PhD-FSTM-2023-142
The Faculty of Science, Technology and Medicine

DISSERTATION

Defence held on 18/12/2023 in Luxembourg

to obtain the degree of

DOCTEUR DE L'UNIVERSITÉ DU LUXEMBOURG

EN INFORMATIQUE

by

Sergio POTENCIANO MENCI
Born on 31st March 1992 in Madrid, (Spain)

SYSTEM ORGANIZATION AND OPERATION IN THE CONTEXT OF LOCAL FLEXIBILITY MARKETS AT DISTRIBUTION LEVEL

Dissertation defence committee

Dr Gilbert Fridgen, dissertation supervisor
Professor, Université du Luxembourg

Dr Friederich Kupzog
Head of Competence Unit Power and Renewable Gas Systems bei AIT Austrian Institute of Technology GmbH

Dr Susanne Siebentritt, Chair
Professor, Université du Luxembourg

Dr José Pablo Chavez Ávila
Professor, Universidad Pontificia Comillas

Dr Nils Löhndorf, Vice Chairman
Professor, Université du Luxembourg

Sergio Potenciano Menci: *System organization and operation in the context of local flexibility markets at distribution level* ,

SUPERVISOR:
Prof. Dr. Gilbert Fridgen

LOCATION:
University of Luxembourg, Kirchberg Campus
Interdisciplinary Centre for Security, Reliability and Trust (SnT)
29, Avenue J.F Kennedy
L-1855 Luxembourg

"Lo que de raíz se aprende, nunca del todo se olvida."

Lucio Anneo Séneca (4 BC - 65 AC)

"El modo de dar una vez en el clavo es dar cien veces en la herradura."

Miguel de Unamuno (1864-1936)

Acknowledgements

I express my gratitude to Prof. Dr. Gilbert Fridgen for providing me the opportunity to be a part of a dynamic group. Together, with my colleagues we shaped and refined it, enhancing our collective learning journey. I'm thankful to my Thesis Supervision Committee (CET), Prof. Dr. Nils Löhndodf and Dr. Friederich Kupzog, for evaluating and enhancing the contributions of this thesis. I extend special thanks to Dr. Friederich Kupzog, who not only motivated me to embark on this academic journey but remained a pillar of support even as our paths diverged.

Further, I wish to extend my gratitude to Dr. Ivan Pavić for his invaluable feedback on my final contributions, Dr. Alex Riger for his unwavering enthusiasm and collaborative spirit, and Dr. Michael Schöpf for providing me the opportunity to contribute, shape, and organize to the Energy Markets team at FINATRAX Group, steered by Prof. Dr. Gilbert Fridgen.

Moreover, I would like to acknowledge that this work has been supported by the Kopernikus-project "SynErgie" by the German Federal Ministry of Education and Research (BMBF), by the Luxembourg National Research Fund (FNR) and PayPal, PEARL grant reference 13342933/Gilbert Fridgen, and by the grant TED2021-131365B-C43 funded by MCIN/AEI/ 10.13039/501100011033 and by the "European Union NextGenerationEU/PRTR. I would like to express their gratitude for the project supervision by the project management organization Projektträger Jülich (PtJ).

- © 2021 IEEE. Reprinted, with permission, from Sergio Potenciano Menci, Barbara Herndler, Friederich Kupzog, Marisca Zweistra, Robert Steegh, and Marcel Willems, Scalability and Replicability Analysis of Grid Management Services in Low Voltage Networks in Local Flexibility Markets: an InterFlex analysis, 2021 IEEE Madrid PowerTech, June/2021.
- © 2023 IEEE. Reprinted, with permission, from Joaquín Delgado Fernández, Sergio Potenciano Menci, Ivan Pavić, Towards a peer-to-peer residential short-term load forecasting with federated learning, 2023 IEEE Belgrade PowerTech, June/2023

In closing, my heartfelt thanks go to my family, who have been my persistent pillars of strength, molding my character and perspective even as I navigated life away from my beloved homeland, Spain, over the past nine years. To my partner, Anna Warum, whose relentless support and patience have been instrumental in these challenging times. To my PhD colleagues, both present (Joaquin, Tom, Reilly, Orestis, Renan, Timotheé, Esti, Iván, Ravi, Eduard, Linda Egor, Christine, Alexandra, Hanna, Pol, Ramin, Laura, Alexandre, Tamara, Rawan and Martin) and past (Charles, Rajon and Caroline), for the unforgettable memories and unwavering support in Luxembourg, an interesting land. And, albeit somewhat selfish, a note to my future self: *"Cuando mires atrás y veas lo que has conseguido, no dudes que esto es un reflejo de ti como persona y como profesional."*

Abstract

The energy sector is presently undergoing a significant transformation towards modern grids, also known as smart grids. Among the various smart grid solutions, local flexibility markets have emerged as a crucial aspect of this transition, particularly for distribution system operators to complement their operations. These are complex market-based solutions that encompass many systems and sub-systems, with their supporting tools offering a wide range of services. Their tools or toolkits must operate seamlessly under current and future scenarios, adapting to evolving policy and performance requirements. Given the complexity of these systems, the large number of tools or toolsets used, and the need for seamless operation across different scenarios, it is necessary to understand their overall design and their limitations in terms of performance for successful evolution, widespread adoption, and practical operation.

This thesis explores two research directions, system organization and operation, across seven peer-reviewed research publications to contribute to the understanding of these emerging solutions. It proposes and analyzes local flexibility markets as a system, along with the tools and toolkits used for their operation. The first two papers focus on the system organization of these solutions by decoding a service-oriented design from a holistic point of view and proposing an integration information system solution to allow for competing local flexibility market solutions. The remaining five research papers focus on the system operation. Two research papers contribute by analyzing specific toolsets used for local flexibility market operations, considering current and future scenarios. Meanwhile, the remaining three research publications focus on specifically designed tools for local collaborative residential forecasting and industrial forecast scheduling that can support stakeholders involved in local flexibility markets. The insights from the seven research contributions can guide and support their practical design, analysis, and application and refine academic discussions.

Zusammenfassung

Der Energiesektor durchläuft derzeit einen bedeutenden Wandel hin zu modernen Netzen, die auch als intelligente Netze bezeichnet werden. Unter den verschiedenen Lösungen für intelligente Netze haben sich lokale Flexibilitätsmärkte als entscheidender Aspekt dieses Übergangs herauskristallisiert, insbesondere für Verteilernetzbetreiber zur Ergänzung ihres Betriebs. Dabei handelt es sich um komplexe marktorientierte Lösungen, die viele Systeme und Teilsysteme umfassen und deren unterstützende Werkzeuge eine breite Palette von Dienstleistungen anbieten. Ihre Werkzeuge oder Toolkits müssen unter aktuellen und zukünftigen Szenarien nahtlos funktionieren und sich an die sich entwickelnden politischen und Leistungsanforderungen anpassen. In Anbetracht der Komplexität dieser Systeme, der großen Zahl der verwendeten Tools oder Toolkits und der Notwendigkeit eines nahtlosen Betriebs in verschiedenen Szenarien ist es notwendig, ihr Gesamtdesign und ihre Leistungsgrenzen zu verstehen, um eine erfolgreiche Weiterentwicklung, eine breite Akzeptanz und einen praktischen Betrieb zu gewährleisten.

Diese Arbeit untersucht zwei Forschungsrichtungen, die Systemorganisation und den Betrieb, in sieben von Experten begutachteten Forschungspublikationen, um zum Verständnis dieser neuen Lösungen beizutragen. Sie schlägt lokale Flexibilitätsmärkte als System vor und analysiert sie, ebenso wie die für ihren Betrieb verwendeten Instrumente und Toolkits. Die ersten beiden Beiträge konzentrieren sich auf die Systemorganisation dieser Lösungen, indem sie ein dienstleistungsorientiertes Design von einem ganzheitlichen Standpunkt aus entschlüsseln und eine Lösung für ein Integrationsinformationssystem vorschlagen, das konkurrierende lokale Flexibilitätsmarktlösungen ermöglicht. Die übrigen fünf Forschungsarbeiten konzentrieren sich auf den Systembetrieb. Zwei Forschungsarbeiten leisten einen Beitrag durch die Analyse spezifischer Instrumente für den Betrieb lokaler Flexibilitätsmärkte unter Berücksichtigung aktueller und zukünftiger Szenarien. Die verbleibenden drei Forschungspublikationen konzentrieren sich auf speziell entwickelte Werkzeuge für lokale, kooperative Prognosen für Haushalte und industrielle Prognosen, die die an lokalen Flexibilitätsmärkten beteiligten Akteure unterstützen können. Die Erkenntnisse aus den sieben Forschungsbeiträgen können bei der praktischen Gestaltung, Analyse und Anwendung helfen und die akademische Diskussion bereichern.

Resumen

El sector energético está experimentando actualmente una importante transformación hacia redes modernas, también conocidas como redes inteligentes. Entre las diversas soluciones de redes inteligentes, los mercados locales de flexibilidad han surgido como un aspecto crucial de esta transición, sobre todo para que los operadores de sistemas de distribución complementen sus operaciones. Se trata de soluciones complejas basadas en el mercado que abarcan muchos sistemas y subsistemas, con sus herramientas de apoyo que ofrecen una amplia gama de servicios. Sus herramientas o conjuntos de herramientas deben funcionar sin problemas en los escenarios actuales y futuros, adaptándose a la evolución de las políticas y los requisitos de rendimiento. Dada la complejidad de estos sistemas, el gran número de herramientas o conjuntos de herramientas utilizados y la necesidad de un funcionamiento sin fisuras en diferentes escenarios, es necesario comprender su diseño general y sus limitaciones en términos de rendimiento para una evolución satisfactoria, una adopción generalizada y un funcionamiento práctico.

Esta tesis explora dos direcciones de investigación, la organización y el funcionamiento del sistema, a través de siete publicaciones de investigación revisadas por pares para contribuir a la comprensión de estas soluciones emergentes. Propone y analiza los mercados locales de flexibilidad como un sistema, junto con las herramientas y los conjuntos de herramientas utilizados para su funcionamiento. Las dos primeras publicaciones se centran en la organización en sistema de estas soluciones, descodificando un diseño orientado a los servicios desde un punto de vista holístico y proponiendo una solución de sistema de información de integración para permitir la competencia entre soluciones de mercados locales de flexibilidad. Las cinco restantes publicaciones se centran en el funcionamiento del sistema. Dos publicaciones contribuyen analizando conjuntos de herramientas específicos utilizados para las operaciones del mercado local de flexibilidad, considerando escenarios actuales y futuros. Mientras tanto, las tres publicaciones restantes se centran en herramientas específicamente diseñadas para la previsión residencial colaborativa local y la programación de la previsión industrial que pueden apoyar a las partes interesadas que participan en los mercados de flexibilidad locales. Los resultados de las siete publicaciones pueden orientar y apoyar su diseño, análisis y aplicación prácticos, así como perfeccionar los debates académicos.

Declaration

I, Segio Potenciano Menci, declare that this thesis is solely my original work and has not been previously submitted for any other degree or professional qualification. I have acknowledged any contributions made by other authors in jointly-authored research papers and have provided accurate citations and references throughout the thesis. To improve the clarity and flow of my work, I have utilized various AI tools, such as ChatGPT, Grammarly, and Writefull. I have reviewed the output generated by these tools to ensure it accurately conveys my intended message and is free of grammatical errors.

Moreover, I have no financial interests to declare and adhere to the principles of transparency and integrity in both public and professional life. I fully understand and commit to ethical research practices and academic honesty. This thesis represents the culmination of my efforts, and I am open to addressing any questions or concerns regarding its content or veracity in an honest and forthright manner.

Luxembourg, 18/12/2023

Sergio Potenciano Menci

Table of Contents

List of Figures

List of Tables

List of Acronyms

ACER Agency for the Cooperation of Energy Regulators. Page 12, 13, 23, 29

BRP balance responsible party. Page 18, 23

CEP Clean Energy Package. Page 27

CP company platform. Page 33

DER distributed energy resource. Page 3, 15, 28, 39

DL deep learning. Page 40, 41, 45

DR demand response. Page 15, 29

DSM demand side management. Page 15

DSO distribution system operator. Page 2, 7, 8, 15, 17, 18, 22–25, 27–30, 34, 36–39

DSR Design Science Research. Page 9, 10

DSRM Design Science Research Methodology Process Model. Page 9–11

DTW dynamic time warping. Page 41, 42

EC European Commission. Page 27–29, 35

EES electrochemical Energy Storage. Page 15

EFDM energy flexibility data model. Page 15, 33, 42

ENTSO-E European Network of Transmission System Operators for Electricity. Page 12–14

ESP Energy Synchronization Platform. Page 33

ESS energy storage system. Page 38

EU European Union. Page 1, 2, 5, 7, 8, 22, 23, 25–29, 35, 38, 40, 43

EV electric vehicle. Page 37, 38

RP research publication. Page 3, 5, 11

RTU remote terminal unit. Page 24

SaaS software as a service. Page 18

SCADA supervisory control and data acquisition. Page 7

SGAM Smart Grid Architecture Model. Page iii, 7, 20, 21, 25, 32, 36

SO system operator. Page 1, 2, 12, 14, 17–19, 22, 23, 27–29, 39

SOA Service-oriented Architecture. Page 8

SoS System of Systems. Page 6, 7, 31

SOTA state-of-the-art. Page 40

SRA Scalability and Replicability Analysis. Page 35–38, 45

SSU smart storage unit. Page 37

STLF short-term load forecasting. Page 40, 41

TF Task Force. Page 35

TLS traffic light system. Page 17, 38, 39

TSO transmission system operator. Page 17, 18, 24, 30, 38

USEF universal smart energy framework. Page iii, 17

VPP virtual power plant. Page 38

XaaS X as a Service. Page 16

I Introduction

1.1 Motivation

As technology and time continue to advance, traditional power systems face new challenges, ranging from efficiency and cost issues to integration, planning, control, and policy constraints, pushing them perilously close to obsolescence [1]. The escalating global climate challenges, such as rising temperatures frequently emphasized during the first quarter of the 21st century [2], along with the natural aging of network components like transformer stations [3], have become pressing catalysts for the need to update and reconsider how we conceive, plan, and operate power systems. These have led to the emergence of a so-called transition period, which in the European Union (EU) roots back to the late part of the 20th century [4].

This transition period has led to the inclusion of renewable energy resources (RES), further inspired by international agreements like the Paris Agreement [5] and stimulated by policy objectives crafted by entities like the EU. For instance, a primary focus in the EU is the aggressive pursuit of electricity generation decarbonization, hailed as a pivotal strategy in the fight against global warming [6]. However, these decarbonization initiatives are broader than electricity production. Over the past decade, the distributed electrification process to contribute towards decarbonization has gained momentum [7], influencing transportation, industrial processes [8, 9], and even residential (consumers' premises) [10].

While these developments of incorporating RES and electrification are positive, desirable, and will further intensify in the forthcoming years [11], they bring their operational challenges from a power system perspective, especially to system operators (SOs) [12]. The integration of RES introduces a degree of volatility due to their weather-dependent nature and varying locations across the electrical network [13]. They can produce reverse power flows, voltage, and current deviations, reducing the hosting capacity of networks, congesting lines, and directly impacting planning, operation [14], and electricity prices [15]. Likewise, the electrification process, spanning different sectors (i.e., transportation, industrial and residential), poses new challenges, including managing peak loads, coordinating with renewable integration, and adapting to changes in demand patterns that can render traditional forecast systems outdated and ineffective [16]. These challenges create an atmosphere of uncertainty at various levels within the power system and challenge the transition.

In their efforts to overcome operational challenges, SOs are increasingly implementing smart grid solutions that utilize flexibility sources as a strategic response. Smart grids —while defined differently across literature [17] — essentially represent bidirectional energy networks capable of monitoring energy flows and adapting to changes in energy supply and demand through two-way communication systems [18]. Meanwhile, flexibility sources can adjust their operation in response to dynamic incoming signals [19]. These smart grid solutions offering using sources can be an alternative or complement to conventional network upgrades and non-wired interventions, such as the curtailment of renewable generation or demand disconnection. By doing so, they aim to lower operational costs and enhance the integration of renewable energy sources and electrification efforts. However, they come with their organization and operation challenges, given the vast amount of devices and stakeholders involved.

SOs can incorporate flexibility solutions through non-market-based or market-based smart grid solutions [20]. Non-market-based solutions aim for direct control of units from the perspective of an SO, such as through direct agreements for conditional connection or disconnection. In turn, market-based solutions strive to control using market processes, usually based on offer-demand intersections or dynamic tariffs (given that the price stems from the wholesale market). However, certain jurisdictions (such as the EU) prefer market-based solutions [21, 22].

While various smart grid market-based solutions exist, local flexibility markets (LFMs) emerge as a pivotal solution as they aim to enable services to any energy actor. Especially, LFM are highly relevant to SOs, in particular, distribution system operators (DSOs) given the nature of LFM offering services at the local level. DSOs can potentially highly benefit from LFM as smart grid solutions to mitigate their voltage and especially congestion management problems [23, 24].

LFMs organization and operation complexity arise from integrating diverse systems (including distribution, transmission, market, consumption, and generation) and sub-systems (e.g., forecasting systems), the variety of stakeholders managing these systems and sub-systems, and the diverse toolkit—comprising models, applications, and functions—necessary for their efficacious planning, communication, and operation. Furthermore, the complexity increases as LFMs and their associated tools need to maintain seamless operation under current and future scenarios. The design of these LFM solutions and their tools must be adaptable to meet evolving policy and performance requirements. For example, policy stipulations may mandate a particular level of distributed energy resources (DERs), thus demanding that the tools function effectively across varying network scales, the number of assets, actors, and information and communication technology (ICT) interconnections. Concurrently, performance requirements defined by stakeholders might require the tools to enhance forecasting metrics to improve efficiency at both individual and system levels. Alternatively, given the diverse operational horizons, operational tools may also need to converge within specified timeframes.

In light of the organization and operation complexity of LFM solutions and their tools, it is necessary to understand their overall design and their limitations in terms of performance against current and future operational performance. This understanding is essential for the successful evolution, widespread adoption, and practical operation of LFMs and the services they offer.

As a result of this understanding necessity, this thesis enhances the understanding of LFMs, focusing on system organization and operation as research directions across seven research publications (RPs), as summarized in Table I.1. Two RPs, address system organization, developing tools to simplify the complexity inherent in LFM solutions by decoding a service-oriented design and proposing an integration solution. The other five RPs research LFM toolkits or tools that can support LFM operation to understand their design and limits in current and future scenarios. The insights provided herein not only guide practical application but also refine academic discussions, enabling precise predictions about performance, events, and behavior within LFMs. Additionally, it further assists in prescribing system and tool designs through guidelines or rules tailored to specific circumstances, ensuring optimal system functionality.

Table I.1: Research publications overview relevant to this thesis.

RP#	Title	Research direction[1]	Reference	Role[2]
RP1	Decoding design characteristics of local flexibility markets for congestion management with a multi-layered taxonomy	Org.	Potenciano Menci and Valarezo [25]	L
RP2	Energy synchronization platform to enable and streamline automated industrial demand response	Org.	Stiphoudt et al. [26]	C
RP3	Scalability and replicability analysis of grid management services in low voltage networks in local flexibility markets: an InterFlex analysis	Op.	Potenciano Menci et al. [27]	L
RP4	Functional scalability and replicability analysis for smart grid functions: The InteGrid project approach	Op.	Potenciano Menci et al. [28]	C
RP5	Privacy-preserving federated learning for residential short-term load forecasting	Op.	Delgado Fernández et al. [29]	S
RP6	Towards a peer-to-peer residential short-term load forecasting with federated learning	Op.	Delgado Fernández et al. [30]	C
RP7	Optimal industrial flexibility scheduling based on generic data format	Op.	Bahmani et al. [31]	C

[1] Org. = Organization, Op. = Operation. [2] L = Lead, C = Co-Author, S = Subordinate Author.

1.2 Thesis structure

This thesis consists of seven primary sections, each focusing on distinct but interconnected aspects of the research covered.

Section I serves as the introduction, delineating the motivation for the research, the research directions explored and its publications, and the structure of the thesis.

Next, Section II offers a comprehensive view of the research approach. It outlines the theoretical background that provides the framework for understanding the research perspective. Additionally, it introduces the central research methodology that guides the investigation carried out in the seven RPs included in this thesis.

Section III delves into the core concept of LFMs, examining them as smart grid solutions. It explores their main concepts (i.e., the definition, flexibility, services, infrastructure, actors, and representation). Furthermore, it provides the regulation context to understand the EU regulation push for such LFM solutions and the challenges they face.

Sections IV and V engage with the contributions to system organization and operation, respectively. Section IV focuses on exploring two contribution tools: a taxonomy and a multi-sided platform design concept. Conversely, Section V investigates various supporting tools and methods such as the analysis for future scenarios and the tool's performance, including operating at distribution level in the context of LFM solutions to mitigate voltage and especially congestion problems caused by the potential increase of RES and electrification on the power system. The other explored tools focus on forecasting and scheduling systems at the consumer side, i.e., residential and industrial levels respectively.

Section VI synthesizes the research conducted, highlighting its limitations and potential future contributions.

The concluding Section VII provides an statement to recognize the research effort is a result of collaboration and benefits from previous research.

The thesis incorporates an Appendix in Section A, divided into three parts. First, it offers a comprehensive summary of the publication portfolio. Second, it outlines the specific contributions for each relevant RPs. Lastly, it includes the pertinent RPs that were instrumental for the thesis' completion.

II Research background

2.1 Theoretical background

Four main concepts serve as the theoretical background to develop the work in this thesis for studying LFM as a smart grid solution.

2.1.1 Concept 1: Power Systems are human artifacts

The first concept emanates from the theories proposed by Simon Herbert in the *"Science of the Artificial"* [32]. In this context, Herbert distinguishes between natural and artificial phenomena, with the former seeking to understand *'what is'* in the natural sciences. At the same time, the latter focuses on *'how things ought to be'* and involves designing, inventing, and implementing systems or artifacts to meet human needs. As complex artificial artifacts, power systems transport and distribute electricity, fulfilling human energy needs. By recognizing power systems as artificial designs, this thesis studies their design and operation and uses simulations to extract knowledge. The use of simulations do not require perfect representations of the studied objects but should align with research intentions, aiming to save computational resources and manage the inherent complexity of power systems.

2.1.2 Concept 2: Power Systems as Systems of Systems

The second concept addresses the conception of power systems as System of Systems (SoS). Ackoff [33] referred to SoS as a manner to describe a combination of individual systems working together for a purpose; meanwhile, Freng [34] issued the following definition: *"A SoS is a system which results from the coupling of a number of constituent systems at some point in their life cycles"* as pointed by Henshaw [35]. Thus, technologically, power systems encompass a collection of interconnected subsystems such as transportation, distribution, generation, consumption, communication, and market systems. As smart grids represent the natural evolution of power systems, incorporating technological advancements to improve energy management, they, too, exhibit characteristics of SoS.

Various authors have adopted different approaches to analyze and design modern energy smart grids. For instance, Lopes et al. [36] present a SoS approach using Model-Based Systems Engineering (MBSE), decomposing the smart grid based on different domains defined by the National Institute of Standards and Technology (NIST). This SoS perspective provides a comprehensive understanding of the interconnections and interactions among the smart grid subsystems. Another approach currently used in the EU is the Smart Grid Architecture Model (SGAM) framework [37]. It provides a consistent and standardized approach to visualize, communicate, and, in some cases, analyze the interconnected systems. For instance, RP4-[28] the SGAM serves as a foundation to represent the different systems interconnected to support congestion management and voltage control services. Furthermore, its use enables the performance analysis of the different systems interconnected by the various actors that participate in the congestion management and voltage control services.

2.1.3 Concept 3: Holonic Structure within Smart Grids

Smart grids necessitate structured organization. Given the intricate nature of these smart grid systems comprising many systems, some can be perceived as holons. The term "holon", as coined by Arthur Köstler, denotes entities that simultaneously function as self-contained wholes while being components of a more extensive system [38]. This duality aptly encapsulates the essence of smart grids, where individual holons amalgamate to create a cohesive, interdependent system and provide a specific use case of smart grids by their conjunct operation.

