methodology to assess whether the best practices for REST API development had been followed was defined. A list of up to 69 best practices was collected from existing studies, divided into seven categories: Uniform Resource Identifier (URI) design, request methods, error handling, metadata design, representation design, client concerns, and versioning. UMEI developers were asked to fill in a questionnaire answering, for each best practice, whether it had been followed during the development stage. Possible answers included: "Yes", "No", "Not sure", or "Not applicable N/A". An overall compliance rating for each category was obtained.

3.3.4. Step 4: Perform SRA for Each Dimension and Draw SRA Conclusions and Rules

The main results are presented below for illustrative purposes. Data collection is particularly critical for the simulation-based analyses performed under the functional layer. Moreover, the evaluation of this dimension is especially complex. Thus, while steps 4 and 5 will be presented together for the business and information layers, the outcomes for the functional layer will be further disaggregated into different steps. Further details on these results can be found in D10.4 [40].

Functional SRA—Data Collection

The quantitative SRA described in Figure 14 requires running extensive power flow studies and optimization problems. The necessary input data were gathered for each demo site, being the most relevant network data (grid topology, impedances, and operational limits), load and generation profiles, and the characteristics of FSPs (rated power, available flexibility, flexibility costs and other constraints). For the sake of illustration, Tables 5–8 summarize the characteristics of the Portuguese network evaluated in the functional SRA.

Table 5. IElectrix HLUC groups for functional analysis (source: [33]).

Group	MV	LV	HLUC Objectives
Group 1	X		Maximize the quantity of local consumption of RES generation thanks to the forecasting and scheduling of DER within the integrated local energy system
			Optimize consumers' participation in DR programs to reduce curtailment or export from local PV production

Table 5. *Cont.*

| Group	MV	LV	HLUC Objectives
Group 2	X		Optimize location and operation of a mobile battery to reduce overloads
			Optimize location and operation of a mobile battery to reduce overvoltages and undervoltages
Group 3		X	Optimize the use of a battery system to reduce local PV generation curtailment and to avoid or differ grid reinforcement due to unbalance loads and DGs
			Optimize consumers' participation in DR programs to reduce curtailment or export from local PV production
Group 4		X	Optimize the resilience of the microgrid due to the islanding capabilities of the local energy system
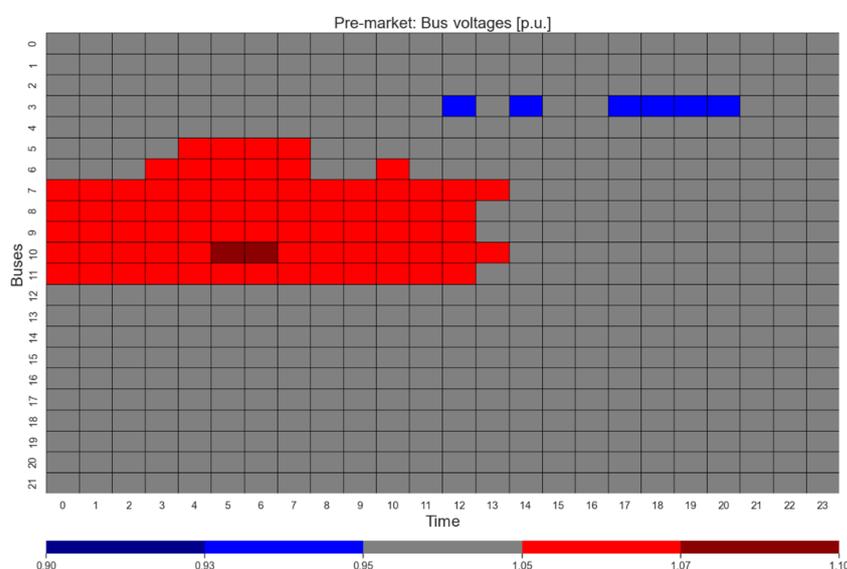
Figure 14. Summary of bus voltage violations [p.u.] for the EUniversal Polish network (source: [40]).