This dynamic underpins the intrinsic complexity of smart grid solutions. Many internal systems of the smart grid manifest as holons, characterized by their hierarchical architecture and that are autonomous and individual systems. Take, for example, the distribution system overseen by the DSO as an organization[1]. This hierarchy is evident as field components, like measurement and control apparatus within a secondary substation, fall under the aegis of overarching control systems such as supervisory control and data acquisition (SCADA) and operate autonomously without the interaction of

[1] See Ackoff [33] for further information about organizations in the context of systems.

any other external system. Similarly, emerging actors like aggregators organize numerous customers within their portfolio hierarchically, exerting control over various devices and operate autonomously based on certain instructions. Strasser et al. [39] provide examples of this approach and its trend to conceiving smart grids as holonic structures. They explore the trend toward this holonic architecture in future energy systems, utilizing multi-agent systems (MAS) and Service-oriented Architecture (SOA) approaches.

Notably, this hierarchical framework extends beyond a mere single organization, permeating the ICT layers as many of these systems are distributed, being this "a collection of autonomous computing elements that appears to its users as a single coherent system" according to Van Steen and Tanenbaum [40]. In these layers, devices like smart meters, often distributed among consumers, sometimes relay information to data concentrators. These concentrators collect the data, forwarding it to advanced systems, such as a telemetry system within the DSO hierarchy, especially in jurisdictions like the EU.

2.1.4 Concept 4: Local flexibility market solutions are human-designed smart grid solutions composed of a collection of systems, and present a holonic structure

By synthesizing three aforementioned concepts: (1) smart grids as human-crafted constructs, (2) consisting of interconnected systems, and (3) exhibiting a holonic hierarchy, I understand LFMs as intricately human-designed smart grids composed of a collection of systems arranged in a particular hierarchical organization structure where individual systems and sub-systems can operate independently yet cohesively.

This conceptual framework, summarized in Table II.1, facilitates a two-sided analysis of LFMs as holistic systems, and their constituent sub-systems using tools and toolkits to support operation. This thesis, therefore, directs its analytical lens towards system organization and operation, employing modeling and simulation to examine and understand the intricacies of LFMs concerning their design, integration, and operation. The goal is to produce insights that contribute to the development of sustainable energy at the distribution network level.

Table II.1: Local flexibility market literature definitions.

Concept	Basis	Implication
1 - Power Systems are human artifacts	Herbert A [32]	Smart grids belong to power systems and are human-designed artifacts. Thus, their design is necessary to analyze where simulations can be a tool for extracting information.
2 - Power Systems as Systems of Systems	Ackoff [33], Henshaw [35] and Freng [34]	Smart grid solutions are Systems of Systems and thus are LFM solutions.
3 - Holonic Structure within Smart Grids	Koestler [38], Strasser et al. [39] and Van Steen and Tanenbaum [40]	Smart grids can have holonic structures in their forming systems that are autonomous and individual systems.
4 - LFM solutions are human-designed smart grid solutions composed of a collection of systems and present a holonic structure	This thesis	Provides theoretical background to analyze their system organization and operation based on their design from either a holistic or sub-system angle.

2.2 Research approach: Design science research

This thesis follows and implements the Design Science Research Methodology Process Model (DSRM) from [41] considering the research guidelines from [42] as the central methodology [2] to research to achieve the objectives of designing, improving, and analyzing the models and tools (artifacts) created in order to contribute to the development of LFM solutions.

Design Science Research (DSR) is a research method within Information Systems (IS) [41]. It belongs to the design science family of methods extending with computational methods, the traditional qualitative, quantitative, and mixed methods [43]. It emerged to bridge the gap between theory and practice and provide solutions to real-world challenges where creating tangible artifacts, like engineering, computational, and information systems, is essential [41, 43].

[2] I understand research methodology as "a term that describes the strategy of inquiry used to answer a research question" following Recker [43].

The use of DSR serves three purposes. Firstly, it aids in problem-solving by creating new and innovative solutions by constructing novel artifacts [41, 42, 43]. Secondly, it provides a clear set of steps that allow for the ongoing improvement and refinement of the created artifacts (output of the DSRM) through iterative rounds [41]. Thirdly, methods such as quantitative and qualitative can complement it [43].

Concerning its iterative nature, the DSR methodology contains six differentiated steps [41]: 1) problem identification and motivation, 2) objectives of a solution, 3) design and development, 4) demonstration, 5) evaluation, and 6) communication. Several of these steps have entry points for conducting the research, as illustrated in Figure II.1. These entry points are in steps 1 (problem-centered), 2 (objective-centered), 3 (design & development-centered), and 4 (client/context-centered). They provide the researcher with the flexibility to adapt and adjust their entry point to the circumstances and environment data availability, type of solution, and objectives established for the research conducted.

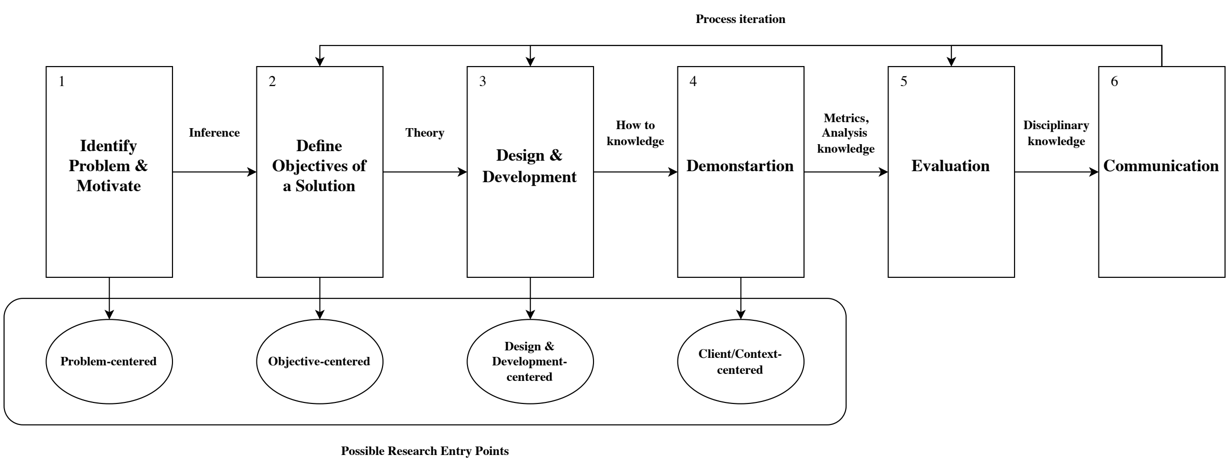


Figure II.1: DSR methodology taken from [41].

Concerning the steps, even though Peffers et al. [41] describe them in detail, for the sake of convenience, these are summarized as follows:

1. Identify Problem & Motivate: Identify a problem or opportunity and explain why it's important to address.
2. Define Objects of a Solution: Clearly state solution goals for the identified problem.

3. Design & Development: Develop the artifact (a solution) based on the defined objectives. It involves designing the conceptual framework, building the artifact, and iterating as necessary.

4. Demonstration: Showcase the artifact's capabilities and functionality. This step allows stakeholders and users to interact with the artifact and provide feedback.

5. Evaluation: Assess the artifact's effectiveness, usability, and impact in the real-world context. It involves collecting data, analyzing results, and refining the artifact based on the evaluation outcomes.

6. Communication: Disseminate the research findings, including the developed artifact, through selected communication channels.

Thus, DSRM serves as a foundational methodology for this thesis to conduct research and combine it with other approaches to create new artifacts that can be used to extract information. From a general point of view, although the seven peer-reviewed RPs contribute to different research directions (i.e., organization and operation), they follow DSRM and combine it with qualitative and qualitative approaches using distant methods, as depicted in Figure II.2.

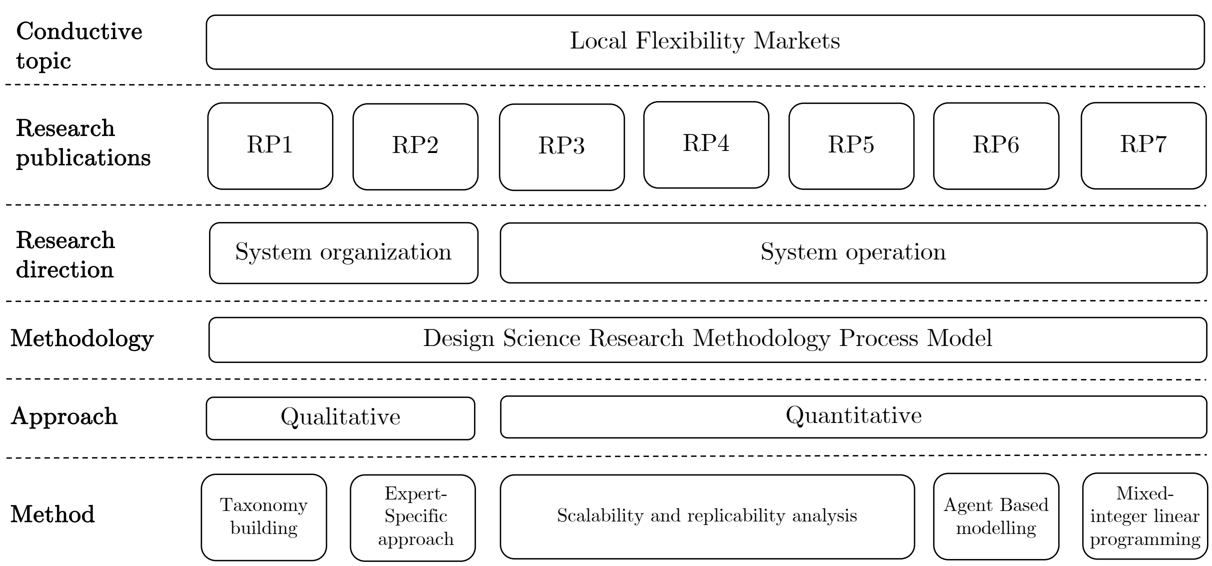


Figure II.2: Methodology, approach, and method overview of the different publications.

III Local flexibility market fundamentals

LFMs are complex smart grid solutions. Consequently, this chapter provides an overview of the intricacies of LFMs. The objective is to explain their foundational and basic concepts, trace their evolution spurred by regulatory paradigms, and delve into the current challenges.

3.1 Concepts

This section examines different concepts related to LFM, including their definition, flexibility, services, architecture, and representation.

3.1.1 Definition

Defining a concept is a complex task [44]. In the case of an emerging concept, it additionally comes with challenges beyond mere semantic exercises and has profound sociopolitical implications [45, 46]. These implications can affect various sectors' academic discourse, policy formulation, and practice. The situation proves to be no exception in LFMs. The definitional challenge stems partly from the novel, inherently dynamic, and evolutionary nature of LFMs as research on this topic gains more traction. When a topic is in such a nascent evolutionary stage, its discourse opens up to new actors with their interests, interpretations, and understandings [46, 47]. This is reflected in a burgeoning body of literature, encompassing academic papers, gray literature, and authoritative insights from key industry stakeholders such as regulatory bodies agencies like Agency for the Cooperation of Energy Regulators (ACER) and SOs associations like European Network of Transmission System Operators for Electricity (ENTSO-E) RP1-[25]. The many interpretations proposed as collected in Table III.1 taken from RP1-[25] underscore the complexity of arriving at a commonly accepted definition for LFM, a term replete with evolving nuances and potentially divergent implications. When choosing a specific definition for LFM, the risk emerges to substantially determine future developments, including, for instance, inadvertently stifling the proliferation of innovative business models.

Table III.1: Local flexibility market literature definitions adapted from RP1-[25].

Author	Year	LFM Definition
Ramos et al. [48]	2016	*Long- or short-term trading actions for flexibility in a specific geographical location, voltage level, and system operator (DSO and TSO), given by grid conditions or balancing needs, where participants in a relevant market can be aggregated to provide flexibility services*
Olivella-Rosell et al. [49]	2018	*An electricity flexibility trading platform to trade flexibility in geographically limited areas such as neighborhoods, communities, towns, and small cities.*
Radecke et al. [50]	2019	*Mechanism that i) aims to relieve congestion in the distribution grid, ii) works through impacting the dispatch of generation, load and/or storage assets, with iii) voluntary participation, and iv) remuneration that is determined based on participants' bids*
Correa-Florez et al. [51]	2020	*Independent trading space/platform with specific bidding rules*
Ziras et al. [52]	2021	*A market-based solution to trade flexibility locally between flexibility providers and Distribution System Operators (DSOs).*
Dronne et al. [53]	2021	*A local flexibility market is typically used to provide services for the flexibility needs inherent to the Distribution Network Operator (DNO).*
Faregard et al. [54]	2021	*Enablers of explicit DSF, which can be used for several purposes such as managing grid congestions*
Singh et al. [55]	2022	*Trading mechanism for electrical flexibility in geographically constrained regions like communities, neighborhoods, and towns. The LFM provides a competitive trading platform that allows flexibility purchasers, such as DSOs and Balance Responsible Parties (BRPs), to trade flexibility with flexibility sellers, such as aggregators and prosumers.*
ENTSO-E [56]	2022	*Specifically aimed solutions at resolving constraints on the distribution network.*
ACER [57]	2022	*Markets where service providers offer products for local SO services*
Valarezo et al. [58]	2023	*A marketplace that enables buyers and sellers to trade flexibility services to address local needs.*
Potenciano Menci and Valarezo [25]	2023	*Information system solutions that enable buyers and sellers to trade flexibility-services to address local needs."*

In the case of LFM solutions, excessive inclusivity could result in an assemblage of sub-concepts with marginal differences, engendering needless complexity and hindering a comprehensive understanding of the energy system RP1-[25]. To strike a judicious balance and pragmatism, the proposed operational definition for LFM is: "*Information* *system solutions that enable buyers and sellers to trade flexibility-services to address local needs*" RP1-[25]. This definition incorporates the terms "local" and "flexibility" (See Section 3.1.2, allowing for specificity in geographic considerations while preserving the intrinsic flexibility required for dynamic market configurations. It also incorporates the term "information system" to remark that these systems go beyond a mere marketplace and, although seen as one system, it require many other systems in reality. It is important to note that in economic terms, given that LFM are markets -*"Any institution or mechanism that brings together buyers (demanders) and sellers (suppliers) of a particular good or service"* [59][1]. A service is *"An (intangible) act or use for which a consumer, firm, or government is willing to pay"* [59][2]. Achieving a harmonized and inclusive definition can be essential for advancing theoretical constructs and actionable strategies in this emergent field. In the case of Europe, it is essential as the EU Commission considers LFM a pivotal part to contribute and help the EU become a climate-neutral continent by 2050 [60].

3.1.2 Flexibility

The construct of "flexibility" in the power system exhibits a bifurcated definition. When observed from a holistic vantage point, ENTSO-E defines flexibility as the system's ability to cope with variability and uncertainty in demand, generation, and grid availability. Conversely, when viewed from an asset-centric perspective, it refers to the potential emanating from an array of assets to provide a service by adapting its operation to dynamic and changing signals [19, 61].

From this asset-centric perspective, academic literature categorizes flexibility sources in the power system into three cardinal types: grid-side, supply-side, and demand-side sources [62].

Grid-side resources under active distribution grids encompass mechanisms not limited to network reconfiguration [63] and on load tap changers (OLTCs) RP4-[28]. These mechanisms enable SOs to recalibrate owned assets to meet emergent demands. However, the mechanical nature of these solutions, coupled with their finite operational lifespan, wanes with increased use. Hence, SOs optimize their operation and consider other sources of flexibilities as complements to minimize their use.

[1] Taken from the glossary: G-17 [59] [2] Taken from the glossary: G-25 [59]

On the supply side, DERs — ranging from wind and solar to hydro, hydrogen, biogas, biomass, and storage solutions — herald flexibility by dynamically modulating their operations [64].

Electrical consumers dominate demand-side as they drive alterations in electricity consumption patterns. Approaches like sector coupling, which synergistically integrates energy-demanding sectors with the broader energy matrix [65], utilize Power-to-X technologies, thus becoming alternative flexibility sources for solutions like LFMs. Further supporting demand-side flexibility is incorporating electricity consumers as flexibility sources. Programs such as demand side management (DSM) can unlock the demand sector's potential, given possibilities from the industrial sector [66]. To harvest the demand-side flexibility, although DSM aims at a longer-term horizon, demand response (DR), focused on shorter-term horizons [67], can become a cornerstone for certain LFM services, such as DSO-oriented services that might require this shorter-horizon flexibility RP1-[25].

The corpus of literature is substantial when considering the attributes and characteristics that define these flexibility sources. The most prominent being direction, rate of change, response time, duration, and location [68]. Nevertheless, the panorama is more intricate with lesser-cited attributes like delivery time, availability, predictability, and controllability, adding to the granularity of their descriptions [68]. These nuanced attributes underscore the fact that flexibility sources are not monolithic. Their service offerings are contingent on their technical attributes. For instance, while a photovoltaic (PV) system's service requires daylight hours, an electrochemical Energy Storage (EES) can operate unfettered by such daylight constraints. Furthermore, service requisites differ; some demand swift response times, while others prioritize extended durations as Figure III.1 depicts [69].

Consequently, effectively describing technical information in a way that allows it to be shared when using or considering a service is crucial. Naturally, data models offer the structure to share "flexibility" information. Although it is challenging to capture the complexity of incorporating many different attributes and yet provide a customizable, harmonized, and generic data model, literature has expanded in this direction. For instance, a comprehensive and generic data model like the energy flexibility data model

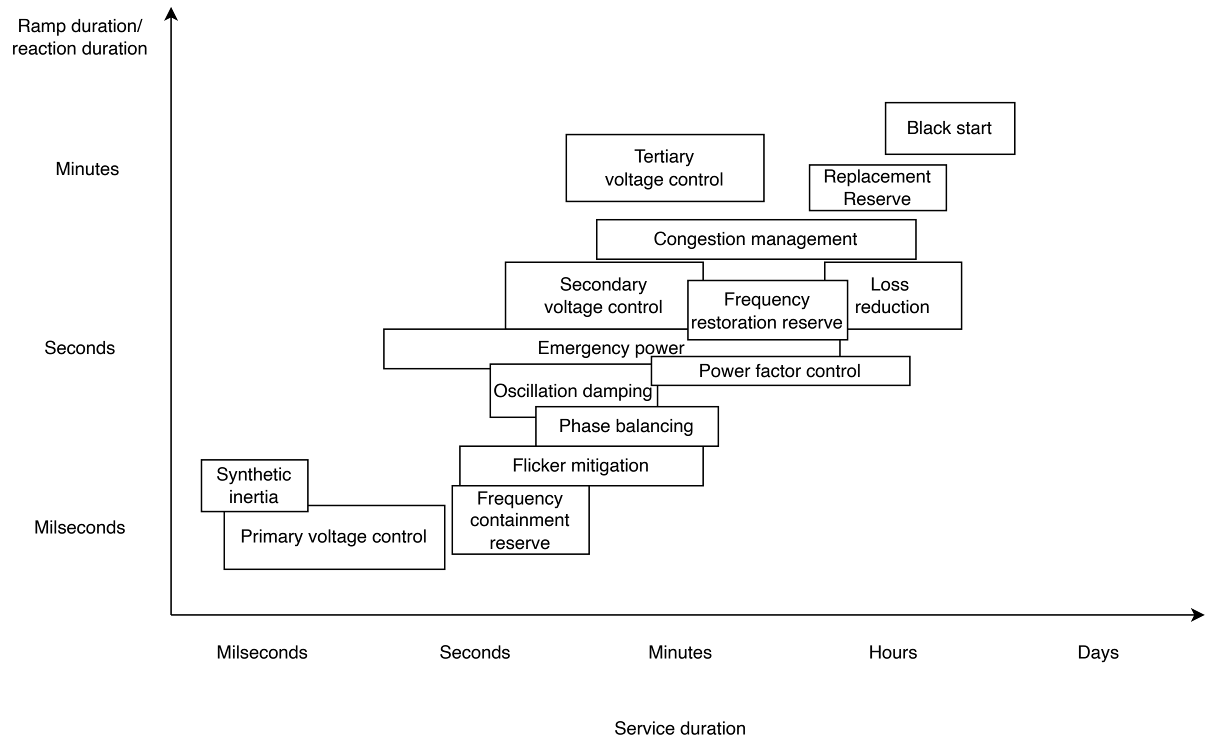


Figure III.1: Service time constraint based on [69].

(EFDM) can be used to describe flexibility in terms of the attributes based on the service needs as proposed in [70], enhanced in [71] and used in [31].

3.1.3 Services

Section 3.1.1 defined LFM and incorporated the notion of "service" within. Grasping this concept is important to comprehend the plethora of emerging services in the energy sector. Indeed, the energy sector is transforming, emphasizing the service model. For instance, Singh et al. [72] examined 240 start-ups offering X as a Service (XaaS) models that emerged between 2014 and 2020 in Germany. Though to a lesser extent, this trend also impacts LFMs. These markets host various services, and Figure III.2 illustrates a simplified overview, categorizing these services based on key stakeholders engaging with LFMs. However, this landscape of these services remains in oscillation, with many services expected to undergo adaptation, reorientation, and evolution as the final direction of LFMs is not yet clear from a regulatory point of view in Europe [57].

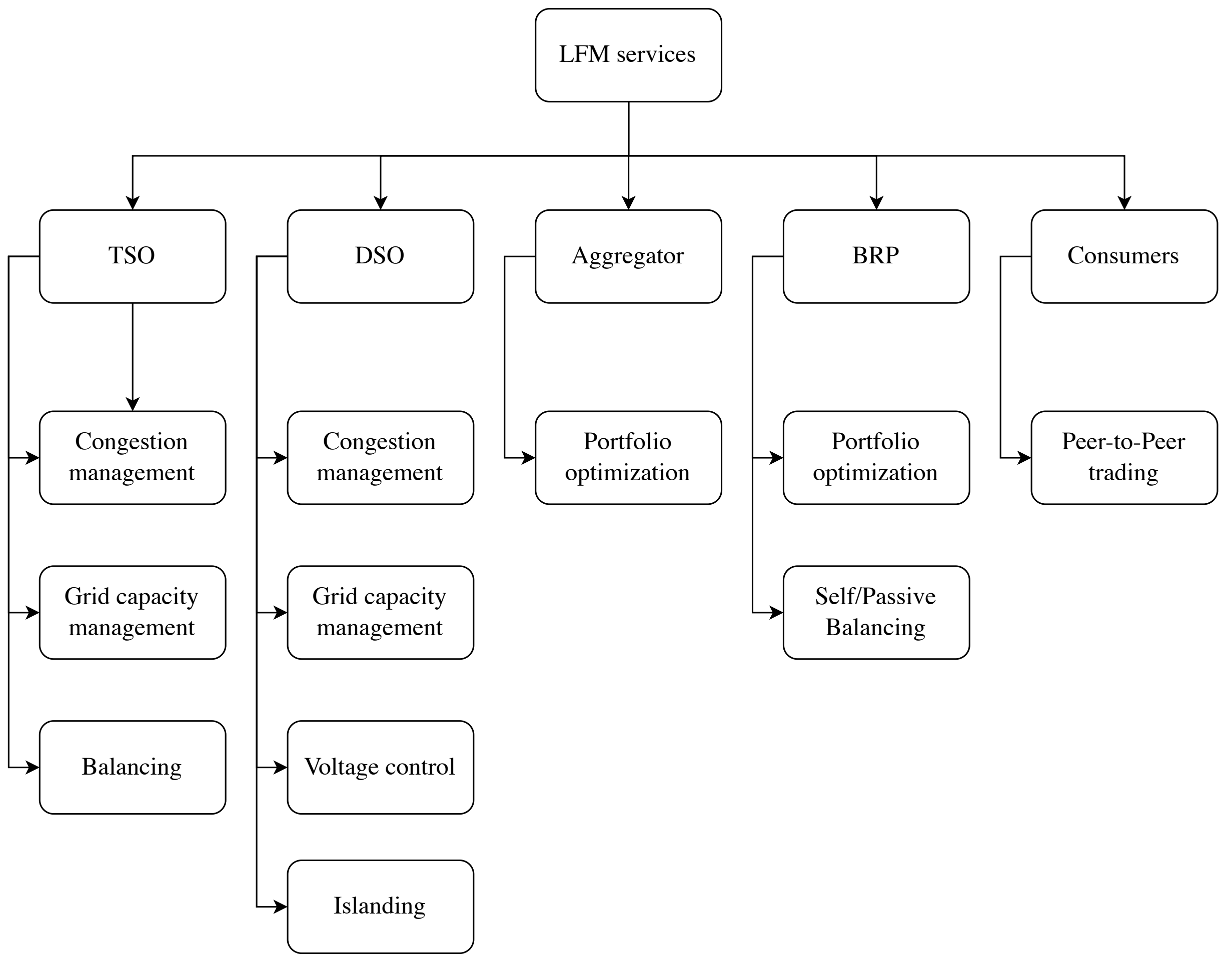


Figure III.2: Service categorization per actor based on universal smart energy framework (USEF) [73].