Table 6. IElectrix list of categories and their attribute component/link relevance for ICT scalability (source: [37]).

Category	Attributes (C—Component; L—Link)
Reliability	Autonomy (C)
	Protocol Robustness (L)
	Protocol Availability (C)
	Cyber-Security (C & L)
	Redundancy (C)
Computational resources	Storage (C)
	Processing speed (C)
	Channel capacity (L)
	Channel latency (L)
Manageability	I/O Handling (C)
	Configuration effort/Complexity (C & L)
	Automation (C & L)
	Tech. generation (C)

Table 7. Overview of EUniversal BUCs tested by the demos and simulated in the functional SRA (source: [39]).

Demo	Network	Demo LFM Models	Additional SRA LFM Models
Germany	DE-NET1-LV DE-NET2-LV	CMVC-P CMVC-Q	CMVC-PQ CM-PQ/P/Q
Poland	PL-NET1-MV		
Portugal	PT-NET1-MV-LV	CM-P VC-PQ	CMVC-PQ CM-PQ/Q VC-P/Q

Table 8. Overview of input data for the Portuguese grid analyzed in the EUniversal functional SRA (source: [32]).

Network ID	PT-NET1-MV-LV
Network modeling	Anonymized grid provided by the DSO
Grid level	MV-LV grid 15/0.4 kV
Network elements	1602 buses, 800 lines, 38 transformers, 326 load points (household LV, MV loads, and aggregated secondary substations loads), 18 DGs (PV in LV), 4 storage
Load and generation profiles	Yearly profiles (8760 h) Load profiles based on BTNA-B-C ERSE profiles, and depending on annual consumption of load points. PV profiles based on PVGIS information
FSPs	Selection of FSPs based on demo information: 24 FSPs (load, generation, and storage)

Similarly, Table 9 presents the characteristics of the FSPs modeled.

Table 9. Overview of FSP data for the Polish grid analyzed in the EUniversal functional SRA (source: [39]).

FSP ID	FSP Type	Nominal Capacity [MVA]	Active Power Up/Down Capacity [%]	P Upward Cost [€/MWh]	P Downward Cost [€/MWh]	Reactive Power Up/Down Capacity [%]	Q Upward Cost [€/MWh]	Q Downward Cost [€/MWh]
fsp0		0.8	5%/5%	39.99	39.62		2	1.98
fsp1		0.6		39.41	39.97		1.97	2
fsp2	generation	0.6	0%/5%	39.58	39.91		1.98	2
fsp3		3.2		39.89	40.1	5%/5%	1.99	2.01
fsp4		1.6		40	40.01		2	2
fsp5	storage	0.75	5%/5%	39.57	39.6		1.98	1.98

This information was directly collected from the DSOs leading the project demos whenever possible, subject to NDAs. However, further work was required in some cases. The Polish demo could not provide the real grid topology, so a realistic synthetic network was built with similar characteristics to the real one (voltage level, grid length, or share overhead lines). To this purpose, open data on electrical infrastructure and standard grid components matching the real grid characteristics were used. Furthermore, since several of the demos included LV consumers, real load profiles could not be accessed due to data protection constraints. In these cases, available standard load profiles or average load profiles were iteratively allocated to the individual LV consumers attending to available statistics for the demo areas (e.g., share of residential vs. commercial LV consumers, or

the share of consumers with electric heaters) and power flow data in the corresponding secondary substations.

Functional SRA—Perform the Simulations for the Selected Scenarios

For illustration, an excerpt of the Polish demo SRA results is presented. The complete SRA results are reported in D10.2 [32]. Figure 14 shows the buses experiencing voltage violations for every bus (vertical axis) during the 24 h of the most critical day (horizontal axis). In this case, undervoltages (in blue) were observed in bus 3 between 12 h and 14 h and 17 h–20 h, whereas overvoltages (in red) were identified in buses 5–11 at night and in the morning. Additionally, some overloads were identified; two lines were overloaded in the same feeder where overvoltages were observed, both caused by DG. At the same time, a parallel feeder to the overloaded one was experiencing undervoltages (assuming an acceptable range of ±5%) during peak demand hours as this feeder supplied the largest towns in the area.

After the identification of grid constraints, the LFM modeling environment was run with different LFM specifications and a range of sensitivity scenarios to the available flexibility. These sensitivities, shown in Table 10, represent the scalability in density analysis. Since replicability can be strongly affected by the admissible voltage limits permitted, a replicability sensitivity to the allowable voltage range was performed.

Table 10. Sensitivities to the SRA parameters for scalability, Scenario 1, PL-NET1-MV (Source: [40]).

Parameter	Parameter Description	Sensitivity Range
M01–M02	Limits of maximum and minimum permissible voltage levels for buses	$M0x = [v_{min}, v_{max}]$ $M01 = [0.95, 1.05]$ $M02 = [0.93, 1.07]$
F01–F05	Increase in available flexibility from FSPs	F0x = [5%, 10%, 15%, 20%, 25%]
SK01–SK02	Increase in storage capacity of FSP 5	SK0x = [Nominal Capacity, Twice Nominal Capacity]

Figure 15 displays the resulting values for the avoided KPI restrictions through the use of local flexibility markets as compared to the scenario without flexibility, both in number (voltage constraints and overloads represented through blue and orange bars respectively—left-hand vertical axis) and as percentage (red dots—right-hand vertical axis), for two different LFM specifications: CMVC-P and CMVC-Q. Each set of bars and dot corresponds to a sensitivity scenario; the code shown in the horizontal axis matches the convention shown in Table 10.
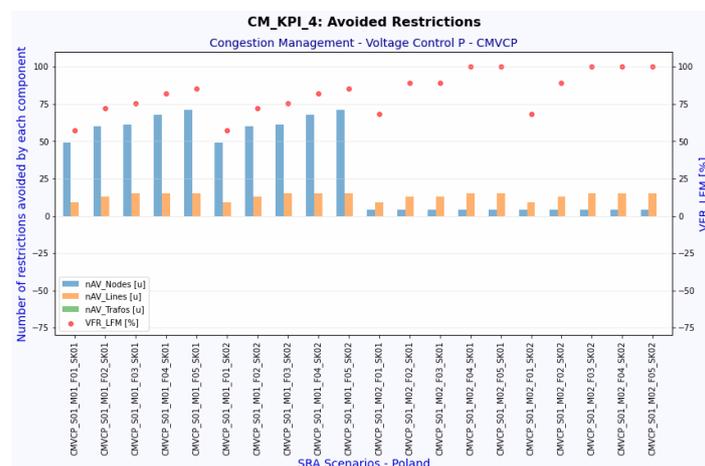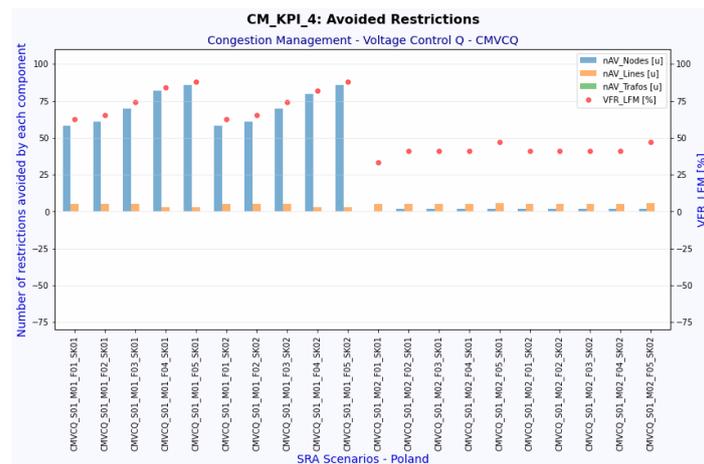

Figure 15. *Cont.*

Figure 15. Example of results for EUniversal Polish demo. Values of the avoided KPI restrictions for the cases of CMVC-p and CMVC-Q (source: [40]).