In relation to the services themselves, SOs, comprising both transmission system operator (TSO) and DSO, may employ varying services to support their operational efficiency. Specifically, TSOs, by leveraging coordination mechanisms within LFM like a traffic light system (TLS) [74], can harness local resources situated at the distribution level for tasks like congestion management, grid capacity management, or balancing.

It is essential to distinguish between congestion management and grid capacity management. While often used intermingled, they are conceptually different, although current LFM solutions include capacity management as a longer-term product to trade flexibility under congestion management services RP1-[25]. Congestion management is concerned with mitigating peak loads to avoid system components becoming overloaded, thus preventing potential failures. This approach is a temporary measure applied when the grid cannot cope with an increase in load or generation on time [73]. Meanwhile, grid capacity management involves leveraging flexibility to improve operational efficiency without impeding on dispatch, trade, or connection freedom. The SO is responsible for this long-term solution, which adheres to the copper plate principle and aims to reinforce the grid [73].

On the other hand, the DSO using LFM might only sometimes necessitate coordination systems if other SOs participate in the same LFM. Similarly to the case of the TSO, they can independently manage congestion and grid capacity or include these with other services such as voltage control. An instance worth mentioning is islanding—a niche yet potent tool for DSOs when maneuvering microgrids [75].

Aggregators can participate in LFM solutions to refine their local portfolios, drawing parallels with strategies formulated by balance responsible partys (BRPs) to avert imbalances and, in turn, evade penalties levied by the TSO. In contrast, customers can exploit LFM solutions, tuning both their consumption and generation profiles for optimal outcomes. However their participation in these services might conflict with SOs operation as they can cause potential problems in the network RP4-[28].

3.1.4 Infrastructure

To deliver their services, LFMs use digital platforms. In simpler terms, platforms can be defined as a set of digital resources, which includes services and content that facilitate value-creating interactions between external producers and consumers [76].

The increasing adoption of platforms is a clear indication of the ongoing digitalization trend in various industries [77]. Even the energy sector has not been immune to this trend. While large companies incorporate platforms into their operations, many other energy service providers have developed their digital infrastructure. A comprehensive study by Duda et al. [78] examined 46 European energy platforms. They classified them into different types (archetype) based on a taxonomy: (1) Research-driven Energy Platforms, (2) Energy Flexibility Platforms, (3) software as a service (SaaS)-Aggregators/Virtual Power Plants, and (4) (Manufacturing) Internet Of Things (IoT)-Platforms.

Positioning LFM within their taxonomy aligns with the second archetype: the Energy Flexibility Platforms. More in detail, RP1-[25] conducted a review concerning 53 use cases of LFM solutions aimed at distribution level offering services for the SO. The examined solutions are collected in Table III.2, a modified Table from RP1-[25], to remark that all these developed, tested, and ongoing solutions use platform infrastructures. From these solutions, it is clear that research is creating and using mainly self-developed platforms, while few only use third-party platforms, like NODES [79] or Piclo [80].

Table III.2: Overview of local flexibility market solutions implemented in Europe since 2016 based and adapted from RP1-[25].

Use Cases	Status	Countries	Platform?	Name
Ecogrid 2.0: BC3 Flexibility services at DSO level	2016-2019	DK	✓	Own platform
Cornwall LEM	2016-2020	UK	✓	Own platform
InterFlex: FR-UC3, NL demo	2017-2019	FR-NL	✓	Own platform
Enera: Northwest of Germany use case	2017-2020	DE	✓	Own platform
EU-SysFlex: Portuguese demo PT-FxH-RP	2017-2020	PT	✓	Own platform
EU-SysFlex: FI demo	2017-2021	FI	✓	Own platform
EU-SysFlex: Italian demo IT-AP	2017-2021	IT	✓	Own platform
NODES: Mitnetz	2018-2021	DE	✓	NODES
CoordiNet: BUC-ES-1b, BUC-SE-1a/1b	2019-2022	ES-SE	✓	Own platform
CoordiNet: BUC-GR-2a/2b	2019-2022	GR	✓	Own platform
CoordiNet: BUC-GR-1a/1b	2019-2022	GR	✓	Own platform
CoordiNet: BUC-ES-4	2019-2022	ES	✓	Own platform
NODES: NorFlex	2019-2022	NO	✓	NODES
EUniversal: BUC-PT1	2020-2023	PT	✓	NODES
OneNet: WECL-ES-01/02, EACL-HU-02, EACL-SL-01	2020-2023	ES-HU-SL	✓	Own platform
OneNet: EACL-HU-01, EACL-SL-02	2020-2023	HU-SL	✓	Own platform
OneNet: EACL-CZ-01/02/03	2020-2023	CZ	✓	Own platform
OneNet: SOCL-CY-01/02, EACL-PL-01/02/03/04	2020-2023	CY-PL	✓	Own platform
EUniversal: BUC-PT2	2020-2023	PT	✓	Own platform
EUniversal: BUC-DE-AP/RP, BUC-PL-AP/RP, BUC-PT3/4	2020-2023	DE-PL-PT	✓	Own platform

Continued on next page

Table III.2 – Continued

Use Cases	Status	Countries	Platform?	Platform
Flexible Power: National Grid Electricity Distribution, SP Energy Networks, Northern Power Grid, Scottish and Southern Electricity Networks	In operation	UK	✓	Flexible Power
NODES: Smart Senja	In operation	DE-NO	✓	NODES
NODES: SthlmFlex	In operation	SE	✓	NODES
Piclo: UK Power Networks, Electricity Northwest	In operation	UK	✓	Piclo
GOPACS	In operation	NL	✓	GOPACS
Enedis: local flexibility platform	In operation	FR	✓	Own platform
OMIE: IREMEL and DRES2Market	In development	ES	✓	Own platform

Yet, behind the scenes, LFM platforms, like all digital platforms, require a combination of infrastructure and components to deliver their services. To provide a holistic overview of the different infrastructure required for LFM solutions, Jin et al. [23] and Zikos et al. [81] highlight four main infrastructures: (1) Power grid layer, (2) ICT layer, (3) Control layer, and (4) Market layer. Going into further detail, it's worth noting that LFM solutions fall under the umbrella of smart grid solutions as discussed in Section II. A consistent and standardized approach that provides a deeper overview of these infrastructure solutions is the SGAM, whose origins can be traced back to the M/490 EU mandate [37]. At its heart, the SGAM disseminates a smart grid solution across five interoperable layers as depicted in Figure III.3. These layers are:

1. Business layer: This layer provides a business perspective on the information exchange related to Smart Grids. It allows the mapping of regulatory and economic structures.

2. Function layer: This layer describes the services in the Smart Grid and their relationships from an architectural viewpoint.

3. Information layer: This layer describes the information objects being exchanged and the underlying canonical data models.

4. Communication layer: It describes the protocols and mechanisms used to exchange information between components.

5. Component layer: This layer deals with the physical distribution of all participating components, including the power system and ICT equipment.

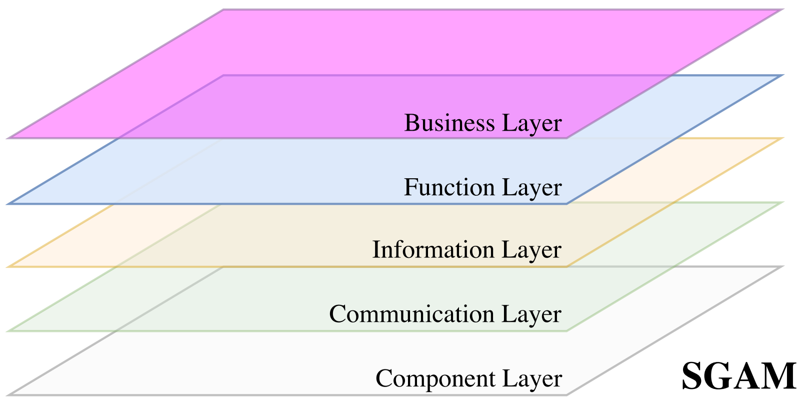


Figure III.3: Simple SGAM representation.

The SGAM framework is widely used in the European energy sector and has gained popularity in various research initiatives and task forces across Europe. It is known for its effectiveness in capturing a comprehensive overview of solutions and enabling more profound analysis. For example, Potenciano Menci et al. [82] used the SGAM as a basis to create an ICT methodology to analyze the ICT infrastructure layer in two steps to assess the scalability of smart grid solutions. Similarly, RP4-[28] used the SGAM to analyze the core functions' performance in current and future scenarios. Other authors, such as Kupzog et al. [20], used it as a basis to analyze the different architectures of solutions or Paustian et al. [83] to examine the social side of smart grid developments, proposing the inclusion of new layers that account for social interactions. More focused on LFM developments, RP1-[25] used the SGAM as a basis to provide a taxonomy of LFM solutions focused at the distribution layer. Furthermore, the Smart Grid Task Force [84] has included the SGAM as a core framework to analyze specific properties of smart grid solutions, such as their scalability and replicability.

3.1.5 Actors, Roles, and Responsibilities

All LFM solutions have similar actors. I can mainly identify three main actor types: flexibility providers, flexibility requesters, and market operators. These actors are illustrated in a simple chart in Figure III.4. However, this list is not exhaustive as it does not include financial institutions that manage payments, for example. Each of these actor types has different responsibilities based on their purpose.

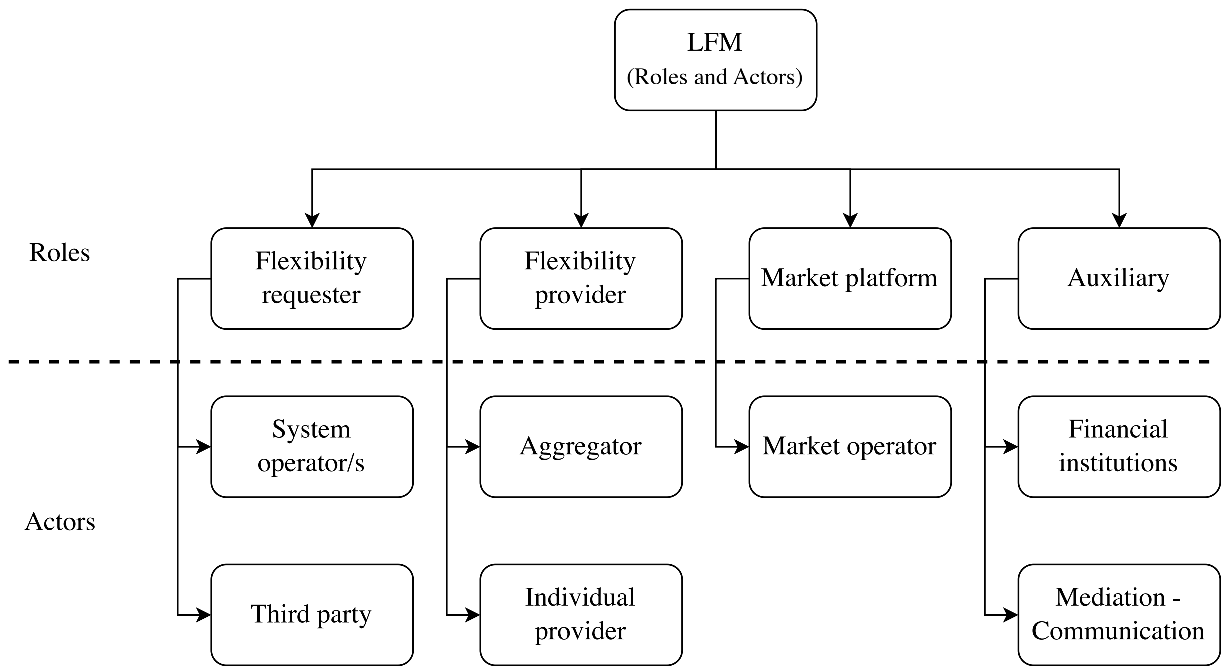


Figure III.4: Simple organization classification of LFM actors based on [85].

The flexibility requester role is usually taken by the actor interested in procuring a certain service from the LFM, as previously introduced in Section 3.1.3. Currently, mainly SOs are the prominent actors across most LFM solutions in the EU. Specifically, DSOs are the most prominent actors. Their responsibility is service delivery to pay for the service. However, given that the service to be provided focuses on flexibility, in some cases, it is not straightforward, as flexibility providers need to motivate their change in consumption or generation using baselines to demonstrate they provided their service RP1-[25].

The entity that offers flexibility at the platform for a specific type of service takes the flexibility provider role. As discussed in Section 3.1.2, many sources of flexibility exist, and depending on the service and the market characteristics, interested parties offering their flexibility might need to fulfill certain criteria to participate RP1-[25]. For instance, small individual consumers might be unable to participate in certain LFM designs as the service might require a minimum power and/or capacity to trade RP1-[25]. The responsibility of the flexibility provider is mainly to deliver the service they opt to participate in. Failing to provide the service, in many solutions, they will face payment cuts (i.e., penalties) due to service unfulfillment RP1-[25]. Within the more complicated responsibilities, it is unclear how these actors must inform their BRPs about the change of operation given they provide flexibility, which changes their supposed operation [86].

The flexible market operator fulfills the market platform role. It uses the platform as a means of bringing together the flexibility provider and the flexibility requester. It orchestrates the service match using a clearing function[3]. Concerning the responsibilities, these are still not clear and harmonized within the EU, and new guidelines such as the one from ACER do not deep dive into their specification [57].

The auxiliary role in the case of LFM is usually undertaken by several actors, which can complement the entire service offering. These are generally not present in most solution descriptions, but it is necessary to acknowledge them for completion.

Nevertheless, depending on the LFM market design, these roles can be undertaken by the same actor. A clear example case is when the SO, mainly the DSO, take the role of a service requester and the role of the market operator RP1-[25]. This integration of roles is not clear by regulation as it is still under development. Future regulation might force SOs to unbundle following the same logic as the third-energy package in the EU introduced where SO cannot have generation units and participate in wholesale markets.

3.1.6 Components

LFM solutions, while leveraging standard digital platform infrastructures for service hosting such as proposed in [87] for service integration, require specialized components due to their unique focus on electrical flexibility trading and the involvement of diverse actors, as detailed in Section 3.1.5. The diversity in actors and services complicates the

[3] Jin et al. [23] provide a detailed overview of different clearing mechanisms for a clearing function.

creation of a universal list of essential components, making it a potential area for further research.

Moreover, certain components might be indispensable in specific scenarios but redundant in others. For instance, LFMs integrated with existing power markets need coordination mechanisms, while isolated ones do not RP1-[25]. Flexibility providers might use field components, such as remote terminal units (RTUs), for controlling their flexibility units RP4-[28].

However, most LFM components are function-oriented, designed to serve specific tasks. Therefore, understanding from the actors' and functions' perspectives can offer insights into potential components a solution might need and thus get the required components for the solution. Visual tools used to represent LFM solutions, complemented by a detailed use case description, can provide a holistic overview of these components.

3.1.7 Visiual representation

Different visual representation approaches exist to depict LFM solutions, just as for any other smart grid solution. The approach chosen depends on the aim of the representation. For instance, Roncancio et al. [88] use block diagrams to depict the relationship between their platform and actors in their proposed solution. Similarly, Liu et al. [89] depict the operation for their solution targeting LFM focused on a congestion management service. Or RP3-[27] depicts the main actors, and the data flows for their congestion management service in their LFM approach.

Meanwhile, Vicente-Pastor et al. [90] use timeline diagrams to exemplify the coordination between the DSO and TSO in LFM solutions. Bouloumpasis et al. [91] provides a decision diagram to clarify the decision-based system of the LFM operation to select between long-term, short-term, or real-term service-oriented flexibility products. In contrast, others focus more on representing the relationship between the different functions and interfaces. Zeiselmair and Köppl [92] visualize the relationship between functions and interfaces between flexibility providers and demanders.

In some cases, the purpose is to provide an overview of the different messages interchanged between actor using sequence diagrams. For example, Paredes and Aguado [93] provide a sequence diagram for their solution, including actors and messages. Similarly, Heinrich et al. [94] use a sequence diagram to clarify how the DSO service request works. In the case of RP2-[26], they use a sequence diagram to showcase the interactions and messages between several platforms that integrate any LFM connected to their market platform. In other cases, the visualization aims to provide a general overview of their solution. Olivella-Rosell et al. [95] provide an overview of the LFM approach or Olivella-Rosell et al. [49] provide a general design of their solution.

However, most visual representations of the solutions targeting holistic overviews do not use a standard approach. Thus, although communicated, information only covers some aspects but does not provide a complete overview of the solution. In such cases to aim for holistic overviews, the SGAM as discussed in Section 3.1.4 offers the possibility of providing a holistic representation of the system.

3.2 Fit in the current European electricity market

It is necessary to provide an overview of how they fit into the complex structure of the current electricity markets in the EU, to fully understand these markets and their fundamentals. Some academic literature considers this fundamental aspect of where to position these markets. For instance, Ramos et al. [48], although mainly examining the different market design characteristics of these solutions, provides a general overview visualization of these markets to position them at the same level as wholesale markets. Meeus [96], explain the market sequence of European markets, including flexibility markets. However, their sequence assumes that flexibility markets operate close to gate closure; empirical evidence from RP1-[25], highlights that many horizons exit, depicting their sequence complex. Furthermore, Schittekatte and Meeus [97] provide details of the different markets currently in Europe, except for flexibility markets and thereof LFM.

Consequently, Figure III.5 provides a simple organizational structure representation of the current electricity market in the EU. In it, electricity is the leading resource, and it considers the current markets based on Meeus [96], Schittekatte and Meeus [97], and integrates and specifies only LFMs based on Ramos et al. [48] and RP1-[25]. The positioning of local markets at the same tier as other markets, rather than subordinating them within flexibility markets, stems from the inherent versatility of local markets.

Within these local markets, sub-markets can emerge, trading distinct commodities. A prime example is the trading of energy in local peer-to-peer (P2P) solutions as Lüth et al. [98] explore. This structural nuance highlights the multidimensionality and potential expansiveness of local markets.

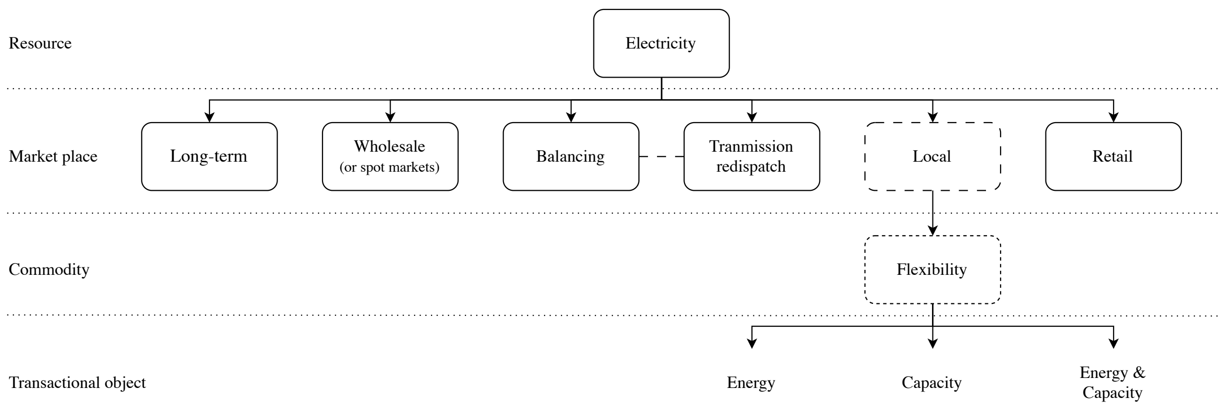


Figure III.5: Simple organizational classification of established and LFMs.

It is necessary to consider that although Figure III.5 provides a simple organizational structure representation of the current electricity market in the EU, each marketplace has its characteristics and serves a purpose, not highlighted in such an illustration.

In some jurisdictions, the wholesale or spot market, although technically not a spot market given that it is technically a forward market [99], has three different integrated markets: the intraday auction, intraday continuous, and day-ahead auction. In the case of the balancing market, a similar structure arises as three different markets exist: primary response, secondary response, and tertiary response markets. Technically, in the case of transmission and redispatch markets, markets are integrated with the balancing market [96, 97]. Similarly, in the case of local markets, as previously stated. In this case, only the commodity or product of flexibility is highlighted [58]. The main product traded in the case of LFM solutions is flexibility. Further in detail, based on RP1-[25], the transactional object could be generalized to all flexibility markets, even though their object of study is congestion management service provided through LFM solutions. The underlying rationale is that flexibility, irrespective of its varied characteristics and services as discussed in Sections 3.1.2 and 3.1.3, essentially oscillates around transacting power, capacity, or a combination thereof. Finally, the retail market is accessible for residential customers, for instance, to procure their electricity without needing to procure it directly in other markets.

3.3 Regulation push

LFMs have emerged as a significant policy priority for the EU. Over the past years, the European Commission (EC) has been rolling out strategic initiatives focused on transforming the power system. Three main motivations have led this evolution: decarbonization, decentralization, and digitalization [100]. The objective behind this transformative thrust has been to foster a resilient and sustainable power infrastructure. To that end, LFMs have been spotlighted as the pivotal solution, envisioned as solutions that can help SOs with their planning and the operation of their grid infrastructure.

The regulatory momentum for the advancement of LFMs has been building steadily over recent years, with the origin of this move dating to 2009. This is when the EU adopted the third energy package, emphasizing the importance of demand-side flexibility for ensuring the security of supply [101]. By 2015, the role and value of demand-side flexibility had increased, with the EC encouraging greater customer participation in the energy market. This drive towards customer participation further stimulated the development of LFM solutions, providing customers with a platform to engage in the energy market, especially the electricity sector.

In 2016, the EC proposed the fourth energy package, also known as the Clean Energy Package (CEP), which established a vision for how DSOs would procure flexibility. The package came into action in 2019. Further policy changes in 2019 promoted the development of LFMs, with the EC communicating and developing the European Green Deal [102]. It contained four Directives and four Regulations [103]. The directives mainly aimed at achieving the following four objectives: 1) increasing energy performance in buildings (Directive (EU) 2018/844) [104], 2) increasing the share of renewable energy sources (Directive (EU) 2018/2001) [105], 3) increasing energy efficiency (Directive (EU) 2018/2002) [106], and 4) setting the rules for the generation, transmission, distribution, supply, and storage of electricity while empowering consumers and establishing a vision for DSOs' flexibility procurement (Directive (EU) 2019/944) [22]. The latter focus on

DSOs' flexibility procurement is particularly critical to developing LFM as it provides the initial regulatory basis to include it as a service for DSO operation.

In 2020, as part of the European Green Deal, the EU adopted the Energy System Integration Plan [107], which encouraged better integration across multiple energy carriers to unlock additional flexibility value. Alongside these moves, there was the EU Digital Strategy [108], which emphasizes the importance of the twin challenges of green and digital transitions in supporting the implementation of the European Green Deal. Specifically, this includes platforms for energy systems, which play a crucial role in the development of LFM solutions as pointed out in Section 3.1.4; all solutions use platforms to provide the services to a selection of energy actors and mainly focusing on distribution level actors such as DSOs. The year after, in 2021, the EU proposed the revision of two directives to accelerate renewables integration in the EU and to achieve the 2030 energy and climate objectives scheduled for 2030. These revisions mainly affect LFM solutions to move faster from a concept face to an actual daily operation face in order to prepare their solutions in terms of scalability to deal with the potential increased penetration of DERs as these revisions aim to accelerate their integration. In the Renewable Energy Directive [109], they highlighted the importance of having national regulatory frameworks that do not discriminate against participation in the electricity market. It includes congestion management and the provision of flexibility and balancing services. The regulatory framework can impact the development of LFM solutions as they might force certain design aspects into them, thus a crucial step towards the direction of development of LFM solutions as highlighted in Section 3.1.1. Thus, these revisions address the primary flexibility sources from the supply and demand sides. From a regulatory perspective, as a result of these and other proposed revisions, the EC adopted in 2021 the Fit For 55 packages, increasing the RES target to 40% by 2030 [110]. With such an increased commitment, the pressure might be built up at the distribution level since most RES are expected to be integrated in a distributed manner [111]. Consequently, they might have a favorable impact to further sustain the business case of LFM solutions as platforms to provide services to SOs.