In the case of the CMVC-P (Figure 15—top) market model, as the sizes of the FSPs increase, the KPI improves both for M01 and M02. In M01, approximately 85% of the criticalities can be solved at most, whereas in M02 all constraints can be solved. This is reasonable since the voltage limits are relaxed in M02. Regarding congestion, all scenarios display similar trends, since the lines' thermal limits may not be relaxed. In the case of the CMVC-Q model (Figure 15—bottom), a similar behavior for M01 can be observed. However, when considering M02, solving the existing criticalities is challenging and no more than 42% of the constraints can be solved. This suggests that reactive power alone may not be effective.

3.3.5. Functional SRA—Step 5—Conclusions and Elaborations of SRA Rules

Assessing the results obtained for the three distribution networks under the different local market specifications, some general conclusions could be drawn.

Regarding the use of different flexibility products, P+Q markets result in lower costs and more constraints solved. This is to be expected as DSOs would have more resources available to address grid constraints. Nonetheless, it is relevant to note that the performance of P-only markets was generally similar in terms of avoided constraints as P+Q, but at a higher cost. On the contrary, Q-only markets may be unable to solve all constraints due to the high R/X ratios, and limited Q availability in the MV and LV grids analyzed. This was observed regardless of the service procured.

On the other hand, when comparing local markets for different services, it was observed that markets where both congestion and voltages are addressed perform better both in technical and economic terms. Voltage control market results are closer to multi-service ones since FSPs solving voltage issues, which are strongly locational, generally contribute to congestion mitigation, but the opposite is not usually true. This rule applies when voltage problems and congestion share the same cause, e.g., increased DG penetration. However, this may not be the case if constraints driven by distinct factors appear in separate areas of the network, e.g., one feeder dominated by voltage drop caused by demand electrification and another one in parallel dominated by DG penetration.

Regulatory and Stakeholder Analysis

Firstly, a set of key open questions about congestion management in distribution grids were defined:

- Is congestion in distribution grids expected to increase, or shall it be avoided through better grid planning?
- Should incentive regulation be enhanced to ensure DSOs take flexibility into account as an alternative to grid reinforcement?

- Under what conditions shall each flexibility mechanism be used and how can adequate TSO-DSO coordination be ensured?

The research and consultation process led to the conclusion that, in spite of applying conservative connection rules for new grid users, some European DSOs face increasing congestion in their grids. Whilst there is no consensus on the changes needed in current distribution planning practices and DSO revenue regulation, third-party market platforms are addressing this gap by proposing alternative flexibility products, market timeframes, and interactions with system operators and existing markets. Lastly, flexibility procurement is expected to be relevant not only for congestion management, but also for voltage control.

The SRA eventually delivered three main recommendations aiming at enabling congestion management through flexibility:

1. Use heatmaps to identify constrained distribution areas and develop guidelines on how to deal with potential trade-offs between flexibility and reinforcements;
2. Be open to several means to contract flexibility, as the impact of combining different approaches is still uncertain;
3. Design legal frameworks for regulatory sandboxes that are clear, open, and up to date, so as to foster innovation in the use of flexibility in distribution grids.