Furthermore, the EU aimed to accelerate the energy transition and enhance the EU's energy independence with the REPower initiative [112]. The plan has three main goals: 1) demand reduction, 2) conventional (fossil) fuel supplier diversification, and 3) acceleration of the incorporation of RES. As a result, in 2022, the EC requested a demand response framework from ACER to advance the integration of demand-side flexibility in the European energy market. The framework calls for simplifying and reducing entry barriers by, for instance, establishing a standardized bidding process and asking to develop transparent market rules, which can affect LFM solutions. It also calls for improving DSO-aggregator coordination using standardized communication channels, data exchange mechanisms, and open standards and protocols. The aim is to improve interoperability and develop DR services in the distribution grid. Such services provide an opportunity to strengthen further the push of LFM solutions focused on those services. Finally, the most relevant point for LFM within the guideline framework proposed by ACER is the inclusion of a particular statement targeting LFM solutions. In the statement, they open the door for LFM solutions to provide services explicitly to SO and do not force one market operator type [57].

The recent and forthcoming policy modifications implemented from the EU significantly influence the regulatory environment, affecting the electrical grid and market structures. These changes encompass the integration of renewable energy sources, promoting electrification processes, stimulating active customer participation, and encouraging DSOs to incorporate flexibility into their planning and operational procedures. These factors challenge the existing conventional power system model. Nonetheless, they simultaneously establish favorable conditions for solutions like LFMs to address and adapt to these regulatory transformations [113].

3.4 Challenges

Smart grid solutions confront multiple challenges, as outlined by Yan et al. [114] and Bouloumpasis et al. [115], and in the case of LFM solutions, they inherit many of these challenges [116, 117]. The European Smart Grid Task Force highlights four primary issues affecting all solutions [118]: standards and interoperability, data privacy and protection, regulatory concerns, and industrial policy and infrastructure.

Standards and interoperability concerns in LFM primarily arise from communication intricacies due to diverse design choices and services. These solutions often engage a spectrum of actors, from traditional ones like SO to newer entities like aggregators [20].

The challenge intensifies when ensuring standard interfaces for these actors, especially when coordinating between entities like DSO-TSO with different data models [116, 117, 119]. This often results in solutions working in isolation to avoid these coordination hurdles RP1-[25].

Challenges in data privacy and protection [117], bolstered by the general data protection regulation (GDPR), emanate from data-sharing and its associated responsibilities. Privacy gains paramount importance when grid data is disseminated among market participants RP1-[25].

Regulatory obstacles in LFM arise from their integration with existing markets and the clarity on the market operator's role, among other concerns [117, 119]. Present regulatory structures are inadequately attuned to these evolving solutions, leading to a governance gap [120, 121].

Infrastructure challenges in LFM revolve around design and the required supporting frameworks [117]. Scalability and replicability issues persist regardless of the design, especially when there's a surge in device numbers, affecting the distribution system [117, 122]. The variability in grid properties further complicates these challenges [123]. Replicability faces economic and technical hindrances, necessitating systems to adjust across diverse jurisdictions and operational conditions.

Addressing these LFM complexities requires deploying tools, which are discussed in the context of organizational and operational domains contributing to mitigate the challenges LFM face. These contributions are further detailed in Sections IV and V, respectively.

IV | System organization

Given that LFM systems are a SoSs with a unified end goal, they nevertheless require a structured organization to operate. To truly grasp these systems' structures and interactions, studying their design is vital. Beyond their design, accomplishing their objectives relies on the collaboration of multiple actors. As detailed in Section 3.1.4, these solutions employ IS—essentially digital platforms—to execute their functions. However, as highlighted in Section 3.4, they confront challenges such as regulatory obstacles emerging from the system complexity and interoperability and standardization that can hinder system organization.

This chapter, therefore, focuses on the system organization research direction. It explores and designs tools to help organize these solutions, given that LFM solutions encompass numerous subtle elements and systems, adding to the topic's complexity for newcomers. Furthermore, traditional practitioners may find selecting and regulating these service-oriented markets challenging, as they demand navigation through complex market designs and system integration mechanisms.

Consequently, this chapter offers two novel tool contributions, each contributing to mitigate the challenges. First, Section 4.1 examines the design attributes of these solutions to understand their system organization structure and interdependences, which can help practitioners design, improve, and regulate and adapt accordingly to these complex solutions. Instead of following the prevailing trend emphasizing market structure, the objective is to present a holistic perspective of their design and decode their design characteristics to understand their organization. Second, Section 4.2 explores how platforms used for LFMs can be seamlessly integrated into a meta-platform as services. Such an approach considered the standard and interoperability concerns towards the design choices of creating services in platforms and especially the information commutation design choices. The overarching platform concept aims to streamline interactions among multiple actors like demand, LFM platforms, and other users such as flexibility requesters.

4.1 Design characteristics

Market design is fundamental in shaping any market structure and, accordingly, its organization. The specific decisions made during this process can inadvertently create barriers for some participants while advantaging others. Moreover, these decisions can lead to the emergence of certain products and determine the success of solutions, especially if they effectively integrate and engage with various stakeholders. However, the core objective of a LFM solution transcends mere market design. The aim is to forge a comprehensive solution that is wholly operational and delivers the intended functions. A narrow focus solely on the market design of a LFM solution can inadvertently overlook the broader intricacies of the entire system. A comprehensive perspective is crucial when crafting a LFM solution to structure and coordinate (i.e., organize) various actors and their associated systems and subsystems. Such an expansive understanding can benefit academic, industrial, and regulatory stakeholders engaged in the creation, deployment, and oversight of these solutions.

In this context, RP1 employs an iterative taxonomy-building approach, facilitating the extraction of distinct design attributes of congestion management service solutions from multiple angles – not just from a market perspective but also from a solutions standpoint. This methodology also yields a standardized classification of these LFM solutions, using the SGAM framework as a foundational lens. It provides the theoretical framework to cover the different systems these LFM solutions use for congestion management services. The strategy incorporates reviewing design attributes and taxonomies, drawing from academic and industry sources. It serves as a first step to create and later refine the taxonomy. To refine the taxonomy, RP1 incorporates insights from expert interviews and the instantiation of the taxonomy with real solutions to provide a richer understanding. Finally, based on these insights, RP1 presents essential findings and suggests ways to potentially enhance these solutions' design, structure, and organization.

4.2 Service integration

Service integration presents a significant challenge for LFM, especially when considering the issues of standardization, interoperability, and infrastructure discussed in Section 3.1.4. Many developed LFM solutions operate as standalone entities, often due to their inherent design, utilizing distinct platforms with specific interfaces [25]. Such an approach erects entry barriers, compelling flexibility providers to dedicate substantial resources for integration. Additionally, the uncertainty regarding the longevity and relevance of a service further complicates matters. Depending on their design, some LFM services might not always be accessible due to specific operation times, and even when available, geographical constraints can limit participation. Such factors compound the difficulty for companies to see substantial returns on their investments in potentially less lucrative services as LFM can be.

Furthermore, LFM solutions often exhibit limited flexibility sources, particularly in sectors like industry. Flexibility is not a primary business case for industrial companies but an occasional opportunity. These companies frequently lack the required infrastructure for essential services like scheduling, forecasting, and flexibility marketing, crucial for integration into LFM services such as congestion management [26].

Consequently, RP2 introduces the Energy Synchronization Platform (ESP), an agnostic-service-integration concept, to address these challenges. The ESP emphasizes the significant flexibility potential of the industrial sector, establishes platforms to integrate industrial demand response, and allows service companies to advertise various demand response services like forecasting or market signal-based scheduling. Furthermore, the concept ensures seamless interoperability between industrial consumers and demand response services by implementing the EFDM, a consistent and agnostic flexibility data model. This uniform data model aims to ease the economic implications of transitioning between services.

The ESP integrates two primary digital platforms: the company platform (CP) and the market platform (MP). The CP caters to industrial entities, offering a platform for the technological connection and management of manufacturing processes. In contrast, without directly operating, the MP acts as a gateway for external market services, such as forecasting or LFM services.

Additionally, RP2 illustrates how this agnostic-service-integration framework can liaise with LFM services, such as congestion management.

V System operation

LFM solutions primarily rely on specialized tools to support the many functions necessary for optimal operation. Understanding their design and performance becomes paramount because the toolkit must function across diverse scenarios over time. Thus, this Chapter focuses on the four different contributions, split into two Sections.

The first Section adopts a broader perspective, delving into the predictive and prescriptive analysis of distribution side toolkits. This exploration considers both the DSO, which requests flexibility, and the aggregator, which provides it. The Section assesses how these toolkit designs perform in current and anticipated future scenarios, especially as the shift towards RES and increased electrification continues and is expected to intensify [124].

The second Section narrows its focus to demand-side tools, emphasizing forecasting and scheduling tools. These tools are paramount in the context of LFM and smart grids due to the consumption variability introduced by the electrification of assets at both residential and industrial levels.

5.1 Scalability and replicability analysis for smart grid solutions

Given the critical nature of the electricity system, toolsets for LFM solutions, like all smart grid solutions, must operate accordingly. As new tools and toolsets emerge for LFM solutions through research and development, assessing their performance under present conditions and anticipated future scenarios becomes imperative before large-scale deployment and operation. Simulations can help with their evaluations [32], ensuring that these solutions are ready.

One simulation approach is to perform a sensitivity analysis; however, this simulation approach usually focuses on optimal system design (e.g., location of a cable sizing, capacitor's location) [125, 126]. Another yet more holistic simulation approach is the Scalability and Replicability Analysis (SRA) for smart grid solutions. In simple terms, it seeks to understand the limits and impact of the design of toolsets for later large-scale implementations under different scenarios. The main difference between the SRAs for smart grids and traditional power system analyses in literature is the number of parameters considered to change in one analysis [28, 127]. Some of the additional parameters the SRA considers are the nominal asset power, the number of assets, asset type, location of assets, control of assets, seasonal aspects, electrical network type, topology, and size [28, 128].

The SRAs for smart grids, in general, is prominent in Europe, particularly in European projects dealing with smart grid solutions [28, 128]. Moreover, the EC has a special Task Force (TF) focused on the SRA for smart grids [129] since many European projects funded by the EC aimed to perform an SRA for smart grids. The TF aimed to create guidelines and generate a repository [129]. These guidelines and the repository enable other projects to build upon previously gathered knowledge and best practices from different EU projects. Consequently, new projects conceptualizing, designing, and developing tools can, rigorously and similarly, perform their respective SRA for their developed smart grid solutions.

The SRAs for smart grids, in general, consists of two parts. The scalability part usually seeks to understand saturation and asset control impact within the electric grid. In contrast, the replicability part seeks to understand the impact of boundary conditions changes through a defined set of scenarios. However, these two parts can be combined. Such scenarios can be derived from general forecasts [130] or crafted in collaboration with organizations possessing specialized insights such as DSO or aggregators.

Mainly, the SRA for smart grids builds upon the SGAM [37] and therefore is a smart gird-oriented holistic analysis which can be broken down into each subsystem if needed [28, 129, 131]. Depending on the SGAM layers considered for analysis, the SRA for smart grids can cover four main areas, functional and ICT, economic and regulatory, as highlighted in [28, 129]. Due to their complexity and extension, each area has its internal methodology to conduct its respective analyses. However, each internal methodology can differ from project to project or analysis. The functional area focuses on validating the technical integration of smart functions (logic and its steps defined for a particular operation or task), analyzing the impact mainly on the distribution network. The ICT area focuses on identifying potential bottlenecks through communication network stress simulations to evaluate future performance. The economic area primarily focuses on a cost-benefit analysis targeting smart functions. Finally, the regulatory mainly focuses on the regulatory drivers and barriers smart grid functions might face under the current and potential future regulatory operation regime.

Usually, smart grid projects perform their SRA after the smart grid demos (i.e., real implementations of the solutions at the field level) have started incorporating real measurement data into their analyses. On certain occasions, the SRA for smart grids, depending on the project scope, use case scope, and/or analysis scope, can take place before a real demonstration or even as a standalone analysis to capture the potential impact of a specific technology roll-out or combination of technologies might have [128]. For instance, grid scenario studies - grid evaluation under different conditions - is a perfect example of a standalone functional-oriented SRA not requiring a complete smart grid project or SGAM.

The prominent developed and applied functional-oriented SRA methodologies are step-oriented methodologies, with some internal iterative internal steps [27, 122, 128, 131]. The typical steps are collecting data for the analysis, creating specific scenarios and defining metrics, selecting simulation tools and simulation scope such as power flow (PF) and/or optimal power flow (OPF) simulations, analyzing the metrics and results, and finally drawing conclusions [28, 128].

Pursuing this direction to analyze the toolsets under different conditions using the SRA for smart grids, two primary contributions emerge from implementing this approach: RP3 and RP4.

RP3 delves into the SRA of tools created and designed by a Dutch DSO for managing congestions at low voltage (LV) within a LFM where the aggregation process for offers is a two-step approach. This two-tiered aggregation process begins with a technical aggregation by providing only the technical flexibility potential, followed by a commercial one. The latter provides a combined prognosis based on all assets to the DSO. Armed with these internal congestion forecasts, the DSO engages in flexibility procurement negotiations using a LFM.

The analysis evaluates two existing substations and, for comprehensive insights, introduces a synthesized third substation derived from the configurations of the former two. This creation aids in gauging performance across potential networks, addressing the location-replication dimension. To further the analysis, it explores five scenarios, altering the power attributes of electric vehicles (EVs), PV, and smart storage unit (SSU). The goal here is to discern the constraints and potential of their solution in the face of escalating demand-side electrification. Replicability, on the other hand, zooms in on seasonal impacts by studying representative weeks across the year while still considering the scaling scenarios.

The findings underscore several insights. Firstly, the asset location presents a significant challenge for LFM, especially in specialized zones where each substation operates distinctly, resulting in limited offers at individual nodes. Additionally, the operation of SSU emerges as a potential congestion trigger, especially if used for arbitrage. Overdimensioning, although from an operational point of view an advance, from the economic point of view, might be a concern for flexibility service providers (FSPs), confining congestion primarily to specific seasons. It suggests that solution designs must be conscious, anticipating fluctuating offers and potential scarcities in specific localities. Such scarcities might necessitate more attractive incentives to elicit new offers. Moreover, the potential challenge of multi-service provision (i.e., arbitrage and capacity limitation) in low-voltage areas could amplify congestion. Thus, it underscores the essential role of coordination between the DSO and other stakeholders to preempt and mitigate severe congestion peaks, especially at the low voltage level.

RP4 delves into the SRA of three different solutions spread across two different EU countries: Portugal and Slovenia. These solutions implement a similar toolset but have different objectives. Moreover, RP4 considers three cases to analyze and provides a potential replication path for similar actors in other jurisdictions to adopt these tools and implement them if they see fit. For each of these cases, the SRA has its objectives to understand and evaluate the design of these solutions under new conditions by modifying penetration of RES, flexibility availability and quantities, network size, introducing other resources such as OLTCs and capacitor banks or even EVs, energy storage system (ESS), network types, bid prices, forecasts accuracy and modify historical data availability or incorporating metering data at primary substation to assess the forecasting performance of the forecasting tools.

The first case in Portugal focuses on the provision of flexibility at medium voltage (MV) for the predictive operation of MV networks through a LFM interconnecting the DSO and FSPs, which in this case is a specific type of virtual power plant (VPP), which its only business-case is to provide flexibility to the DSO. For its operation, the DSO uses a toolset composed of the following tools: a MV load and RES forecasting tool, MV load allocation tool, a novel multi-period optimal power flow (MPOPF) and a tVPP tool to participate in a LFM.

The second case, also in Portugal, focuses on providing flexibility for the DSO at LV distribution level using a LV Load and RES forecasting tool,LV state estimator tool, a LV controller, and flexibility from home energy management systemss (HEMSs).

The third case, located in Slovenia, focuses on the provision of large customers' flexibility in a local market where the TSO can use the resources of a commercial VPP as a FSP to provide flexibility for frequency related services without disturbing the DSO network. Thus, this case uses a different toolset composed of a MV load and RES forecasting tool (same as in the first case), a project convived, designed, and developed TLS, and a commercial VPP.

The results highlight the diversity of the solutions to solve current and future potential congestion and voltage problems at the distribution side, given that they are scalable and replicable across different electrical network characteristics and can handle newly added asset types. However, the results also provide more details on the technicalities. Voltage optimization can reduce power losses, accurate data impacts forecasting tools in activating flexibility, or the location importance of assets to get activated might impose certain unfairness. Other results focus on the narrow but positive impact of storage systems at the secondary of the substation, the mismatch between technical and economic interests from different stakeholders, which can lead to suboptimal solutions, flexibility price overrules location and the requirement for coordination schemes such as a TLS when facing higher penetration of DERs and electrification.

5.2 Forecasting and scheduling tools

Power systems naturally experience deviations due to the ongoing challenge of balancing energy supply with demand. These deviations primarily arise from the physical principle that electricity needs to be consumed as generated. Thus, larger mismatches usually result in greater economic implications for stakeholders. In this context, forecasting emerges as a vital function for all actors in both traditional and modern grids, such as smart grids.

SO leverage forecasting tools to anticipate potential operational issues like congestion or voltage deviations, especially in the domain of DSO [27]. Similarly, other stakeholders, such as aggregators or energy suppliers, employ forecasting tools to predict electricity prices, adjusting their operations accordingly. This is often done in tandem with forecasts for generation and demand, offering advanced insights into the performance of their assets.

However, the ongoing shift towards smart grid solutions, which prioritize enhanced efficiency in energy utilization, is introducing new complexities. The increasing electrification across various voltage levels, combined with a surge in DER—especially generation-centric ones like PV and storage systems—is complicating the task of predicting consumer behavior. This affects all consumer categories, from individual households to large-scale industrial companies. This evolution underscores the diminishing relevance of traditional forecasting tools, which have often relied on standard load profiles. As consumers transition from static and predictable consumption patterns to more dynamic and active ones, there is a pressing need for innovative forecasting tools that can more accurately anticipate consumption behaviors. In the case of industries, their behavior change affects their scheduling process, which requires new tools to predict their new schedules.

Consequently, this section introduces three contributions concerning demand-side forecasting and scheduling: two targeting residential forecasting (RP5 and RP6) and the other focusing on the industrial sector (RP7).

5.2.1 Residential collaborative local load forecasting

Residential electricity demand, being the second largest consumer after the industrial sector [132], holds significant importance for both system operations and businesses reliant on precise forecasting, like energy suppliers [16].

On the other hand, advanced forecasting methods, such as machine learning (ML) or deep learning (DL), could help. However, they require granular data. The global digital transformation, especially the EU's rollout of smart meters, has provoked a burst in electricity consumption data. These devices facilitate not only remote communication but also remote electricity monitoring. However, accessibility to this data can be hampered in places like the EU due to stringent metering regulations and privacy concerns. Thus, while smart meters have democratized data collection, their sharing across interested stakeholders who do not have direct data access or have little data remains challenging in some jurisdictions. Collaborative private forecast models might offer a viable solution to navigate these data-sharing hurdles in localized areas and benefit LFMs with accurate and local predictive models.

Thus, RP5 delves into short-term load forecasting (STLF), analyzing forecasting windows ranging from near real-time intervals of a few minutes up to a week ahead for electricity consumption [133]. The core objective is to evaluate the performance of collaborative and privacy-preserving collaborative models. Unlike traditional methods that distribute raw smart meter data, these models share model-specific data with involved peers, enhancing data privacy while promoting collective learning. The analysis consists of four parts and uses an open dataset detailing 30-minute interval electricity consumption of real households in the United Kingdom [134].

The first part focuses on a comprehensive review of existing load forecasting models, specifically on STLF models, to discern the state-of-the-art (SOTA) and choose a baseline model. The second part compares a centralized model, which accesses all available smart meter data, and a decentralized collaborative model like federated learning (FL) to assess the performance drop of FL with a perfect information model. In the third part, the analysis aims to refine forecasting accuracy by establishing correlations between peers in the collaborative model and integrating more complex neural architectures for models to train. The fourth part zeroes in on implementing specific privacy-preserving techniques. These techniques, such as differential privacy, offer mathematical privacy guarantees or safeguard communication via secure aggregation in collaborative models. The analysis evaluates the scalability impact of participants to understand computational constraints.

Key quantitative findings reveal that collaborative forecasting using advanced ML and DL models can produce similar results to centralized forecasting systems, although with a higher computation time. Other design findings reveal that DL models, particularly autoencoder architectures, have risen as the preferred choice for STLF due to their capability to capture data nonlinearities. However, these models face challenges when incorporating privacy-preserving techniques like differential privacy. The noise introduced during this process disrupts the learning mechanism. Conversely, simpler DL structures, like long short-term memory (LSTM), offer advantages like avoiding overfitting and seamlessly integrating with privacy-preserving methods. In terms of privacy assurance, while differential privacy provides a mathematical guarantee, it does come at the cost of performance. Secure aggregation, on the other hand, offers advantages in computational efficiency and overall performance when mathematical privacy guarantees are not mandatory.

Meanwhile, RP6 introduces a fully decentralized approach as an alternative to the centralized clustering method observed in RP5. The primary motivation behind this shift is the impracticality of the centralized clustering algorithm, which demands access to all data before initiating collaborative learning—a scenario unlikely in real-world applications.

Moreover, RP6 delves into a comparative study of clustering techniques, contrasting the more commonplace Euclidean distance with the dynamic time warping (DTW) method used to measure the distance between peers in a cluster. Intriguingly, the findings indicate that using the straightforward Euclidean distance for measuring peer distances in clustering not only simplifies computations but also yields performance comparable to the more intricate DTW metric. It suggests simpler clustering metrics can be as effective without incurring additional computational costs.

5.2.2 Industrial flexibility scheduling

The industrial sector is the primary consumer of electricity on the demand side [135]. Consequently, identifying flexible assets within this sector is a key area of research. Yet, merely recognizing and modeling these potential flexibility assets is insufficient for industrial companies. They need to anticipate what can be achieved with this flexibility regarding operations and how to market it, whether in established markets or emerging ones like LFMs. The challenge of predicting the behavior of industrial flexible assets can be reframed as a scheduling optimization problem. Essentially, it will be an operating schedule based on optimizing specific parameters, such as the monetary benefits of participating in specific electricity markets (see Section 3.2).

Consequently, RP7 explores flexibility modeling and scheduling within the industrial sector. It provides a mathematical optimization tool to assist industrial companies in determining the optimal times, locations (i.e., markets), and schedules for marketing their flexibility, aiming to maximize profit, which can help convince industries to become flexible if they need to explore potential earning streams or facilitate their decision to participate in electricity markets. The mathematical optimization using mixed-integer linear programming requires an open-source, generic, and industry-agnostic data model known as the EFDM. This model allows companies to represent flexibility without revealing intricate details about their production, energy consumption, or other proprietary information. The design of the EFDM achieves this by bifurcating the data model into two classes: a flexibility space description, which represents the potential for flexibility, and a flexibility load measure description. The results of the evaluations of the optimization model indicate its competency across diverse use cases, even those of an intricate nature with multiple loads and storage elements. However, it is worth noting that as the complexity of use cases amplifies, the computational time required for optimization also escalates.

VI Conclusion

This cumulative thesis, encompassing seven research publications, has contributed to system organization and system operation pertaining to LFM solutions. LFM solutions continue to emerge, the work presented here offers a foundational framework for subsequent research while acknowledging inherent limitations. This section encapsulates the contributions, emphasizing their potential impact on the existing body of knowledge. Furthermore, it discusses the constraints encountered during this research and concludes by shedding light on potential future research avenues to further enhance the rapidly evolving field of LFM.

6.1 Synthesis

From an academic and applied standpoint, this work's contributions offer guidance in predictive and prescriptive knowledge based on meticulous analysis of different aspects revolving around developing LFM solutions.

The knowledge classification related to LFM is key in clarifying terminologies and concepts. These are frequently employed but often misunderstood or misapplied in numerous discussions. This harmonized classification, grounded in theoretical frameworks, can be instrumental for newcomers and advanced experts in designing and developing LFM solutions. Moreover, other researchers can incorporate the proposed classification as a foundation, extending knowledge organization within the field. This classification approach can harmonize descriptions, facilitating comprehension and emphasizing innovative aspects within their respective domains, notably for projects within the EU, which typically orbit around similar thematic areas.

The design of information systems, while inherently challenging and somewhat distant from real-world applications due to regulatory hurdles and the absence of explicit business models, provides foundational insights into how we should conceive the design of LFM solutions. By framing LFMs as service-oriented solutions, they can be assimilated into similarly structured solutions. This approach could simplify the intricacies of smart grids solutions, which are becoming more market-driven, promoting their integration and competition and expediting their widespread deployment.

In terms of system operation, the contributions offer a straight approach to toolkit analysis. Stakeholders committed to understanding the network-level impact of various designed and developed solutions and their adaptability to the prevailing trends of decentralization and decarbonization can utilize these insights for analogous analyses. Furthermore, the emphasis on forecasting systems lays the groundwork for understanding the design and impact of these systems but also contributes prescriptive knowledge. This serves as a roadmap for future designs. Additionally, conceptualizing agnostic optimization tools could encourage industrial enterprises to consider industrial flexibility for demand response purposes. Such an approach could significantly enhance LFM's flexibility pools, especially since they would not require granular private information about the flexible industrial processes.

6.2 Limitations and outlook

While the contributions of this cumulative work offer advancements to the body of knowledge, there are inherent limitations within the broader context of LFM solutions and the specific details of these contributions.

A primary limitation is the thesis's minimal focus on the economic aspects of LFM solutions despite their market-based nature. Many emerging publications devote significant attention to the challenges arising from the economic dimensions of these solutions.

Another overarching limitation is the lack of a comprehensive proposal for a LFM solution, drawing from the experiences and insights gained during this work. The root of this limitation is the initial lack of foundational understanding at the outset of this thesis. As a result, the emphasis of the contributions has been more on grasping these foundational elements from a broad and technical perspective.

In the context of individual contributions, while detailed and seemingly beneficial, the taxonomy has yet to be practically implemented to assess its real-world applicability. Future research might validate or challenge its utility. It also focuses only on LFMs offering congestion management services.

Regarding the SRA for toolset analysis, a significant limitation is the omission of industrial flexibility and evaluating its actual versus theoretical impact, as illustrated in references like [136].

The computational demands associated with forecasting tools present distinct challenges. In the specific arena of FL, the simulations on decentralization do not factor in the intricacies and real-world hurdles posed by ICT infrastructure. Additionally, the simulations focus on a limited number of peers, potentially failing to mirror the consumer landscape where these collaborative mechanisms might be deployed.

Concerning the scheduling optimization, the absence of a practical example can be attributed to the lack of data involving real industrial entities participating in LFM. It underscores the broader challenges of data opacity and sharing in this domain, especially as many LFM solutions are designed around pay-as-bid remuneration schemes and do not provide time series prices—required by the tool.

Lastly, to finish positively, the challenges identified serve as opportunities for future interdisciplinary contributions to the emerging field of LFMs. They allow for a rich integration of diverse perspectives and expertise to an area that requires it, given its system complexity.

For instance, the future inclusion of detailed economic dimension in the design and operation of LFMs, the inclusion of industrial flexibility in SRA to provide even a more detailed analysis before large-scale industrial flexibility deployment, addressing potential node disturbances or introducing corrupt data in ML and DL when using multiparty computations solutions such as FL, especially in light of the escalating trend of cyberattacks aimed at causing systemic disruptions and evaluating local training of collaborative models from an economic point of view.

VII Recognition of previous and related work

The maxim *"standing on the shoulders of giants"* (i.e., in Latin *"nani gigantum humeris insidentes"*) encapsulates the essence of academic progress, highlighting the significance of building upon the knowledge and discoveries of those who came before us. This dissertation follows that spirit, as it is the realization of collective knowledge drawn from an extensive array of experiences and collaborations within and beyond the Digital Financial Services and Cross-Organisational Digital Transformations (FINATRAX) research group at the University of Luxembourg's Interdisciplinary Centre for Security, Reliability, and Trust (SnT).

The extent of the research presented is only possible due to my time as a Ph.D. candite at the FINATRAX research group, as my time as a researcher at the Austrian Institute (AIT) of Technology, the enriching period spent at the Technical Research Institute (ITT) of Comillas in Madrid and the network my professor established across Germany. They have been a cornerstone in fostering the collaborations that have significantly contributed to this work.

The diverse array of partnerships and work that has influenced this thesis is reflected directly in the range of co-authored research publications. RP1 is a result of the cooperation with Orlando Valerazo from ITT Comillas and related to ITT Comillas' previous general research lines in power systems focused on energy markets and operation (see Koliou et al. [137], Gomez [138], Koirala et al. [139], and Burger et al. [140]). In contrast, RP2 was only possible with the insights from colleagues at the FINATRAX group and a consortium of German academia and research institutes and their several research lines in flexibility and digitalization (see Schott et al. [141], Ländner et al. [142], Roth et al. [143], Bauer et al. [144], Keller et al. [145], Bauer et al. [146, 147], and Roth et al. [148]).

Similarly, RP3 is the result of extensive collaboration between my old colleagues from the AIT and Dutch energy companies such as Enexis and Elaad in the context of smart grids and flexibility (see Iglesias Vázquez et al. [149], Kamphuis et al. [150], Meisel et al. [151], Einfalt et al. [152], Übermasser et al. [153], and Zweistra et al. [154]).

Meanwhile, RP4 success is due to and my colleagues from the AIT and other research and energy companies across Portugal (e.g., INESC-TEC and EDP) and Slovenia (Elektro Ljubljana d.d. and CyberGrid) effort in different research lines such as energy digitalization, smart grids and power system operation (see Bletterie et al. [155], Findrik et al. [156], Esterl et al. [157], Rossi et al. [158], Baut et al. [159], Kupzog et al. [160], Kadam et al. [161], Bletterie et al. [162], Kintzler et al. [163], Bessa et al. [164, 165], Fonseca et al. [166], Retorta et al. [167], and Belhomme et al. [168]).

Although within the FINATRAX research group, my colleagues and I collectively contributed to RP5 and RP6 starting the forecasting research line, my CET's previous related work in forecasting influenced our work (see Valgaev and Kupzog [169] and Valgaev et al. [170]). This internal cooperation within FINATRAX has been indispensable to the thesis's efforts, aiming to produce research that is as innovative as it is interdisciplinary.

Lastly, RP7, although developed within the FINATRAX research group, previous work from my professor's network has impacted the idea generation (see Bank et al. [171], Lindner et al. [172], Bachmann et al. [173], Rusche et al. [174], and Wederhake et al. [175]).

VIII | References

[1] M. Çolak and E. Irmak. "A state-of-the-art review on electric power systems and digital transformation". In: *Electric power components and systems* 51.11 (2023), pp. 1089–1112. DOI: 10.1080/15325008.2023.2189760. eprint: https://doi.org/10.1080/15325008.2023.2189760. URL: https://doi.org/10.1080/15325008.2023.2189760.

[2] Álvaro Enríquez-de Salamanca. "Environmental impacts of climate change adaptation". In: *Environmental impact assessment review* 64 (2017), pp. 87–96. DOI: 10.1016/J.EIAR.2017.03.005.

[3] M. Hashmi, S. Hänninen, and K. Mäki. "Survey of smart grid concepts, architectures, and technological demonstrations worldwide". In: *2011 IEEE PES conference on innovative smart grid technologies Latin America (ISGT LA)*. IEEE. 2011, pp. 1–7.

[4] G. Verbong. "The ongoing energy transition: lessons from a socio-technical, multi-level analysis of the dutch electricity system (1960-2004)". In: *Energy policy* 35 (2007), pp. 1025–1037. DOI: 10.1016/J.ENPOL.2006.02.010.

[5] C. A. Horowitz. "Paris agreement". In: *International legal materials* 55.4 (2016), 740–755. DOI: 10.1017/S0020782900004253.

[6] G. Dreyfus. "Mitigating climate disruption in time: a self-consistent approach for avoiding both near-term and long-term global warming". In: *Proceedings of the national academy of sciences of the united states of america* 119 (2022). DOI: 10.1073/pnas.2123536119.

[7] D. Tim, H. Medert, and C. Halici. *Electrification with renewables driving the transformation of energy services driving the transformation of energy services*. Tech. rep. International Renewable Energy Agency (IRENA), 2019.

[8] R. Heffron, M.-F. Körner, J. Wagner, M. Weibelzahl, and G. Fridgen. "Industrial demand-side flexibility: a key element of a just energy transition and industrial development". In: *Applied energy* 269 (2020), p. 115026. ISSN: 0306-2619. DOI: htt

ps://doi.org/10.1016/j.apenergy.2020.115026. URL: https://www.sciencedirect.com/science/article/pii/S0306261920305389.

[9] F. Bühler, B. Zühlsdorf, T.-V. Nguyen, and B. Elmegaard. "A comparative assessment of electrification strategies for industrial sites: case of milk powder production". In: *Applied energy* 250 (2019), pp. 1383–1401. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2019.05.071. URL: https://www.sciencedirect.com/science/article/pii/S030626191930916X.

[10] F. Un-Noor, S. Padmanaban, L. Mihet-Popa, M. N. Mollah, and E. Hossain. "A comprehensive study of key electric vehicle (ev) components, technologies, challenges, impacts, and future direction of development". In: *Energies* 10.8 (2017). ISSN: 1996-1073. DOI: 10.3390/en10081217. URL: https://www.mdpi.com/1996-1073/10/8/1217.

[11] D. Bogdanov. "Full energy sector transition towards 100supply: integrating power, heat, transport and industry sectors including desalination". In: *Applied energy* (2020), p. 116273. DOI: 10.1016/j.apenergy.2020.116273.

[12] A. S. Gaur, D. Z. Fitiwi, M. Lynch, and G. Longoria. "Implications of heating sector electrification on the irish power system in view of the climate action plan". In: *Energy policy* 168 (2022), p. 113136. ISSN: 0301-4215. DOI: https://doi.org/10.1016/j.enpol.2022.113136. URL: https://www.sciencedirect.com/science/article/pii/S0301421522003615.

[13] A. S. Anees. "Grid integration of renewable energy sources: challenges, issues and possible solutions". In: *2012 IEEE 5th India International Conference on Power Electronics (IICPE)*. 2012, pp. 1–6. DOI: 10.1109/IICPE.2012.6450514.

[14] R. A. Verzijlbergh, L. J. De Vries, and Z. Lukszo. "Renewable energy sources and responsive demand. do we need congestion management in the distribution grid?" In: *Ieee transactions on power systems* 29.5 (2014), pp. 2119–2128. DOI: 10.1109/TPWRS.2014.2300941.

[15] J. A. Lopes, A. Madureira, M. Matos, R. Bessa, V. Monteiro, J. Afonso, S. Santos, J. Catalão, C. Antunes, and P. Magalhães. "The future of power systems: challenges, trends, and upcoming paradigms". In: *Wiley interdisciplinary reviews: energy and environment* 9 (2019), e368. DOI: 10.1002/wene.368.

[16] I. K. Nti, M. Teimeh, O. Nyarko-Boateng, and A. F. Adekoya. "Electricity load forecasting: a systematic review". In: *Journal of electrical systems and information technology* 7.1 (2020), p. 13. DOI: 10.1186/s43067-020-00021-8. URL: https://doi.org/10.1186/s43067-020-00021-8.

[17] M. L. Tuballa and M. L. Abundo. "A review of the development of smart grid technologies". In: *Renewable and sustainable energy reviews* 59 (2016), pp. 710–725.

[18] European Commission. *Smart grids and meters*. Accessed: 2023-03-04. 2018. URL: https://energy.ec.europa.eu/topics/markets-and-consumers/smart-grids-and-meters_en.

[19] P. D. Lund, J. Lindgren, J. Mikkola, and J. Salpakari. "Review of energy system flexibility measures to enable high levels of variable renewable electricity". In: *Renewable and sustainable energy reviews* 45 (2015), pp. 785–807. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2015.01.057. URL: https://www.sciencedirect.com/science/article/pii/S1364032115000672.

[20] F. Kupzog, O. Genest, A. Ahmadifar, F. Berthomé, M. Cupelli, J. Kazmi, M. Savic, and A. Monti. "SGAM-based comparative study of interoperability challenges in european flexibility demonstrators: methodology and results". In: *2018 IEEE 16th International Conference on Industrial Informatics (INDIN)*. IEEE. 2018, pp. 692–697.

[21] THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION. "Regulation (eu) 2019/943 of the european parliament and of the council of 5 june 2019 on the internal market for electricity". In: *Official journal of the european union* L 158 (2019-06-14), pp. 54–124.

[22] THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION. "Directive (eu) 2019/944 of the european parliament and of the council of 5 june 2019 on common rules for the internal market for electricity and amending directive 2012/27/eu". In: *Official journal of the european union* L 158 (2019-06-14), pp. 125–199.

[23] X. Jin, Q. Wu, and H. Jia. "Local flexibility markets: Literature review on concepts, models and clearing methods". In: *Applied energy* 261 (2020). ISSN: 03062619. DOI: 10.1016/j.apenergy.2019.114387.

[24] O. Valarezo, T. Gómez, J. P. Chaves-Avila, L. Lind, M. Correa, D. Ulrich Ziegler, and R. Escobar. "Analysis of new flexibility market models in europe". In: *Energies* 14.12 (2021). ISSN: 1996-1073. DOI: 10.3390/en14123521. URL: https://www.mdpi.com/1996-1073/14/12/3521.

[25] S. Potenciano Menci and O. Valarezo. "Decoding design characteristics of local flexibility markets for congestion management with a multi-layered taxonomy". In: *Applied energy* 357 (2024), p. 122203. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2023.122203. URL: https://www.sciencedirect.com/science/article/pii/S0306261923015672.

[26] C. van Stiphoudt, S. Potenciano Menci, C. Kaymakci, S. Wenninger, D. Bauer, S. Duda, G. Fridgen, and A. Sauer. "Energy synchronization platform concept to enable and streamline automated industrial demand response (Accepted for publication)". In: *15th International Conference on Applied Energy (ICAE 2023)*. 2023. DOI: Pending.

[27] S. Potenciano Menci, B. Herndler, F. Kupzog, M. Zweistra, R. Steegh, and M. Willems. "Scalability and replicability analysis of grid management services in low voltage networks in local flexibility markets: an interflex analysis". In: *2021 IEEE Madrid PowerTech*. 2021, pp. 1–6. DOI: 10.1109/PowerTech46648.2021.9495061.

[28] S. Potenciano Menci, R. J. Bessa, B. Herndler, C. Korner, B.-V. Rao, F. Leimgruber, A. A. Madureira, D. Rua, F. Coelho, J. V. Silva, J. R. Andrade, G. Sampaio, H. Teixeira, M. Simões, J. Viana, L. Oliveira, D. Castro, U. Krisper, and R. André. "Functional scalability and replicability analysis for smart grid functions: the integrid project approach". In: *Energies* 14.18 (2021). ISSN: 1996-1073. DOI: 10.3390/en14185685. URL: https://www.mdpi.com/1996-1073/14/18/5685.

[29] J. Delgado Fernández, S. Potenciano Menci, C. M. Lee, A. Rieger, and G. Fridgen. "Privacy-preserving federated learning for residential short-term load forecasting". In: *Applied energy* 326 (2022), p. 119915. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2022.119915. URL: https://www.sciencedirect.com/science/article/pii/S0306261922011722.

[30] J. Delgado Fernández, S. Potenciano Menci, and I. Pavic. “Towards a peer-to-peer residential short-term load forecasting with federated learning”. In: *2023 IEEE Belgrade PowerTech*. 2023, pp. 1–6. DOI: 10.1109/PowerTech55446.2023.10202782.

[31] R. Bahmani, C. van Stiphoudt, S. Potenciano Menci, M. Schöpf, and G. Fridgen. “Optimal industrial flexibility scheduling based on generic data format”. In: *Energy informatics* 5.1 (2022), p. 26. ISSN: 2520-8942. DOI: 10.1186/s42162-022-00198-4. URL: https://doi.org/10.1186/s42162-022-00198-4 (visited on 05/26/2023).

[32] S. Herbert A. *The sciences of the artificial, reissue of the third edition with a new introduction by john laird*. MIT press, 2019.

[33] R. L. Ackoff. “Towards a system of systems concepts”. In: *Management science* 17.11 (1971), pp. 661–671. ISSN: 00251909, 15265501. URL: http://www.jstor.org/stable/2629308 (visited on 10/02/2023).

[34] P. B. Freng. “On the nature of systems of systems”. In: *Incose international symposium* 26.1 (2016), pp. 1477–1493. DOI: https://doi.org/10.1002/j.2334-5837.2016.00240.x. eprint: https://incose.onlinelibrary.wiley.com/doi/pdf/10.1002/j.2334-5837.2016.00240.x. URL: https://incose.onlinelibrary.wiley.com/doi/abs/10.1002/j.2334-5837.2016.00240.x.

[35] M. d. C. Henshaw. “Systems of systems, cyber-physical systems, the internet-of-things... whatever next?” In: *Insight* 19.3 (2016), pp. 51–54. DOI: https://doi.org/10.1002/inst.12109. eprint: https://incose.onlinelibrary.wiley.com/doi/pdf/10.1002/inst.12109. URL: https://incose.onlinelibrary.wiley.com/doi/abs/10.1002/inst.12109.

[36] A. J. Lopes, R Lezama, and R. Pineda. “Model based systems engineering for smart grids as systems of systems”. In: *Procedia computer science* 6 (2011), pp. 441–450.

[37] Cen(2012). *CEN-CENELEC-ETSI Smart Grid Coordination Group. Smart Grid Reference Architecture*. Tech. rep. Accessed: 2020-11-19. CEN-CENELEC-ETSI, 2012. URL: https://www.cencenelec.eu/media/CEN-CENELEC/AreasOfWork/CEN-CENELEC_Topics/Smart\%20Grids\%20and\%20Meters/Smart\%20Grids/4_sgcg_methodology_sgamusermanual.pdf.

[38] A. Koestler. *The ghost in the machine*. Macmillan, 1967.

[39] T. I. Strasser, F. P. Andrén, J. Kathan, C. Cecati, C. Buccella, P. Siano, P. Leitão, G. Zhabelova, V. Vyatkin, P. Vrba, and V. Marík. "A review of architectures and concepts for intelligence in future electric energy systems". In: *Ieee transactions on industrial electronics* 62 (2015), pp. 2424–2438. URL: https://api.semanticscholar.org/CorpusID:31086789.

[40] M. Van Steen and A. S. Tanenbaum. *Distributed systems*. 4th. distributed-systems.net, 2023.

[41] K. Peffers, T. Tuunanen, M. A. Rothenberger, and S. Chatterjee. "A Design Science Research Methodology for Information Systems Research". In: *Journal of management information systems* 24.3 (2007), pp. 45–77. DOI: 10.2753/MIS0742-1222240302. URL: https://doi.org/10.2753/MIS0742-1222240302.

[42] A. R. Hevner, S. T. March, J. Park, and S. Ram. "Design science in information systems research". In: *Mis quarterly* 28.1 (2004), pp. 75–105. ISSN: 02767783. URL: http://www.jstor.org/stable/25148625.

[43] J. Recker. *Scientific research in information systems: a beginner's guide*. Vol. 27. 3. Springer, 2013.

[44] H. H. Dubs. "Definition and its problems". In: *The philosophical review* 52.6 (1943), pp. 566–577. ISSN: 00318108, 15581470. URL: http://www.jstor.org/stable/2181259 (visited on 09/20/2023).

[45] F. R. Baumgartner and C. Mahoney. "Forum section: the two faces of framing: individual-level framing and collective issue definition in the european union". In: *European union politics* 9.3 (2008), pp. 435–449. DOI: 10.1177/1465116508093492. eprint: https://doi.org/10.1177/1465116508093492. URL: https://doi.org/10.1177/1465116508093492.

[46] T. J. Pinch and W. E. Bijker. "The social construction of facts and artefacts: or how the sociology of science and the sociology of technology might benefit each other". In: *Social studies of science* 14.3 (1984), pp. 399–441. ISSN: 03063127. URL: http://www.jstor.org/stable/285355 (visited on 10/16/2023).

[47] F. W. Geels and J. Schot. "Typology of sociotechnical transition pathways". In: *Research policy* 36.3 (2007), pp. 399–417. ISSN: 0048-7333. DOI: https://doi.org/10

.1016/j.respol.2007.01.003. URL: https://www.sciencedirect.com/science/article/pii/S0048733307000248.

[48] A. Ramos, C. De Jonghe, V. Gómez, and R. Belmans. "Realizing the smart grid's potential: Defining local markets for flexibility". In: *Utilities policy* 40 (2016), pp. 26–35. ISSN: 09571787. DOI: 10.1016/j.jup.2016.03.006.

[49] P. Olivella-Rosell, E. Bullich-Massagué, M. Aragüés-Peñalba, A. Sumper, S. Ø. Ottesen, J.-A. Vidal-Clos, and R. Villafáfila-Robles. "Optimization problem for meeting distribution system operator requests in local flexibility markets with distributed energy resources". In: *Applied energy* 210 (2018), pp. 881–895. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2017.08.136. URL: https://www.sciencedirect.com/science/article/pii/S0306261917311522.

[50] J. Radecke, J. Hefele, and L. Hirth. "Markets for Local Flexibility in Distribution Networks". eng. In: (2019), p. 17. URL: http://hdl.handle.net/10419/204559.

[51] C. A. Correa-Florez, A. Michiorri, and G. Kariniotakis. "Optimal participation of residential aggregators in energy and local flexibility markets". In: *Ieee transactions on smart grid* 11.2 (2020), pp. 1644–1656. DOI: 10.1109/TSG.2019.2941687.

[52] C. Ziras, C. Heinrich, and H. W. Bindner. "Why baselines are not suited for local flexibility markets". In: *Renewable and sustainable energy reviews* 135 (2021), p. 110357. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2020.110357. URL: https://www.sciencedirect.com/science/article/pii/S1364032120306456.

[53] T. Dronne, F. Roques, and M. Saguan. "Local flexibility markets for distribution network congestion-management in center-western europe: which design for which needs?" In: *Energies* 14.14 (2021). ISSN: 1996-1073. DOI: 10.3390/en14144113. URL: https://www.mdpi.com/1996-1073/14/14/4113.

[54] S. Färegård and M. Miletic. "A swedish perspective on aggregators and local flexibility markets: considerations and barriers for aggregators and sthlmflex together with their potential to manage grid congestions in stockholm". MA thesis. KTH - Kungliga Tekniska högskolan, 2021.

[55] R. Singh, R. Vijay, P. Mathuria, and R. Bhakar. "Local flexibility markets in the context of reactive power provision by distributed energy resources". In: *2022 4th*

International Conference on Energy, Power and Environment (ICEPE). 2022, pp. 1–6. DOI: 10.1109/ICEPE55035.2022.9798333.

[56] V. Charbonnier, C. Dikaiakos, M. Foresti, N. Appleman, M. Cooper, A. Hussein, D. Roberts, and A. Siriyatorn. *Review of flexibility platforms*. Tech. rep. ENTSO-E and Frontier Economics Ltd, 2021.

[57] European Union Agency for the Cooperation of Energy Regulators (ACER). *Framework guideline on demand response*. Accessed: 2023-03-04. URL: https://acer.europa.eu/Official_documents/Acts_of_the_Agency/Framework_Guidelines/Framework%20Guidelines/FG_DemandResponse.pdf.

[58] O. Valarezo, J. P. Chaves-Avila, J. Rossi, E. Hillberg, and M. Baron. "Survey results on local markets to enable societal value". In: *2021 IEEE Madrid PowerTech*. Vol. 1. 2021. DOI: 10.1109/PowerTech46648.2021.9495089.

[59] C. R. Mcconnell, S. L. Brue, and S. M. Flynn. *Economics. principles, problems and policies (PDF)*. New York: McGraw-Hill, 2009.

[60] *Flexibility markets*. 2023. URL: https://energy.ec.europa.eu/topics/research-and-technology/flexibility-markets_en.

[61] Eurelectric. *Flexibility and aggregation requirements for their interaction in the market*. Tech. rep. Eurelectric, 2014. URL: https://www.usef.energy/app/uploads/2016/12/EURELECTRIC-Flexibility-and-Aggregation-jan-2014.pdf.

[62] Y. Zhang, P. E. Campana, Y. Yang, B. Stridh, A. Lundblad, and J. Yan. "Energy flexibility from the consumer: integrating local electricity and heat supplies in a building". In: *Applied energy* 223 (2018), pp. 430–442. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2018.04.041. URL: https://www.sciencedirect.com/science/article/pii/S0306261918305993.

[63] X. Jin, Y. Mu, H. Jia, J. Wu, X. Xu, and X. Yu. "Optimal day-ahead scheduling of integrated urban energy systems". In: *Applied energy* 180 (2016), pp. 1–13. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2016.07.071. URL: https://www.sciencedirect.com/science/article/pii/S0306261916310121.