Information Layer—Software Replicability

Figure 16 summarizes the main results (reported in full in D10.4 [40]) obtained for this dimension, i.e., the degree of compliance of the UMEI API with the best practices for REST API design. The percent score for each category was calculated by dividing the number of "Yes" responses over the total number of practices for each category (excluding those where the answer was "N/A"). It was found that the UMEI API allows for a certain degree of freedom when implementing it. Due to this, two cases are shown. The blue line represents the baseline, a situation where none of the implementation-dependent practices are followed; and the orange dashed line (potential case) is obtained assuming all optional best practices are followed during implementation.
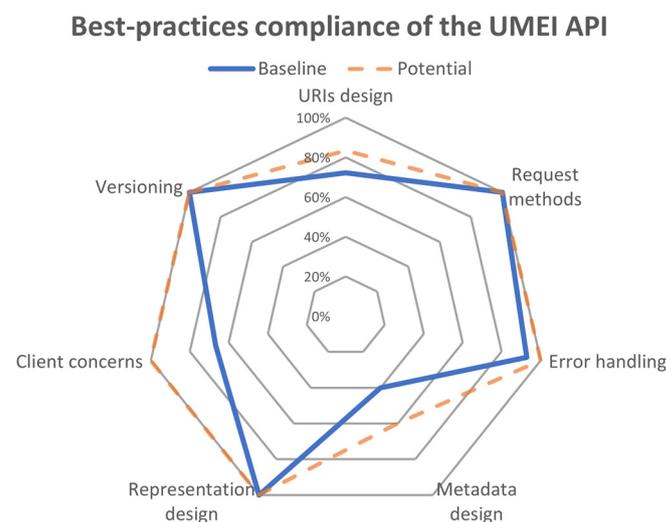

Figure 16. EUniversal information layer SRA main results (source: [40]).

It is shown that, overall, the UMEI presents a high compliance with best practices in REST API design for most categories. The one where the UMEI rated the lowest is metadata design, followed by client concerns (see Figure 16). However, expert developers generally consider these two as the least relevant.

4. Comparative Analysis of Alternative SRA Guideline Applications

Section 3 has shown that the same SRA guidelines can be successfully implemented by smart grid projects tackling different scopes and technologies. The review presented above allowed for lessons to be learned concerning the guidelines' application to each step of the process:

Step 1—Select SGAM layers: The three projects analyzed agreed that the adoption of the SGAM approach provided a useful representation and analysis of smart grid use cases in an architecturally and technologically neutral manner and enabled a better understanding of the activities in the demos. It could be noticed that the three projects analyzed addressed the function, communication, and business layers, while the information and component layers were often not adequately investigated. The business layers include aspects like regulation, business model analysis, and stakeholder acceptance, while the functional layer focuses on the use case definition and impact.

Step 2—Select SRA dimensions: When setting the scope of the SRA for the selected layers, the projects have all encountered a common barrier, which is the limited availability of data needed for the regulatory and technical analyses. Concerning regulatory information, confidentiality is not a major barrier. Instead, the main issue is to gather complete and updated data considering the continuously evolving regulatory environment in European electricity systems. The reviewed projects addressed this challenge by ensuring national stakeholders, generally project partners, provided the required information through ad hoc detailed questionnaires.

On the contrary, technical data collection does face important data access limitations. In fact, as highlighted by Platone and EUniversal, the most important obstacle that hampers technical analysis is represented by the availability of network models that can be used to perform the simulations. Platone solved this issue with the adoption of a set of reference networks that are representative of the average characteristics of the European distribution grids. EUniversal performed SRA simulations using confidential data provided by the project partners. These data are protected by a non-disclosure agreement.

Another significant barrier identified in the projects consists of the adoption of non-standard proprietary solutions or vulnerability to cybersecurity threats and, particularly, the replicability of the selected ICT architecture as more devices are connected and controlled. Note that this is not a barrier per se for performing the SRA, but for the actual replication of the demonstrated solutions. This is why continuous knowledge-sharing efforts to identify and promote standardization are advisable under demo projects.