[64] E. N. of Transmission System Operators for Electricity (ENTSO-E). *Technology factsheets*. Tech. rep. ENTSO-E, 2021.

[65] G. Fridgen, R. Keller, M.-F. Körner, and M. Schöpf. “A holistic view on sector coupling”. In: *Energy policy* 147 (2020), p. 111913. ISSN: 0301-4215. DOI: https://doi.org/10.1016/j.enpol.2020.111913. URL: https://www.sciencedirect.com/science/article/pii/S0301421520306248.

[66] SynErgie-Project. *How the kopernicus project synergie helps industry match its electricity demand to the supply*. Accessed on 04-08-2021. URL: https://www.kopernikus-projekte.de/en/projects/synergie.

[67] P. Palensky and D. Dietrich. “Demand side management: demand response, intelligent energy systems, and smart loads”. In: *Ieee transactions on industrial informatics* 7.3 (2011), pp. 381–388. DOI: 10.1109/TII.2011.2158841.

[68] J. Villar, R. Bessa, and M. Matos. “Flexibility products and markets: literature review”. In: *Electric power systems research* 154 (2018), pp. 329–340. ISSN: 0378-7796. DOI: https://doi.org/10.1016/j.epsr.2017.09.005. URL: https://www.sciencedirect.com/science/article/pii/S0378779617303723.

[69] M. Z. Degefa, I. B. Sperstad, and H. Sæle. “Comprehensive classifications and characterizations of power system flexibility resources”. In: *Electric power systems research* 194 (2021), p. 107022.

[70] P. Schott, J. Sedlmeir, N. Strobel, T. Weber, G. Fridgen, and E. Abele. “A generic data model for describing flexibility in power markets"”. en. In: *Energies* 12.10 (2019), p. 1893. ISSN: 1996-1073. DOI: 10.3390/en12101893. URL: https://www.mdpi.com/1996-1073/12/10/1893.

[71] C. van Stiphoudt, S. Potenciano Menci, M. Schöpf, G. Fridgen, M. Weigold, M. Lindner, H. U. Buhl, S. Duda, P. Schott, M. Weibelzahl, and S. Wenninger. *Energieflexibilitätsdatenmodell der Energiesynchronisationsplattform : Teil der Reihe "Diskussionspapiere V4 - Konzept der Energiesynchronisationsplattform" [Energy flexibility data model of the energy synchronization platform: part of the series "concept of the energy synchronization platform. Discussion papers v4"]*. s.l., 2021. URL: https://eref.uni-bayreuth.de/68094/.

[72] M. Singh, J. Jiao, M. Klobasa, and R. Frietsch. “Emergence of digital and X-as-a-service (XAAS) platforms in German energy sector”. In: 2021.

[73] M. de Heer H.and van der Laan and A. Sáez Armenteros. *Usef: the framework explained: the framework explained, update 25 may 2021*. Framework report. USEF, 2021.

[74] S. Potenciano Menci, C. Korner, B. Herndler, T. Esterl, C. Gutschi, and U. Krisper. "Tso-dso interaction in 2030/2040: scalability of the traffic light system concept in the project integrid". In: *E & i elektrotechnik und informationstechnik* 138.8 (2021), pp. 634–635. DOI: 10.1007/s00502-021-00954-6. URL: https://doi.org/10.1007/s00502-021-00954-6.

[75] B. Herndler, S. Potenciano Menci, J. Kapeller, J. Bruschi, and T. Wagner. "Scalability and replicability analysis of an island microgrid concept". In: *2020 2nd IEEE International Conference on Industrial Electronics for Sustainable Energy Systems (IESES)*. Vol. 1. 2020, pp. 233–239. DOI: 10.1109/IESES45645.2020.9210692.

[76] G Parker, M Van Alstyne, and S Choudary. *How networked markets are transforming the economy-and how to make them work for you*. WW Norton & Company New York, 2016.

[77] P. Constantinides, O. Henfridsson, and G. Parker. "Platforms and infrastructures in the digital age". In: *Information systems research* 29 (2018). DOI: 10.1287/isre.2018.0794.

[78] S. Duda, C. Kaymakci, J. Köberlein, S. Wenninger, T. Haubner, A. Sauer, and J. Schilp. "Structuring the digital energy platform jungle: development of a multilayer taxonomy and implications for practice". In: *Proceedings of the Conference on Production Systems and Logistics: CPSL 2022*. Hannover: publish-Ing. 2022, pp. 42–51.

[79] Nodes. *Nodes - marketplace*. https://nodesmarket.com/. Accessed: 2021-04-08. URL: https://nodesmarket.com/.

[80] Piclo. *The leading independent marketplace for flexibility services.* https://www.piclo.energy/. Accessed: 2023-11-04.

[81] S. Zikos, C. Malavazos, I. Dimitriadou, C. Timplalexis, G. Fernández, D. Ioannidis, and D. Tzovaras. "Local energy and flexibility markets: state of the art and technological gap analysis". In: *2023 8th International Conference on Smart and Sus-*

tainable Technologies (SpliTech). 2023, pp. 1–6. DOI: 10.23919/SpliTech58164.2023.10192975.

[82] S. Potenciano Menci, J. Le Baut, J. Matanza Domingo, G. López López, R. Cossent Arín, and M. Pio Silva. "A novel methodology for the scalability analysis of ict systems for smart grids based on sgam: the integrid project approach". In: *Energies* 13.15 (2020), p. 3818. ISSN: 1996-1073. DOI: 10.3390/en13153818. URL: http://dx.doi.org/10.3390/en13153818.

[83] S. Paustian, J. Köhlke, J. Mattes, and S. Lehnhoff. "The (still unexplored) social side of smart grid development: towards a social layer for the smart grid architecture model (sgam)". In: *Proceedings of the Thirteenth ACM International Conference on Future Energy Systems*. e-Energy '22. Virtual Event: Association for Computing Machinery, 2022, 521–531. ISBN: 9781450393973. DOI: 10.1145/3538637.3539585. URL: https://doi.org/10.1145/3538637.3539585.

[84] Working Group on Data Format and Procedures under the Expert Group 1. *Towards interoperability within the eu for electricity and gas data access & exchange*. Tech. rep. European Commission, 2019.

[85] Ofem. *Ofgem's future insights series flexibility platforms in electricity markets*. Research rep. OFEM, 2019.

[86] A. Sáez Armenteros, H. de Heer, and J. Bjørndalen. *The regulation of independent aggregators: with a focus on compensation mechanisms*. Tech. rep. DNV-GL, 2022.

[87] G. Fridgen, S. Potenciano Menci, C. van Stiphoudt, J. Schilp, J. Köberlein, T. Bauernhansl, A. S. Grigorjan, D. Schel, A. Schlereth, F. Schulz, et al. *Referenzarchitektur der energiesynchronisationsplattform : teil der reihe "diskussionspapiere v4 - konzept der energiesynchronisationsplattform"*. s.l., 2021. URL: http://publica.fraunhofer.de/dokumente/N-642369.html.

[88] J. S. Roncancio, J. Vuelvas, D. Patino, and C. A. Correa-Flórez. "Flower greenhouse energy management to offer local flexibility markets". In: *Energies* 15.13 (2022). ISSN: 1996-1073. DOI: 10.3390/en15134572. URL: https://www.mdpi.com/1996-1073/15/13/4572.

[89] R. Liu, X. Wang, H. Zhao, and Y. Wang. "Distribution system congestion management based on local flexibility market". In: *2021 6th Asia Conference on Power and Electrical Engineering (ACPEE)*. 2021, pp. 1023–1029. DOI: 10.1109/ACPEE51499.2021.9436988.

[90] A. Vicente-Pastor, J. Nieto-Martin, D. W. Bunn, and A. Laur. "Evaluation of flexibility markets for retailer–dso–tso coordination". In: *Ieee transactions on power systems* 34.3 (2019), pp. 2003–2012. DOI: 10.1109/TPWRS.2018.2880123.

[91] I. Bouloumpasis, N. Mirzaei Alavijeh, D. Steen, and A. T. Le. "Local flexibility market framework for grid support services to distribution networks". In: *Electrical engineering* (2021), pp. 1–19.

[92] A. Zeiselmair and S. Köppl. "Constrained optimization as the allocation method in local flexibility markets". In: *Energies* 14.13 (2021). ISSN: 1996-1073. DOI: 10.3390/en14133932. URL: https://www.mdpi.com/1996-1073/14/13/3932.

[93] A. Paredes and J. A. Aguado. "Capacity and energy local flexibility markets for imbalance and congestion management". In: *2021 IEEE International Smart Cities Conference (ISC2)*. 2021, pp. 1–7. DOI: 10.1109/ISC253183.2021.9562971.

[94] C. Heinrich, C. Ziras, A. L. Syrri, and H. W. Bindner. "Ecogrid 2.0: a large-scale field trial of a local flexibility market". In: *Applied energy* 261 (2020), p. 114399. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2019.114399. URL: https://www.sciencedirect.com/science/article/pii/S0306261919320860.

[95] P. Olivella-Rosell, P. Lloret-Gallego, I. Munne-Collado, R. Villafafila-Robles, A. Sumper, S. O. Ottessen, J. Rajasekharan, and B. A. Bremdal. "Local flexibility market design for aggregators providing multiple flexibility services at distribution network level". In: *Energies* 11.4 (2018), pp. 1–19. ISSN: 19961073. DOI: 10.3390/en11040822.

[96] L. Meeus. *The evolution of electricity markets in europe*. Edward Elgar Publishing, 2020.

[97] T. Schittekatte and L. Meeus. *Electricity markets in the eu*. Accesed on: 03/10/2023. 2020. URL: https://fsr.eui.eu/electricity-markets-in-the-eu/ (visited on 10/14/2020).

[98] A. Lüth, J. M. Zepter, P. Crespo del Granado, and R. Egging. "Local electricity market designs for peer-to-peer trading: The role of battery flexibility". In: *Applied energy* 229.July (2018), pp. 1233–1243. ISSN: 03062619. DOI: 10.1016/j.apenergy.2018.08.004.

[99] KU Leuven Energy Institute. *Ei fact sheet: the current electricity market design in europe*. Tech. rep. 2015.

[100] M. L. Di Silvestre, S. Favuzza, E. Riva Sanseverino, and G. Zizzo. "How decarbonization, digitalization and decentralization are changing key power infrastructures". In: *Renewable and sustainable energy reviews* 93 (2018), pp. 483–498. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2018.05.068. URL: https://www.sciencedirect.com/science/article/pii/S1364032118304283.

[101] European Commission. *Third energy package*. Accessed: 2023-03-04. URL: https://energy.ec.europa.eu/topics/markets-and-consumers/market-legislation/third-energy-package_en.

[102] European Commission. *Delivering the european green deal*. Accessed: 2023-03-04. URL: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en#documents.

[103] European Commission and Directorate-General for Energy. *Clean energy for all europeans*. Publications Office, 2019. URL: https://data.europa.eu/doi/10.2833/9937.

[104] THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION. "Directive (eu) 2018/844 of the european parliament and of the council of 30 may 2018 amending directive 2010/31/eu on the energy performance of buildings and directive 2012/27/eu on energy efficiency (text with eea relevance)". In: *Official journal of the european union* L 156 (2018-05-30).

[105] THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION. "Directive (eu) 2018/2001 of the european parliament and of the council of 11 december 2018 on the promotion of the use of energy from renewable sources (recast) (text with eea relevance)". In: *Official journal of the european union* L 328 (2018-12-21), pp. 82–209.

[106] THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION. "Directive (eu) 2018/2002 of the european parliament and of the council of 11 december 2018 amending directive 2012/27/eu on energy efficiency (text with eea relevance)". In: *Official journal of the european union* L 328 (2018-12-1), pp. 210–230.

[107] European Commission. *Framework guideline on demand response*. Accessed: 2023-03-04. URL: https://energy.ec.europa.eu/topics/energy-systems-integration/eu-strategy-energy-system-integration_en.

[108] European Commission, Directorate-General for Informatics. *Strategic plan 2020-2024*. Tech. rep. Accessed: 2023-03-04. European Commission, 2020. URL: https://commission.europa.eu/publications/strategic-plan-2020-2024-energy_en.

[109] European Commission. *Proposal for a directive of the european parliament and of the council amending directive (eu) 2018/2001 of the european parliament and of the council, regulation (eu) 2018/1999 of the european parliament and of the council and directive 98/70/ec of the european parliament and of the council as regards the promotion of energy from renewable sources, and repealing council directive (eu) 2015/652*. Accessed: 2023-03-04. URL: https://eur-lex.europa.eu/resource.html?uri=cellar:dbb7eb9c-e575-11eb-a1a5-01aa75ed71a1.0001.02/DOC_1&format=PDF.

[110] European Commission. *Communication from the commission to the european parliament, the council, the european economic and social committee and the committee of the regions 'fit for 55': delivering the eu's 2030 climate target on the way to climate neutrality*. Accessed: 2023-03-04. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC0550.

[111] International Renewable Energy Agency (IRENA). *Market integration of distributed energy resources*. Tech. rep. IRENA, 2019.

[112] THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION. *Communication from the commission to the european parliament, the european council, the council, the european economic and social committee and the committee of the regions repowereu plan*. 2022-05-18.

[113] S Chondrogiannis, J Vasiljevska, A Marinopoulos, I Papaioannou, and G Flego. "Local electricity flexibility markets in europe". In: *Publications office of the european union* KJ-NA-31-194-EN-N (online) (2022). ISSN: 1831-9424 (online). DOI: 10.2760/9977(online).

[114] Y. Yan, Y. Qian, H. Sharif, and D. Tipper. "A survey on smart grid communication infrastructures: motivations, requirements and challenges". In: *Ieee communications surveys & tutorials* 15.1 (2012), pp. 5–20.

[115] I. Bouloumpasis, D. Steen, and L. A. Tuan. "Congestion management using local flexibility markets: recent development and challenges". In: *2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*. 2019, pp. 1–5. DOI: 10.1109/ISGTEurope.2019.8905489.

[116] S. Bjarghov, M. Löschenbrand, A. U. N. Ibn Saif, R. Alonso Pedrero, C. Pfeiffer, S. K. Khadem, M. Rabelhofer, F. Revheim, and H. Farahmand. "Developments and challenges in local electricity markets: a comprehensive review". In: *Ieee access* 9 (2021), pp. 58910–58943. DOI: 10.1109/ACCESS.2021.3071830.

[117] K. Zabaleta, D. Casado-Mansilla, E. Kapassa, C. E. Borges, G. Preßmair, M. Themistocleous, and D. López-de Ipiña. "Barriers to widespread the adoption of electric flexibility markets: a triangulation approach". In: *2020 5th International Conference on Smart and Sustainable Technologies (SpliTech)*. IEEE. 2020, pp. 1–7.

[118] C. Filiou. *Challenges & actions for smart grid deployment in the eu internal energy market*. Tech. rep. Directorate-General for Energy European Commission, 2016.

[119] T. Schittekatte and L. Meeus. "Flexibility markets: q&a with project pioneers". In: *Utilities policy* 63 (2020), p. 101017. ISSN: 0957-1787. DOI: https://doi.org/10.1016/j.jup.2020.101017. URL: https://www.sciencedirect.com/science/article/pii/S0957178720300126.

[120] O. Rebenaque, C. Schmitt, K. Schumann, T. Dronne, and F. Roques. "Success of local flexibility market implementation: a review of current projects". In: *Utilities policy* 80 (2023), p. 101491. ISSN: 0957-1787. DOI: https://doi.org/10.1016/j.jup.2023.101491. URL: https://www.sciencedirect.com/science/article/pii/S0957178723000036.

[121] H. Regina, F. Sarah, C. Mihai, W. Anjali, and W. Steven. “Challenges and opportunities of flexibility markets related to operational planning”. In: *2023 19th International Conference on the European Energy Market (EEM)*. 2023, pp. 1–5. DOI: 10.1109/EEM58374.2023.10161787.

[122] J. Le Baut, S. Potenciano Menci, B. Herndler, C. Korner, and et al. *Technical scalability and replicability of the integrid smart grid functionalities*. Tech. rep. D8.1. Accessed on 21-06-2021. H2020 InteGrid Project, 2019. URL: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5cac508d4&appId=PPGMS.

[123] S. Potenciano Menci, B. Herndler, F. Mesureur, A. Ahmadifar, and A. Izimova. *D3.8 scalability and replicability analysis (sra) for all use cases*. Research rep. InterFlex Project, 2019.

[124] IRENA. *Mart electrification with renewables: driving the transformation of energy services*. Tech. rep. International Renewable Energy Agency (IRENA), 2022.

[125] R. Kasturi and P. Dorraju. “Sensitivity analysis of power systems”. In: *Ieee transactions on power apparatus and systems* PAS-88.10 (1969), pp. 1521–1529. DOI: 10.1109/TPAS.1969.292280.

[126] J. Chureemart and P. Churueang. “Sensitivity analysis and its applications in power system improvements”. In: *2008 5th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology*. Vol. 2. 2008, pp. 945–948. DOI: 10.1109/ECTICON.2008.4600587.

[127] S. Eftekharnejad, V. Vittal, G. T. Heydt, B. Keel, and J. Loehr. “Impact of increased penetration of photovoltaic generation on power systems”. In: *Ieee transactions on power systems* 28.2 (2012), pp. 893–901.

[128] S. Potenciano Menci, R. Schwalbe, C. Corner, B. Herndler, J. Kahtan, C. Gutschi, and T. Gross. “Functional scalability and replicability analysis framework for distribution grids”. In: *CIRED 2021 - The 26th International Conference and Exhibition on Electricity Distribution*. Vol. 2021. 2021, pp. 2099–2103. DOI: 10.1049/icp.2021.1610.

[129] Data, L. ALACREU GARCIA, and M. BRACKEN. *Bridge 2020 annual report replicability and scalability task force*. Tech. rep. European Comission, 2021.

[130] Fraunhofer ISE. *Net installed electricity generation capacity in germany*. 2023. URL: https://www.energy-charts.info/charts/installed_power/chart.htm?l=en&c=DE&chartColumnSorting=default.

[131] A. Rodriguez-Calvo, R. Cossent, and P. Frías. "Scalability and replicability analysis of large-scale smart grid implementations: Approaches and proposals in Europe". In: *Renewable and sustainable energy reviews* 93 (2018), pp. 1–15. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2018.03.041. URL: https://www.sciencedirect.com/science/article/pii/S136403211830131X.

[132] I. E. Agency. *Electricity final consumption by sector, germany*. Accessed on 04-08-2021. 2021. URL: https://www.iea.org/fuels-and-technologies/electricity.

[133] F. Petropoulos, D. Apiletti, V. Assimakopoulos, M. Z. Babai, D. K. Barrow, S. B. Taieb, C. Bergmeir, R. J. Bessa, J. Bijak, J. E. Boylan, et al. "Forecasting: theory and practice". In: *International journal of forecasting* 38.3 (2022), pp. 705–871. ISSN: 0169-2070. DOI: https://doi.org/10.1016/j.ijforecast.2021.11.001. URL: https://www.sciencedirect.com/science/article/pii/S0169207021001758.

[134] J.-M. D. *Smart meter data from london area*. 2019. URL: https://www.kaggle.com/jeanmidev/smart-meters-in-london.

[135] S. Lorenczik, P. Becerra Zavala, and P. Fraser. *Electricity market report*. Tech. rep. International Energy Agency (IEA), 2016.

[136] A. Sauer, E. Abele, and H. Buhl. *Energieflexibilität in der deutschen Industrie: ergebnisse aus dem Kopernikus-Projekt - Synchronisierte und energieadaptive Produktionstechnik zur flexiblen Ausrichtung von Industrieprozessen auf eine fluktuierende Energieversorgung (SynErgie) [Energy flexibility in german industry: Results of the project kopernikus - synchronized and energy-adaptive production techonolgy for the flexible alignment of industrial processes to a fluctuating energy supply (SynErgie)]*. de. Ed. by A. Sauer, E. Abele, and H. Buhl. Stuttgart: Fraunhofer Verlag, 2019.

[137] E. Koliou, C. Eid, J. Chaves-Ávila, and R. Hakvoort. "Demand response in liberalized electricity markets: analysis of aggregated load participation in the german balancing mechanism". In: *Energy* 71 (2014). DOI: 10.1016/j.energy.2014.04.067.

[138] T. Gomez. “Monopoly regulation”. In: *Power systems* 61 (2013), pp. 151–198. DOI: 10.1007/978-1-4471-5034-3_4.

[139] B. Koirala, J. Chaves-Ávila, T. Gomez, R. Hakvoort, and P. Herder. “Local alternative for energy supply: performance assessment of integrated community energy systems”. In: *Energies* 9 (2016), p. 981. DOI: 10.3390/en9120981.

[140] S. Burger, J. Chaves-Ávila, C. Batlle, and I. Perez-Arriaga. “A review of the value of aggregators in electricity systems”. In: *Renewable and sustainable energy reviews* 77 (2017), pp. 395–405. DOI: 10.1016/j.rser.2017.04.014.

[141] P. Schott, R. Ahrens, D. Bauer, F. Häring, R. Keller, J. Pullmann, D. Schel, J. Schimmelpfennig, P. Simon, T. Weber, E. Abele, T. Bauernhansl, G. Fridgen, M. Jarke, and G. Reinhart. “Flexible it platform for synchronizing energy demands with volatile markets”. In: *It - information technology* 60 (2018). DOI: 10.1515/itit-2018-0001.

[142] E.-M. Ländner, A. Märtz, M. Schöpf, and M. Weibelzahl. “From energy legislation to investment determination: shaping future electricity markets with different flexibility options”. In: *Energy policy* 129 (2019), pp. 1100–1110. DOI: 10.1016 /j.enpol.2019.02.012.

[143] S. Roth, P. Schott, K. Ebinger, S. Halbrügge, B. Kleinertz, J. Köberlein, D. Püschel, H. Buhl, O. Steffi, G. Reinhart, and S. Roon. “The challenges and opportunities of energy-flexible factories: a holistic case study of the model region augsburg in germany”. In: *Sustainability* 12 (2020), p. 360. DOI: 10.3390/su12010360.

[144] D. Bauer, A. Hieronymus, C. Kaymakci, J. Köberlein, J. Schimmelpfennig, S. Wenninger, and R. Zeiser. “Wie it die energieflexibilitätsvermarktung von industrieunternehmen ermöglicht und die energiewende unterstützt”. In: *Hmd praxis der wirtschaftsinformatik* 58 (2021), pp. 1–14. DOI: 10.1365/s40702-020-00679-8.

[145] R. Keller, M.-F. Körner, D. Bauer, A. Schlereth, P. Simon, M. Rösch, T. Bauernhansl, G. Fridgen, and G. Reinhart. “Extending the automation pyramid for industrial demand side management”. In: *Procedia CIRP*. Ed. by P. Butala, E. Govekar, and R. Vrabic. Vol. 81. 52nd CIRP Conference on Manufacturing Systems 81. 2019, pp. 998 –1003. DOI: 10.1016/j.procir.2019.03.241.

[146] D. Bauer, A. Hieronymus, C. O. Kaymakci, J. Köberlein, J. Schimmelpfennig, S. Wenninger, and R. Zeiser. "Wie it die energieflexibilitätsvermarktung von industrieunternehmen ermöglicht und die energiewende unterstützt." In: *Hmd* 58.1 (2021), pp. 102–115.

[147] D. Bauer, E. Abele, R. Ahrens, T. Bauernhansl, G. Fridgen, M. Jarke, F. Keller, R. Keller, J. Pullmann, R. Reiners, G. Reinhart, D. Schel, M. Schöpf, P. Schraml, and P. Simon. "Flexible it-platform to synchronize energy demands with volatile markets". In: *Procedia cirp* 63 (2017). Manufacturing Systems 4.0 – Proceedings of the 50th CIRP Conference on Manufacturing Systems, pp. 318–323. ISSN: 2212-8271. DOI: https://doi.org/10.1016/j.procir.2017.03.088. URL: https://www.sciencedirect.com/science/article/pii/S2212827117302342.

[148] S. Roth, M. Thimmel, J. Fischer, M. Schöpf, E. Unterberger, S. Braunreuther, H. U. Buhl, and G. Reinhart. "Simulation-based analysis of energy flexible factories in a regional energy supply system". In: *Procedia manufacturing* 33 (2019). Sustainable Manufacturing for Global Circular Economy: Proceedings of the 16th Global Conference on Sustainable Manufacturing, pp. 75–82. ISSN: 2351-9789. DOI: https://doi.org/10.1016/j.promfg.2019.04.011. URL: https://www.sciencedirect.com/science/article/pii/S2351978919304883.

[149] F. Iglesias Vázquez, P. Palensky, S. Cantos, and F. Kupzog. "Demand side management for stand-alone hybrid power systems based on load identification". In: *Energies* 5 (2012), pp. 4517–4532. DOI: 10.3390/en5114517.

[150] R. Kamphuis, S. Galsworthy, M. Stifter, T. Esterl, S. Kaser, S. Widergren, M. Galus, R. Targosz, D. Brodén, L. Nordstrőm, M. Renting, A. Rijneveld, and S. Doolla. "Integrating demand flexibility with distributed generation – renewable energy sources (dg-res) at the residential household and commercial customer level in electricity grids". In: *Cired - open access proceedings journal* 2017 (2017), pp. 1827–1830. DOI: 10.1049/oap-cired.2017.0567.

[151] M. Meisel, M. Ornetzeder, A. Schiffleitner, T Leber, J Haslinger, M. Stachura, F. Kupzog, J. Krieger-Lamina, P. Wächter, and K Pollhammer. "Demand response for austrian smart grids". In: (2013).

[152] A. Einfalt, S. Cejka, K. Diwold, A. Frischenschlager, M. Faschang, M. Stefan, and F. Kupzog. “Interaction of smart grid applications supporting plug & automate for intelligent secondary substations”. In: *Cired, open access proceedings journal* 2017 (2017). DOI: 10.1049/oap-cired.2017.1080.

[153] S. Übermasser, T. Leber, M. Stifter, W. Hribernik, F. Leimgruber, and M. Meisel. “Maximizing local renewable energy consumption by shifting flexible electrical loads in time and space”. In: vol. 131. 2014. DOI: 10.1007/s00502-014-0256-3.

[154] M. Zweistra, S. Janssen, and F. Geerts. “Large scale smart charging of electric vehicles in practice”. In: *Energies* 13.2 (2020). ISSN: 1996-1073. DOI: 10.3390/en13020298. URL: https://www.mdpi.com/1996-1073/13/2/298.

[155] B. Bletterie, S. Kadam, and J. Baut. “Increased hosting capacity by means of active power curtailment”. In: 2016, 194 (4 .)–194 (4 .) DOI: 10.1049/cp.2016.0794.

[156] M. Findrik, P. Smith, J. Kazmi, M. Faschang, and F. Kupzog. “Towards secure and resilient networked power distribution grids: process and tool adoption”. In: 2016, pp. 435–440. DOI: 10.1109/SmartGridComm.2016.7778800.

[157] T. Esterl, R. Schwalbe, D. Burnier de Castro, F. Kupzog, S. Kadam, and M. Kolenc. “Impact of market-based flexibility on distribution grids”. In: 2016, 220 (4 .)–220 (4 .) DOI: 10.1049/cp.2016.0820.

[158] M. Rossi, B. Bletterie, M. Viana, and J. Varela. “On the definition and applicability of key performance indicators for evaluating the performance of smart grid concepts”. In: 2015.

[159] J. Baut, P. Zehetbauer, S. Kadam, B. Bletterie, N. Hatziargyriou, J. Smith, and M. Rylander. “Probabilistic evaluation of the hosting capacity in distribution networks”. In: 2016, pp. 1–6. DOI: 10.1109/ISGTEurope.2016.7856213.

[160] F. Kupzog, W. Elmenreich, and R. Bieber. “Managing data and complexity in energy systems”. In: *Computer science - research and development* 32 (2017), pp. 1–2. DOI: 10.1007/s00450-016-0322-7.

[161] S. Kadam, B. Bletterie, and W. Gawlik. “A large scale grid data analysis platform for dsos”. In: *Energies* 10 (2017), p. 1099. DOI: 10.3390/en10081099.

[162] B. Bletterie, A. Latif, P. Zehetbauer, S. Martinez Villanueva, E. Romero-Ramos, and H. Renner. “On the impact of load modelling on distribution network studies”. In: 2017, pp. 1–6. DOI: 10.1109/ISGTEurope.2017.8260262.

[163] F. Kintzler, T. Gawron-Deutsch, S. Cejka, J. Schulte, M. Uslar, E. Veith, E. Piatkowska, P. Smith, F. Kupzog, H. Sandberg, M. Chong, D. Umsonst, and M. Mittelsdorf. “Large scale rollout of smart grid services”. In: 2018. DOI: 10.1109/GIOTS.2018.8534432.

[164] R. Bessa, F. Soares, J. A. Lopes, and M. Matos. “Models for the ev aggregation agent business”. In: 2011. DOI: 10.1109/PTC.2011.6019221.

[165] R. Bessa, M. Matos, F. Soares, and J. A. Lopes. “Optimized bidding of a ev aggregation agent in the electricity market”. In: *Smart grid, ieee transactions on* 3 (2012), pp. 443–452. DOI: 10.1109/TSG.2011.2159632.

[166] N. Fonseca, J. Silva, A. Silva, J. Sumaili, L. Seca, R. Bessa, J. Pereira, M. Matos, P. Matos, A. Morais, M. Caujolle, and M. Sebastian-Viana. “Evolvdso grid management tools to support tso-dso cooperation”. In: 2016, 72 (4 .)–72 (4 .) DOI: 10.1049/cp.2016.0672.

[167] F. Retorta, C. Gouveia, G. Sampaio, R. Bessa, and J. Villar. “Local flexibility need estimation based on distribution grid segmentation”. In: 2022. DOI: 10.1109/EEM54602.2022.9920997.

[168] R. Belhomme, E. Corsetti, C. Gutschi, K. Kessels, A. Virag, M. Qadrdan, X. Xu, H. Li, and J. Jurasz. “Bottom-up flexibility in multi-energy systems: real-world experiences from europe”. In: *Ieee power and energy magazine* 19 (2021), pp. 74–85. DOI: 10.1109/MPE.2021.3072821.

[169] O. Valgaev and F. Kupzog. “Building power demand forecasting”. In: *It - information technology* 58 (2016). DOI: 10.1515/itit-2015-0045.

[170] O. Valgaev, F. Kupzog, and H. Schmeck. “Building power demand forecasting using k-nearest neighbours model – practical application in smart city demo aspern project”. In: *Cired - open access proceedings journal* 2017 (2017), pp. 1601–1604. DOI: 10.1049/oap-cired.2017.0419.

[171] L. Bank, M. Lindner, S. Wenninger, J. Köberlein, C. Kaymakci, M. Weigold, A. Sauer, and J. Schilp. "Integrating energy flexibility in production planning and control - an energy flexibility data model-based approach". In: 2021. DOI: 10.15488/11249.

[172] M. Lindner, S. Wenninger, G. Fridgen, and M. Weigold. "Aggregating energy flexibility for demand-side management in manufacturing companies – a two-step method". In: 2021. ISBN: 978-3-030-78423-2. DOI: 10.1007/978-3-030-78424-9_69.

[173] A. Bachmann, L. Bank, C. Bark, D. Bauer, B. B. Blöchl, M. Brugger, H. U. Buhl, B. Dietz, J. Donnelly, T. Friedl, and et al. *Energieflexibel in die zukunft - wie fabriken zum gelingen der energiewende beitragen können*. 2021. DOI: 10.24406/fit-n-638765. URL: https://publica.fraunhofer.de/handle/publica/301144.

[174] S. Rusche, S. Rockstuhl, and S. Wenninger. "Quantifizierung unternehmerischer nachhaltigkeit in der fertigungsindustrie: entwicklung eines zielorientierten nachhaltigkeitsindex". In: *Z energiewirtsch* 45.4 (2021), pp. 317–343.

[175] L. Wederhake, S. Wenninger, C. Wiethe, and G. Fridgen. "On the surplus accuracy of data-driven energy quantification methods in the residential sector". In: *Energy informatics* 5.1 (2022), pp. 1–24.

[176] T. Hornek, S. Potenciano Menci, J. Delgado Fernández, and I. Pavić. "Comparative analysis of baseline models for rolling price forecasts in the german continuous intraday electricity market (accepted for publication)". In: *15th International Conference on Applied Energy (ICAE 2023)*. 2023. DOI: Pending.

[177] C. M. Lee, J. Delgado Fernández, S. Potenciano Menci, A. Rieger, and G. Fridgen. "Federated learning for credit risk assessment". In: *Proceedings of the 56th Hawaii International Conference on System Sciences*. 2023, p. 10.

[178] S. Potenciano Menci. "Abstracts of the 11th dach+ conference on energy informatics (s53-taxonomy of local flexibility markets)". In: *Energy informatics* 5 (2022).

[179] A. Sauer, H. Buhl, A. Mitsos, and M. Weigold, eds. *Energieflexibilität in der deutschen Industrie. Band 2: Markt- und Stromsystem, Managementsysteme und Technologien energieflexibler Fabriken [Energy flexibility in German industry. Volume 2:*

Market and power systems, management systems and technologies of energy flexible factories]. Fraunhofer Verlag, 2022.

[180] J. Schilp, L. Bank, J. Köberlein, T. Bauernhansl, A. Sauer, A. Schlereth, G. Fridgen, S. Potenciano Menci, M. Weigold, M. Lindner, and A. Oeder. *Konzept der Energiesynchronisationsplattform. Diskussionspapiere V4. Executive Summary [Concept of the Energy Synchronization Platform. Discussion papers v4. Executive summary]*. 2021. DOI: 10.24406/IGCV-N-642368. URL: https://publica.fraunhofer.de/handle/publica/301240.

[181] G. Fridgen, S. Potenciano Menci, C. van Stiphoudt, J. Schilp, J. Köberlein, T. Bauernhansl, A. S. Grigorjan, D. Schel, A. Schlereth, F. Schulz, et al. *Referenzarchitektur der energiesynchronisationsplattform: teil der reihe diskussionspapiere v4 konzept der energiesynchronisationsplattform*. Tech. rep. Fraunhofer, 2021. URL: https://orbilu.uni.lu/handle/10993/49557.

[182] J. Schlip, L. Bank, J. Köberlein, T. Bauernhansl, A. Sauer, G. Fridgen, R. Bahmani, S. Potenciano Menci, M. Schoepf, C. van Stiphoudt, M. Weigold, and M. Lindner. *Optimierung auf der energiesynchronisationsplattform: teil der reihe diskussionspapiere v4 konzept der energiesynchronisationsplattform*. English. Tech. rep. 2021. URL: https://orbilu.uni.lu/handle/10993/49772.

[183] R. Cossent, L. Lind, M. Correa, T. Gómez, N. Pimentel, J. L. Baut, S. Potenciano Menci, and et al. *Economic and regulatory scalability and replicability of the integrid smart grid functionalities*. Tech. rep. D8.2. Accessed on 21-06-2021. H2020 InteGrid Project, 2020. URL: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5cc8e96a0&appId=PPGMS.

A Appendix

This appendix contains three main sections:

Appendix A.1: This section provides a comprehensive overview of the publications included in this dissertation, encompassing both journals and conferences, in light of its cumulative nature. It also offers an overview of excluded publications, both peer-reviewed and non-peer-reviewed. The latter category encompasses book chapters and industry reports, which laid the foundational groundwork for the development of this thesis.

Appendix A.2: To ensure transparency, this section contains contribution statements that detail my specific roles and contributions to each publication incorporated into this dissertation.

Appendix A.3: This section is a repository for the papers referenced in this dissertation. As highlighted in Appendix A, these papers are: A.3.1, A.3.2, A.3.3, A.3.4, A.3.5, A.3.6, and A.3.7.

A.1 Publication portfolio

A.1.1 Included publications

- RP1-Potenciano Menci and Valarezo [25]: S. Potenciano Menci and O. Valarezo. "Decoding design characteristics of local flexibility markets for congestion management with a multi-layered taxonomy". In: *Applied energy* 357 (2024), p. 122203. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2023.122203. URL: https://www.sciencedirect.com/science/article/pii/S0306261923015672. Scopus percentile: **99th**. Metric taken on November 6, 2023.

- RP2-Stiphoudt et al. [26]: C. van Stiphoudt, S. Potenciano Menci, C. Kaymakci, S. Wenninger, D. Bauer, S. Duda, G. Fridgen, and A. Sauer. "Energy synchronization platform concept to enable and streamline automated industrial demand response (Accepted for publication)". In: *15th International Conference on Applied Energy (ICAE 2023)*. 2023. DOI: Pending. GGS rating: Not applicable.

- RP3-Potenciano Menci et al. [27]: S. Potenciano Menci, B. Herndler, F. Kupzog, M. Zweistra, R. Steegh, and M. Willems. "Scalability and replicability analysis of grid management services in low voltage networks in local flexibility markets: an interflex analysis". In: *2021 IEEE Madrid PowerTech*. 2021, pp. 1–6. DOI: 10.1109/PowerTech46648.2021.9495061. GSS rating: Work in progress, Collected classes B. Metric taken on November 6, 2023.

- RP4-Potenciano Menci et al. [28]: S. Potenciano Menci, R. J. Bessa, B. Herndler, C. Korner, B.-V. Rao, F. Leimgruber, A. A. Madureira, D. Rua, F. Coelho, J. V. Silva, J. R. Andrade, G. Sampaio, H. Teixeira, M. Simões, J. Viana, L. Oliveira, D. Castro, U. Krisper, and R. André. "Functional scalability and replicability analysis for smart grid functions: the integrid project approach". In: *Energies* 14.18 (2021). ISSN: 1996-1073. DOI: 10.3390/en14185685. URL: https://www.mdpi.com/1996-1073/14/18/5685. Scopus percentile: **83rd**. Metric taken on November 6, 2023.

- RP5-Delgado Fernández et al. [29]: J. Delgado Fernández, S. Potenciano Menci, C. M. Lee, A. Rieger, and G. Fridgen. "Privacy-preserving federated learning for residential short-term load forecasting". In: *Applied energy* 326 (2022), p. 119915. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2022.119915. URL: https://www.sciencedirect.com/science/article/pii/S0306261922011722. Scopus percentile: **99th**. Metric taken on November 6, 2023.

- RP6-Delgado Fernández et al. [30]: J. Delgado Fernández, S. Potenciano Menci, and I. Pavic. "Towards a peer-to-peer residential short-term load forecasting with federated learning". In: *2023 IEEE Belgrade PowerTech*. 2023, pp. 1–6. DOI: 10.1109/PowerTech55446.2023.10202782. GSS rating: Work in progress, Collected classes B. Metric taken on November 6, 2023.

- RP7-Bahmani et al. [31]: R. Bahmani, C. van Stiphoudt, S. Potenciano Menci, M. Schöpf, and G. Fridgen. "Optimal industrial flexibility scheduling based on generic data format". In: *Energy informatics* 5.1 (2022), p. 26. ISSN: 2520-8942. DOI: 10.1186/s42162-022-00198-4. URL: https://doi.org/10.1186/s42162-022-00198

-4 (visited on 05/26/2023). Scopus percentile: **56th**. Metric taken on November 6, 2023.

A.1.2 Excluded peer-reviewed publications

A.1.2.1 Journal publications

- S. Potenciano Menci, J. Le Baut, J. Matanza Domingo, G. López López, R. Cossent Arín, and M. Pio Silva. “A novel methodology for the scalability analysis of ict systems for smart grids based on sgam: the integrid project approach”. In: *Energies* 13.15 (2020), p. 3818. ISSN: 1996-1073. DOI: 10.3390/en13153818. URL: http://dx.doi.org/10.3390/en13153818
- S. Potenciano Menci, C. Korner, B. Herndler, T. Esterl, C. Gutschi, and U. Krisper. “Tso-dso interaction in 2030/2040: scalability of the traffic light system concept in the project integrid”. In: *E & i elektrotechnik und informationstechnik* 138.8 (2021), pp. 634–635. DOI: 10.1007/s00502-021-00954-6. URL: https://doi.org/10.1007/s00502-021-00954-6

A.1.2.2 Conference publications

- T. Hornek, S. Potenciano Menci, J. Delgado Fernández, and I. Pavić. “Comparative analysis of baseline models for rolling price forecasts in the german continuous intraday electricity market (accepted for publication)”. In: *15th International Conference on Applied Energy (ICAE 2023)*. 2023. DOI: Pending
- C. M. Lee, J. Delgado Fernández, S. Potenciano Menci, A. Rieger, and G. Fridgen. “Federated learning for credit risk assessment”. In: *Proceedings of the 56th Hawaii International Conference on System Sciences*. 2023, p. 10
- S. Potenciano Menci. “Abstracts of the 11th dach+ conference on energy informatics (s53-taxonomy of local flexibility markets)”. In: *Energy informatics* 5 (2022)
- S. Potenciano Menci, R. Schwalbe, C. Corner, B. Herndler, J. Kahtan, C. Gutschi, and T. Gross. “Functional scalability and replicability analysis framework for dis-

tribution grids". In: *CIRED 2021 - The 26th International Conference and Exhibition on Electricity Distribution*. Vol. 2021. 2021, pp. 2099–2103. DOI: 10.1049/icp.2021.1610

- B. Herndler, S. Potenciano Menci, J. Kapeller, J. Bruschi, and T. Wagner. "Scalability and replicability analysis of an island microgrid concept". In: *2020 2nd IEEE International Conference on Industrial Electronics for Sustainable Energy Systems (IESES)*. Vol. 1. 2020, pp. 233–239. DOI: 10.1109/IESES45645.2020.9210692

A.1.3 Excluded non-peer-reviewed publications

A.1.3.1 Book chapters

- Contributed to Chapter B.3. A. Sauer, H. Buhl, A. Mitsos, and M. Weigold, eds. *Energieflexibilität in der deutschen Industrie. Band 2: Markt- und Stromsystem, Managementsysteme und Technologien energieflexibler Fabriken [Energy flexibility in German industry. Volume 2: Market and power systems, management systems and technologies of energy flexible factories]*. Fraunhofer Verlag, 2022

A.1.3.2 Industry reports

- J. Schilp, L. Bank, J. Köberlein, T. Bauernhansl, A. Sauer, A. Schlereth, G. Fridgen, S. Potenciano Menci, M. Weigold, M. Lindner, and A. Oeder. *Konzept der Energiesynchronisationsplattform. Diskussionspapiere V4. Executive Summary [Concept of the Energy Synchronization Platform. Discussion papers v4. Executive summary]*. 2021. DOI: 10.24406/IGCV-N-642368. URL: https://publica.fraunhofer.de/handle/publica/301240

- G. Fridgen, S. Potenciano Menci, C. van Stiphoudt, J. Schilp, J. Köberlein, T. Bauernhansl, A. S. Grigorjan, D. Schel, A. Schlereth, F. Schulz, et al. *Referenzarchitektur der energiesynchronisationsplattform: teil der reihe diskussionspapiere v4 konzept der energiesynchronisationsplattform*. Tech. rep. Fraunhofer, 2021. URL: https://orbilu.uni.lu/handle/10993/49557

- J. Schlip, L. Bank, J. Köberlein, T. Bauernhansl, A. Sauer, G. Fridgen, R. Bahmani, S. Potenciano Menci, M. Schoepf, C. van Stiphoudt, M. Weigold, and M. Lindner. *Optimierung auf der energiesynchronisationsplattform: teil der reihe diskussionspapiere*

v4 konzept der energiesynchronisationsplattform. English. Tech. rep. 2021. URL: https://orbilu.uni.lu/handle/10993/49772

- C. van Stiphoudt, S. Potenciano Menci, M. Schöpf, G. Fridgen, M. Weigold, M. Lindner, H. U. Buhl, S. Duda, P. Schott, M. Weibelzahl, and S. Wenninger. *Energieflexibilitätsdatenmodell der Energiesynchronisationsplattform : Teil der Reihe "Diskussionspapiere V4 - Konzept der Energiesynchronisationsplattform" [Energy flexibility data model of the energy synchronization platform: part of the series "concept of the energy synchronization platform. Discussion papers v4"]*. s.l., 2021. URL: https://eref.uni-bayreuth.de/68094/
- S. Potenciano Menci, B. Herndler, F. Mesureur, A. Ahmadifar, and A. Izimova. *D3.8 scalability and replicability analysis (sra) for all use cases*. Research rep. InterFlex Project, 2019
- J. Le Baut, S. Potenciano Menci, B. Herndler, C. Korner, and et al. *Technical scalability and replicability of the integrid smart grid functionalities*. Tech. rep. D8.1. Accessed on 21-06-2021. H2020 InteGrid Project, 2019. URL: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5cac508d4&appId=PPGMS
- R. Cossent, L. Lind, M. Correa, T. Gómez, N. Pimentel, J. L. Baut, S. Potenciano Menci, and et al. *Economic and regulatory scalability and replicability of the integrid smart grid functionalities*. Tech. rep. D8.2. Accessed on 21-06-2021. H2020 InteGrid Project, 2020. URL: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5cc8e96a0&appId=PPGMS

A.2 Contribution statements

Given that this Ph.D. dissertation is a cumulative work, we have prioritized coherence and clarity. Accordingly, this Section of the Appendix includes credit statements for each appended publication. These credit statements originate directly from the published publications. To offer further clarity, each contribution statement is supplemented with an Addendum that elaborates on my involvement and contributions to each paper. If a publication lacks a contribution statement within its original form, please consult the associated Addendum for that information.

A.2.1 RP1 - Decoding design aspects of local flexibility markets for congestion management with a multi-layered taxonomy

- **Contribution statement**: *Sergio Potenciano Menci: Conceptualization, Methodology, Data Curation, Formal analysis, Writing - Original Draft, Writing - Review & Editing, Visualization. Orlando Valarezo: Data Curation, Formal analysis, Writing - Original Draft, Writing - Review & Editing.*
- **Addendum**: As a lead author, I contributed to the entire paper process. I proposed the idea, developed it, was present in all the interviews, curated the data, analyzed it, wrote the original draft and the subsequent versions based on the substantial comments from the review process.

A.2.2 RP2 - Energy Synchronization Platform to Enable and Streamline Automated Industrial Demand Response

- **Contribution statement**: The published research paper does not have a contribution statement in its publication format.
- **Addendum**: As a co-author, I contributed to the entire paper. This includes conceptualizing a new version, writing, reviewing, creating visualizations, and refining the methodology. It is worth mentioning that this research publication results from the project work carried out during the SynErgie Funding Phase II and is not limited to the authors listed in the publication.

A.2.3 RP3 - Scalability and Replicability Analysis of Grid Management Services in Low Voltage Networks in Local Flexibility Markets: an InterFlex analysis

- **Contribution statement**: The published research paper does not have a contribution statement in its publication format.

- **Addendum**: As the lead author, I was responsible for carrying out the major work of the paper. My listed co-authors provided support in terms of refining and evaluating the results. Specifically, I contributed to the methodology, data curation, simulation, analysis, visualization, drafting of the original manuscript, and incorporating feedback from reviewers.

A.2.4 RP4 - Functional Scalability and Replicability Analysis for Smart Grid Functions: The InteGrid Project Approach

- **Contribution statement**: *Conceptualization, S.P.M., R.J.B., B.H., C.K., B.-V.R., F.L., F.C., J.V.S., H.T., M.S., A.A.M., D.R., G.S., J.V., R.A.; methodology, S.P.M., F.C., M.S., H.T., J.V.S., M.S., L.O.; writing original draft preparation, S.P.M., J.V.S., M.S., J.R.A., D.C.; writing—review and editing, S.P.M., B.H., C.K., M.S., R.J.B.; visualization, S.P.M.; funding acquisition, R.J.B., U.K., R.A. All authors have read and agreed to the published version of the manuscript.*

- **Addendum**: As a co-author, my contributions are mainly to reviewing the results, developing the methodology, conceptualizing the paper structure, analyzing the results, writing the original draft, and the final version based on the substantial received peer-reviewed comments.

A.2.5 RP5 - Privacy-preserving federated learning for residential short-term load forecasting

- **Contribution statement**:*Joaquín Delgado Fernández: Conceptualization, Methodology, Data curation, Writing – original draft, Software, Writing – review & editing, Visualization. Sergio Potenciano Menci: Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing, Visualization. Chul Min Lee: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. Alexander Rieger: Writing – review & editing, Supervision. Gilbert Fridgen: Writing – review & editing, Supervision, Funding acquisition.*

- **Addendum**: As a subordinate author, my contributions to the paper were limited to developing the conceptualization, adjusting the research methodology, creating scenarios, curating data and analyzing results, assisting in visualizations, writing the original draft, and the final version based on the received peer-reviewed comments.