Step 3—Define methodology: The BRIDGE guidelines for SRA lack clear recommendations for the elaboration of the detailed methodologies of each project. The process of defining a specific SRA methodology is usually the result of interactions among project partners and advisors and is oftentimes affected by several endogenous factors like project use cases, data availability, etc. For example, the economic/business layer was addressed both with qualitative assessment (EUniversal, IElectrix) and quantitative assessment (Platone). The quantitative assessment is eased by the adoption of standardized methodologies like the cost–benefit analysis developed by the European Commission Joint Research and with the multi-criteria (MC) analysis proposed by the International Smart Grid Action Network (ISGAN). These approaches allow for the quantification of benefits (economic and non-economic) enabled by alternative solutions and to elaborate a decision-making problem composed of a set of demo or project-specific Key Performance Indicators (KPIs) pertaining different dimensions (e.g., monetary, societal, environmental, etc.). The adoption of non-proprietary standards obliged the EUniversal project to perform only a qualitative analysis of the information, communication, and component layers.

The experience gathered in the three projects allowed to elaborate these good practices for step 3:

- Each project shall perform a preliminary analysis (possibly in the early stage of the project) aimed at adapting the general guidelines proposed by BRIDGE to their specific use cases and KPIs;

- To support project partners in the development of their own methodologies, it could be useful to create a general repository in which past project can share methodologies, data and results that could serve as reference material to elaborate innovative approaches.

Step 4—Perform the SRA: The quantitative SRA approaches implemented in these projects required performing extensive simulations using power flow studies and optimization problems. The most important barrier in this stage is represented by the complexity of the data collection process. In fact, to perform the necessary simulations, network data (grid topology and operational limits), load and generation profiles, and the characteristics of local generation units, loads, and other flexibility sources shall be collected by the project. These data are typically associated with confidentiality constraints and are often difficult to obtain even from project partners. To avoid potential problems and delays in the last stage of the project, these data shall be identified at the initial stages of the project and dedicated confidentiality agreements shall be signed among parties to smooth the data exchange process.

Step 5—Draw conclusions: according to the BRIDGE SRA guidelines "the last stage consists in analyzing the results obtained in the SRA, first for each dimension individually and subsequently trying to relate among them the results for the different dimensions when relevant. A SRA may also be used to deliver an implementation roadmap which may include a timeline and milestones for the implementation and/or exploitation of the technologies or solutions evaluated and perform simulations." These guidelines thus do not foresee a standardized approach to present the results and this hampers comparisons across different projects. This gap might be further investigated in future guidelines elaborated by BRIDGE or other international working groups to support the decision makers in comparing the SRA potential of different projects.

5. Conclusions

This paper presents a comparison of different approaches for performing the scalability and replicability analysis of smart grid pilot projects. Firstly, the need for a comprehensive methodology to perform SRA has been highlighted as expressed by both the European Commission and the International Energy Agency. The general guidelines proposed by the expert task force created under the BRIDGE initiative have been presented. These consist of a list of steps and recommendations that pilot projects funded by national or European funds shall follow in order to ensure a comprehensive and consistent SRA of the solutions tested in the demos.

Next, the paper describes how three important EC-funded projects (Platone, EUniversal, and IElectrix) have adapted and implemented the general guidelines in order to develop a project-specific methodology. The comparison of the different approaches developed by these projects proved that the BRIDGE guidelines are flexible enough so as to be adopted by different types of smart grid projects. However, several open issues remain. The paper draws some general lessons learned from these experiences and recommendations for future applications for each of the steps in the BRIDGE methodology. The most relevant lessons learned may be summarized as follows:

- The adoption of the SGAM architecture provided the project developers with an effective tool to describe and compare the activities in the demos;
- The projects preferred to select the function and business SGAM layers as the core focus of their project-specific SRA methodologies;
- The selection of the dimensions is often limited by the scarce availability of data needed for both the regulatory and technical analyses (in particular of network models that can be used to perform the simulations);
- In the definition of their specific methodology, each project shall perform a preliminary analysis (possibly in the early stage of the project) aimed at adapting the general guidelines proposed by BRIDGE to their specific use cases and KPIs;
- The most important barrier associated with the performance of the quantitative SRA corresponds to the complexity of the data collection process. To avoid a negative

impact of this barrier in the final stages of the project, it is advisable to identify the necessary data for the simulations early in the project and to sign dedicated confidentiality agreements among parties to smooth the data exchange process;

- Finally, the last stage of the BRIDGE guidelines suggests drawing conclusions based on the SRA results. However, the comparison of different approaches demonstrated that a standardized approach to present the project-specific results does not exist. This issue might hamper the comparison of the results of different projects and, consequently, in the creation of a merit order that could be used by project investors to prioritize the deployment of the solutions tested in the demos. The creation of a "use case repository" suggested in the BRIDGE 2022 report represents a positive effort aimed at mitigating this challenge.

Moreover, the outcomes of the exercise performed in this paper allowed for the elaboration of further general recommendations that might be considered by further updates of the BRIDGE SRA guidelines:

1. Early definition of SRA methodology: The process of defining the SRA methodology should commence at the initial stages of the project. Partners responsible for performing the SRA methodology should collaborate with demo leaders in defining the use cases, Key Performance Indicator (KPI) formulas, and calculation processes. This collaboration ensures consistency between the field results and the results of the simulations or qualitative assessments;

2. Consensus on definitions: There is a need to build consensus on the definitions of scalability and replicability analysis and their boundary conditions. It is essential to agree from the beginning on the specific questions to be addressed;

3. Customization of SRA approaches: It is not feasible to develop an SRA approach that fits all potential use cases tested in demos and the corresponding boundary conditions. SRA developers should create specific methodologies tailored to different use cases, boundary conditions, and available data types;

4. Adaptability of the BRIDGE methodology: The BRIDGE methodology can be applied to SRA across various projects. Each step can be adapted to fit the needs of different pilot projects and use cases;

5. Consistency through BRIDGE guidelines: The BRIDGE guidelines enable different projects to develop methodologies that lead to comparable results, even when these projects address different aspects;

6. Linking SRA and cost–benefit analysis: Future projects should explore the links between SRA and CBA further. The BRIDGE guidelines [41] might also provide additional recommendations to guide new projects in linking these two activities, which, according to EC COMMUNICATION 202/2011 [2], are key elements for ensuring the commercial deployment of innovative technologies. This connection may help overcome the challenge of conducting a sensible CBA on the basis of pilot project results considering that many of the smart grid costs do not scale linearly. This is typically the case with centralized software systems. For example, whilst smart meters scale linearly with the number of users engaged, data collection and data analysis infrastructure and systems do not. As a result, benefits assessed on pilot project results are typically insufficient to justify investing in these due to the limited scope of the pilot. SRA results could be used to assess upscaled benefits through the corresponding KPIs so as to carry out a more balanced CBA. Naturally, this would require a coordinated definition of KPIs and benefit quantification formulas so that both analytical approaches are compatible;

7. The experiences gathered from the analyzed projects reaffirm the flexibility and applicability of the BRIDGE guidelines across a diverse range of initiatives. However, to further facilitate their practical implementation in real-world projects, additional examples and more detailed guidelines should be provided, particularly for those seeking to develop a quantitative approach (step 3.4). To support project leaders in this process, it is essential to offer concrete examples from past analyses, aiding in the

8. Furthermore, increased information regarding software tools developed in previous projects should be made available, and the current needs for future software development should be clearly defined by the SRA expert community. For the formulation of SRA scenarios, additional details on existing benchmarks of regulatory parameters, reference networks, and public datasets are necessary;

9. In step 5, the elaboration of SRA conclusions, a standardized format or a structured set of questions should be developed to assist project leaders in formulating conclusions that are not only specific to their projects but also comparable with those of other smart grid projects that address similar use cases or functionalities. This approach will enhance the comparability and generalization of findings across different projects.

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