A.2.6 RP6 - Towards a peer-to-peer residential short-term load forecasting with federated learning

- **Contribution statement**: The published research paper does not have a contribution statement in its publication format.
- **Addendum**: As a co-author, my contributions are mainly to the development of the paper idea, review and improvement of the algorithms, analysis of the results, methodology, writing the original draft, and the final version based on the received peer-reviewed comments.

A.2.7 RP7 - Optimal industrial flexibility scheduling based on generic data format

- **Contribution statement**: *All authors contributed to the conception of the research. RB, MS and SPM contributed to the design of the work. RB, CvS and SPM drafted the first version of the paper. MS and GF supervised the research conception, provided feedback and participated in the paper revision. All authors read and approved the final manuscript.*
- **Addendum**: As a co-author, my contributions are mainly to reviewing the optimization functions, the conceptualization of the paper by providing the final structure, the research methodology, analyzing the results, writing the original draft, and the final version based on the received peer-reviewed comments.

A.3 Appended research publications

A.3.1 Research Paper 1 – *Decoding design aspects of local flexibility markets for congestion management with a multi-layered taxonomy*

Applied Energy 357 (2024) 122203

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Decoding design characteristics of local flexibility markets for congestion management with a multi-layered taxonomy

Sergio Potenciano Menci [a,*], Orlando Valarezo [b]

[a] Interdisciplinary Centre for Security, Reliability and Trust (SnT), 29 Avenue John F. Kennedy, Luxembourg, 1855, Luxembourg
[b] Institute for Research in Technology (IIT), ICAI School of Engineering, Comillas Pontifical University, Madrid, 28015, Spain

ARTICLE INFO

Keywords:
Local flexibility markets
Smart grid architecture model
Congestion management service
Electricity flexibility service
Taxonomy
Classification

ABSTRACT

Local flexibility markets are becoming increasingly popular smart grid solutions. They connect customers who require flexible electricity supply and demand with local flexibility providers. However, the growing number of diverse solutions has led to a proliferation of concepts, projects, and companies in this market, with this diversity making understanding and comparison difficult. To tackle this challenge, we propose a multi-layered taxonomy of local flexibility market solutions. This focuses on congestion management on the distribution side of this activity; a crucial service for distribution system operators. Our taxonomy utilizes the Smart Grid Architecture Model to describe these markets comprehensively. We employ an iterative taxonomy-building method, refining and evaluating it through insights from ongoing implementations and twenty-eight expert interviews. Moreover, we present a complete instantiation of our taxonomy and offer a discussion with practical recommendations for practitioners in the local flexibility market landscape.

1. Introduction

The evolution to "smart grids" from traditional unidirectional and passive power systems accentuates challenges like real-time power system's balancing and congestion, especially with the proliferation of distributed energy resources (DERs) and sector electrification [1,2]. These complexities, notably at the medium voltage (MV) and low voltage (LV) levels, require System Operators (SOs) traditionally resort to congestion management ancillary services that limit electrical power exchange when line and transformer capacities are reached [3,4].

As these services are often not sufficient, both Distribution System Operators (DSOs) and Transmission System Operators (TSOs) have begun to explore alternatives, such as the use of sources of flexibility [5–7]. SOs can incorporate flexibility sources through non-market-based or market-based solutions [8]. However, certain jurisdictions (such as the European Union (EU)) prefer market-based solutions [9, 10]. While various market-based solutions exist, local flexibility markets (LFMs) emerge as a solution for leveraging sources of flexibility and providing services such as congestion management to the SOs [11].

With the burgeoning interest in LFM for managing congestions and delivering local services, academic literature in this domain has proliferated. Nevertheless, existing research tends to focus in isolation on distinct facets of LFMs—ranging from market designs [11–13] and system architectures [14–16], to technical operations [17–19]. This fragmented approach complicates efforts to compare, select, and regulate such markets. Compounding the challenge is the absence of a homogeneous vocabulary and an integrated perspective, which further exacerbates the complexity of understanding and implementing LFM solutions.

To mitigate this fragmentation, lack of homogeneous vocabulary, and holistic view, we introduce a multi-layered taxonomy of LFMs for congestion management focused on the distribution level. Our taxonomy builds on the Smart Grid Architecture Model (SGAM) as a structuring framework [20], and results from an iterative taxonomy-building process that incorporates insights from currently implemented LFM projects, as well as feedback from twenty-eight expert interviews. It is designed to enhance comprehension of both current and forthcoming LFMs solutions for congestion management, catering to academic, industrial, and regulatory stakeholders. This taxonomy not only refines the vocabulary for mutual understanding and fortifies the SGAM market layer with an intricate classification but also lays the groundwork for subsequent research, such as typologies, ontologies, and archetype designs. Most importantly, it will aid the EU's deployment of LFM solutions by offering standardized definitions and consistent descriptive classification formats that can organize knowledge.

The structure of this manuscript is as follows: Section 2 gives a literature overview of LFMs. It includes the theoretical background, the

* Corresponding author.
E-mail address: sergio.potenciano-menci@uni.lu (S. Potenciano Menci).

https://doi.org/10.1016/j.apenergy.2023.122203
Received 2 September 2023; Received in revised form 13 October 2023; Accepted 29 October 2023
Available online 12 December 2023
0306-2619/

direction of regulatory change in the EU regarding the development of these solutions, and a review of the most prominent EU initiatives with relation to LFM solutions. Section 3 outlines our research approach to create a multi-layered taxonomy for LFM focused on congestion management at the distribution level. Section 4 presents the resulting taxonomy, subdivided according to the SGAM interoperability layer structure. Section 5 provides a complete example taxonomy, based on an existing LFM solution, with three additional examples in the Appendix C. Later, Section 6 discusses and provides recommendations based on our proposed taxonomy's results. Finally, Section 7 concludes the manuscript.

2. Related work

2.1. Local flexibility markets: definitions and design characteristics

2.1.1. Definitions

In essence, LFMs represent a subtype of electricity markets that feature spatial and product concerns. Hence, their "local" and "flexibility" designations. The term "local" refers to certain services and products characterized by a specific geographical location (e.g., congestion management for DSO). Only flexibility providers connected to the given location in the electricity grid can provide the required service [21]. The term "flexibility" refers to the adjustability provided by a range of flexibility sources [22].

Although there are numerous interpretations of LFMs, as collected in Table 1, there is a disagreement on the definitions as not all refer to the concept in the same manner. These definitions, especially Agency for the Cooperation of Energy Regulators (ACER) 's and European Network of Transmission System Operators for Electricity (ENTSO-E)'s incorporate design aspects such as the target group (e.g., DSOs), while in other cases, include trading horizon actions, flexibility grid needs, aggregation, and platform independence. These definitions could lead to confusion and limit the scope of these solutions, especially if collected in regulations or frameworks. To avoid this issue, we provide a broader, more inclusive definition of LFMs as *"information system solutions that enable buyers and sellers to trade flexibility-services to address local needs"*. This definition is not specific to any particular market design, implementation, or service (i.e., congestion management), thus encouraging innovation and allowing for adaptation to various contexts and evolving requirements and designs.

2.1.2. Design characteristics

LFMs represent complex smart grid solutions involving multiple actors, numerous information flows, and multiple components necessary for optimal operation. As interest in these solutions grows, numerous proposals have emerged to address operational challenges, such as congestion management, by providing congestion management services (see Section 2.3). The diverse array of proposed solutions raises critical questions about various market designs, functions, components, and communication modes. These questions are paramount to developers, researchers, regulators, SOs, and users who seek a comprehensive understanding of, comparison between, development of, and analysis of these solutions for future real-world implementation.

Several authors have attempted to address these questions by delving into the design aspects of LFM solutions. Ramos et al. [12] provide a high-level description of the market design characteristics relevant to LFM solutions, exploring dimensions such as temporal, spatial, contractual, and price-clearing aspects. Similarly, Radecke et al. [13] focus on market design elements pertinent to congestion management services, including considerations related to market participants, product and remuneration structures, pricing mechanisms, matching procedures, and clearing processes. Meanwhile, Minniti et al. [16] concentrate on other design elements relevant to all LFM solutions, such as the coordination of market players (i.e., TSO-DSO) and the coexistence of various flexibility services. Valarezo et al. [11] conduct a literature review encompassing different flexibility platforms, including LFM solutions for congestion management. They analyze diverse design characteristics such as pricing strategies, market frequency, bidding processes, settlement mechanisms, market operators' income models, and integration with established electricity markets. Similarly, Färegård et al. [26] delve into specific design characteristics of LFMs that offer congestion management services, covering elements like delivery periods, price settlements, trading platforms, and bid sizes. This detailed examination serves as a foundation for comparing and classifying existing solutions. Additionally, Chondrogiannis et al. [31] provide an in-depth description and comparison of current LFM solutions for congestion management, considering functions like pre-qualification procedures, signal dispatch, validation processes, settlement mechanisms, as well as market design characteristics such as trading mechanisms and flexibility product offerings. In the context of solution design, Troncia et al. [32] introduce a theoretical market framework aimed at conceptualizing and designing electricity markets, applicable to LFM solutions.

Table 1
Local flexibility market literature definitions.

Author	Year	LFM definition
Ramos et al. [12]	2016	*Long- or short-term trading actions for flexibility in a specific geographical location, voltage level, and system operator (DSO and TSO), given by grid conditions or balancing needs, where participants in a relevant market can be aggregated to provide flexibility services*
Olivella-Rosell et al. [18]	2018	*An electricity flexibility trading platform to trade flexibility in geographically limited areas such as neighborhoods, communities, towns, and small cities.*
Radecke et al. [13]	2019	*Mechanism that i) aims to relieve congestion in the distribution grid, ii) works through impacting the dispatch of generation, load and/or storage assets, with iii) voluntary participation, and iv) remuneration that is determined based on participants' bids*
Correa-Florez et al. [23]	2020	*Independent trading space/platform with specific bidding rules*
Ziras et al. [24]	2021	*A market-based solution to trade flexibility locally between flexibility providers and Distribution System Operators (DSOs).*
Dronne et al. [25]	2021	*A local flexibility market is typically used to provide services for the flexibility needs inherent to the Distribution Network Operator (DNO).*
Faregard et al. [26]	2021	*Enablers of explicit DSF, which can be used for several purposes such as managing grid congestions*
Singh et al. [27]	2022	*Trading mechanism for electrical flexibility in geographically constrained regions like communities, neighborhoods, and towns. The LFM provides a competitive trading platform that allows flexibility purchasers, such as DSOs and Balance Responsible Parties (BRPs), to trade flexibility with flexibility sellers, such as aggregators and prosumers.*
ENTSO-E [28]	2022	*Specifically aimed solutions at resolving constraints on the distribution network.*
ACER [29]	2022	*Markets where service providers offer products for local SO services*
Valarezo et al. [30]	2023	*A marketplace that enables buyers and sellers to trade flexibility services to address local needs.*

They focus on design characteristics like market architecture, coordination mechanisms between TSO and DSO, optimization processes, market operation, and grid representation.

In a broader context, Acosta et al. [33] propose a market categorization framework that applies to various smart grid solutions, including LFMs. Within this framework, they emphasize market design aspects such as the degree of competition, agreement structures, clearing mechanisms, price formation, price mechanisms, market product offerings, and the duration of market operations.

Building upon this categorization approach, Teske et al. [34] offer a comprehensive classification of local energy markets, specifically focusing on ancillary services, which congestion management services can fall into. This classification distinguishes between LFMs and local capacity allocation markets, highlighting their distinct characteristics concerning objectives, impact on TSOs and DSO, applications, and the primary challenges they face.

Diving into understanding and categorizing the challenges following a taxonomy-based classification approach, Moller [35] develops a taxonomy. The aim is to understand barriers and potential solutions to flexibility in the district energy-electricity system operated by DSOs. This taxonomy proves valuable for designers and regulators seeking insights into the challenges associated with designing and overseeing, for instance, solutions for DSOs that include flexibility at their core, such as LFM solutions.

Likewise, Mengelkamp et al. [36], adopting a more methodological categorization approach, change the focus to a business-oriented perspective. They derive a taxonomy using a hybrid approach that combines empirical research and conceptual methods. Their taxonomy aims to understand business models' intricacies and defining characteristics within the context of local electricity markets (LEMs) and their relation to LFMs. It draws insights from expert interviews and encompasses aspects related to the value proposition, solution perspectives, partnerships, product offerings, cost and revenue considerations, roles, legal aspects, succession factors, and transactional elements within the solution.

However, these contributions offer only a partial view of the myriad design characteristics of LFMs and their services, particularly regarding congestion management. A comprehensive taxonomy encompassing all design aspects of these smart grid solutions for congestion management could serve as the foundation for detailed and harmonized descriptions. Such a comprehensive taxonomy would greatly enhance our ability to compare and analyze LFM solutions, thereby significantly advancing our understanding of these complex systems. Importantly, this taxonomy must encompass many perspectives beyond the purely business aspect, as LFM represents complex smart grid solutions.

2.2. European regulation push towards local flexibility markets

LFMs have become a central policy focus for the EU, catalyzed by the European Commission (EC)'s strategic endeavors to revolutionize the power landscape. Driven by the trinity of decarbonization, decentralization, and digitalization [37], the ambition is a robust, sustainable energy infrastructure, with LFMs at its helm, aiding SOs in efficient grid management.

The genesis of this regulatory trajectory traces back to the third energy package of 2009, which evolved in 2016 with the fourth energy package or Clean Energy Package (CEP) proposal, outlining a framework for DSOs to harness flexibility. Subsequent policy inflections in 2019 further supported LFMs via the European Green Deal [38], with 2020 heralding the Energy System Integration Plan [39] and the EU Digital Strategy [40], both underscoring the salience of platforms like digital LFMs solutions.

In 2021, the scene was set for more radical shifts. Directives on Renewable Energy [41] and Energy Efficiency [42] accentuated non-discriminatory market participation, congestion management, and demand-side flexibility. These culminated in the 2021 'Fit For 55' package, setting an ambitious renewable energy resource (RES) target of 40% by 2030 [43], implying deeper grid complexities at LV and MV levels and a pressing call for LFM solutions for smooth RES assimilation.

Additionally, the EU's REPower initiative [44] sought to expedite the energy shift, seeking demand moderation, fuel source diversification, and higher RES integration. This momentum carried into 2022 when the EU Commission encouraged ACER for a comprehensive demand response framework, emphasizing SOs's pivotal role in local market operations, as it clearly states SO can use LFM to procure flexibility [29].

In sum, the EU's evolving policy landscape profoundly recalibrates the regulatory climate, reshaping grid and market paradigms. As challenges to the legacy power model mount, they concurrently create a push for innovative solutions like LFMs to navigate and thrive amid these changes [31].

2.3. Overview of local flexibility markets for system operators in Europe

LFMs have generated substantial attention as a way to achieve the integration of many regulatory changes while being a cost-effective complement for SOs. Hence, many EU projects have focused on the research and development of LFM solutions. Table 2 presents a comprehensive overview of the most pertinent European initiatives that currently feature LFM solutions for the procurement of SO services via platforms. Many of these initiatives have emerged from the European H2020 research program, including projects such as CoordiNet [45,46], EUniversal [47,48], EU-SysFlex [49,50], InterFlex [51,52], and OneNet [53,54]. These projects involve multiple partners from different European countries, as outlined in Table 2. Furthermore, Germany and Denmark have introduced their own national initiatives, namely Enera [55] and Ecogrid 2.0 [56] – to facilitate the procurement of flexibility services. Additionally, the Cornwall Local Energy Market [57] in the UK – which was led by Centrica and partially funded by the European Regional Development Fund – developed a market-based to DSO and TSO flexibility procurement arrangements.

Other LFM solutions have been developed independently by SOs. For instance, Flexible Power [58] is a collaborative effort of four UK electricity distribution network operators (DNOs): National Grid Electricity Distribution, Northern Powergrid, Scottish and Southern Electricity Networks, and SP Energy Networks. Similarly, Enedis – the main DSO in France – created and operates a local flexibility platform to procure congestion management services [59]. Moreover, GOPACS [60], owned and operated by the Dutch–German TSO TenneT and four DSOs (Stedin, Liander, Enexis Groep, and Westland), serves as an intermediary platform supporting the coordinated market-based procurement of congestion management services. Another relevant flexibility platform is being developed by OMIE, the nominated electricity market operator (NEMO) for the Iberian Peninsula (Spain and Portugal). This initiative builds upon the work carried out in the OneNet [53], DRES2MArket [61] and IREMEL [62] projects.

On the other hand, there are commercial solutions that offer marketplaces for the procurement of flexibility services. For instance, Piclo [63] operates in the UK and has expanded its operations to Ireland, Lithuania, Portugal, and the United States. Similarly, NODES [64] is an independent marketplace that functions as a market operator as part of various projects such as Mitnetz [65], NorFlex [66], Smart Senja [67], SthlmFlex [68], among others. Most of the analyzed initiatives are either fully operational or completed, with the exception of EUniversal, OneNet, and the OMIE LFM, which were at the implementation stage at the time this research was conducted.

Table 2
Overview of local flexibility market platforms implemented in Europe since 2016.

Service objective	Market type	Use Cases	Status	Countries	# UCs
Congestion Management	Flexibility market for DSO	CoordiNet: BUC-ES-1b, BUC-SE-1a/1b	2019–2022	ES-SE	25
		EUniversal: BUC-PT1	2020–2023	PT	
		Flexible Power: National Grid Electricity Distribution, SP Energy Networks, Northern Power Grid, Scottish and Southern Electricity Networks	In operation	UK	
		InterFlex: FR-UC3, NL demo	2017–2019	FR-NL	
		NODES: Mitnetz	2018–2021	DE	
		NODES: Smart Senja	In operation	DE-NO	
		OneNet: WECL-ES-01/02, EACL-HU-02, EACL-SL-01	2020–2023	ES-HU-SL	
		Piclo: UK Power Networks, Electricity Northwest	In operation	UK	
		OMIE: IREMEL and DRES2Market	In development	ES	
		Enedis: local flexibility platform	In operation	FR	
	Flexibility market for DSO and TSO	CoordiNet: BUC-GR-2a/2b	2019–2022	GR	
		Cornwall LEM	2016–2020	UK	
		Enera: Northwest of Germany use case	2017–2020	DE	
		GOPACS	In operation	NL	
Voltage Control	Flexibility market for DSO	EUniversal: BUC-PT2	2020–2023	PT	6
		EU-SysFlex: FI demo	2017–2021	FI	
		OneNet: EACL-HU-01, EACL-SL-02	2020–2023	HU-SL	
	Flexibility market for DSO and TSO	CoordiNet: BUC-GR-1a/1b	2019–2022	GR	
Congestion Management and Voltage Control	Flexibility market for DSO	EUniversal: BUC-DE-AP/RP, BUC-PL-AP/RP, BUC-PT3/4	2020–2023	DE-PL-PT	11
		Ecogrid 2.0: BC3 Flexibility services at DSO level	2016–2019	DK	
		OneNet: EACL-CZ-01/02/03	2020–2023	CZ	
	Flexibility market for DSO and TSO	EU-SysFlex: Portuguese demo PT-FxH-RP	2017–2020	PT	
Congestion Management Balancing	Flexibility market for DSO and TSO	EU-SysFlex: Italian demo IT-AP	2017–2021	IT	3
		NODES: NorFlex	2019–2022	NO	
		NODES: SthlmFlex	In operation	SE	
Congestion Management, Voltage Control Balancing	Flexibility market for DSO and TSO	OneNet: SOCL-CY-01/02, EACL-PL-01/02/03/04	2020–2023	CY-PL	6
Islanding	Flexibility market for DSO	CoordiNet: BUC-ES-4	2019–2022	ES	1

2.3.1. *Observations*

Two types of market designs were identified in these projects: Flexibility Markets for DSOs and Flexibility Markets for DSOs and TSOs. The former represents a market-based mechanism allowing DSOs to procure system services from flexibility service providers (FSPs) to address local needs, with DSOs maintaining exclusive access to DERs. In the latter, flexibility markets for DSOs and TSOs, flexibility is distributed between system operators through market-based coordination, such as bid forwarding, value stacking or priority-in-bid-selection. In this instance, LFMs at distribution level typically function as the initial stage of the process. It is important to highlight that flexibility markets which are used exclusively for TSOs are excluded from the analysis. This is because this paper focuses on LFMs at the distribution level.

Furthermore, we identified and examined fifty-two use cases (UCs), all of which used LFM platforms as collected in Table 2. We categorized them into six groups based on their service objectives.

The first group comprises UCs for testing congestion management solutions. In nineteen of these UCs, the DSO aims to procure flexibility to resolve or mitigate physical congestions (specially, the overloading of lines and/or transformers) using active power products. In the remaining UCs, the TSOs and DSOs procure flexibility to address congestion issues through TSO - DSO coordination schemes [21]. The second group comprises six UCs which provide voltage control services. These UCs share similarities with congestion management UCs. However, their focus diverges slightly as their solutions rectify voltage violations using reactive power or a combination of active and reactive power. The following groups propose market-based solutions that combine congestion management services with voltage control and/or balancing services. For instance, projects such as EUniversal, OneNet, Ecogrid 2.0, and EU-SysFlex have implemented UCs that focused on LFMs for the joint procurement of congestion management and voltage control services. In the market-clearing of these solutions, any active and/or reactive power flexibility bids from providers could solve lines/transformers overloading, bus voltage violation, or both. The last group includes the CoordiNet UC-ES-4, which centers on islanding service (i.e., a type of microgrid operation).

Among the reviewed UCs, congestion management service emerges as the most prevalent service in local flexibility markets. Consequently, the proposed taxonomy concentrates primarily on this service alone and uses these UCs as a foundation to develop it.

3. Research approach

This research paper proposes a multi-layered taxonomy for LFMs focusing on congestion management at the distribution level. We limit our taxonomy to the area of congestion management, as it is the main service for DSOs and where the main pilot projects and companies are directing their efforts (see Section 2.3). We propose our definition of LFMs in Section 2.1. We refer to congestion management services as mitigating the restriction of electrical power exchange through the electrical grid, with this largely dependent on the capacity of transmission/distribution lines and transformers. Line or transformer capacity can be restricted by physical constraints, such as thermal loading or hosting capacity, or by nonphysical factors, such as contract power limitation. This is a particular concern for smaller DSOs when contracting power capacity from larger DSOs.

3.1. Smart grid architecture model framework

The SGAM is a fundamental part of our taxonomy-building approach because LFMs are smart grid solutions. The SGAM can provide a harmonized description of smart grid solutions [20]. It requires a business-case or other use-case as a context from which to provide a description. The SGAM emerges from the M/490 EU mandate, which asks the Smart Grid Coordination Group (CEN, CENELEC, and ETSI members) to develop a framework to enable European standardization in the field of smart grids, while maintaining transverse consistency and promoting continuous innovation [20].

The SGAM framework is widely employed within the EU to provide comprehensive descriptions of smart grid solutions. It is used by various initiatives, such as research projects and their scientific publications [46,51,53,69], as well as task forces in Europe, including the European Smart Grids Task Force Expert Group 1 [70] and the Data Management Working Group [71]. These entities highly recommend using the SGAM to achieve a holistic and harmonized depiction of solutions.

The SGAM divides the description of a smart grid solution into five interoperability layers: (1) Business, (2) Function, (3) Information, (4) Communication, and (5) Component, as we depict in Fig. 1 [20].

The business interoperability layer provides an overview of the economic and regulatory structures of the solution. The function interoperability layer describes the services and tools relationships from an architectural viewpoint. The information interoperability layer describes the exchange of information and its underlying canonical data models. The communication interoperability layer describes the protocols and mechanisms for information exchange between components.

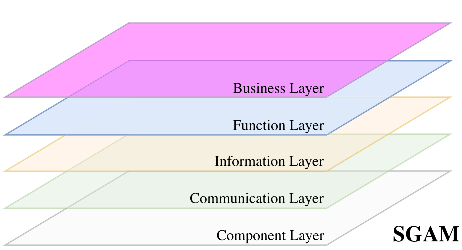


Fig. 1. Interoperability layers of the Smart Grid Architecture Model based on [20].

Finally, the component layer provides an overview of the power system devices and information and communication technology (ICT) equipment used to operate the solution.

As a result, the SGAM offers a harmonized power system framework for the description of smart grid solutions. Consequently, we use it to structure the descriptions in our taxonomy. For each interoperability layer, we create a separate taxonomy. Using a detailed SGAM – such as the one in [72], which covers all five interoperability layers – we can provide a comprehensive, integrated, and harmonized description of our LFM solution. However, even a partially described solution that covers one or more interoperability layers can still help to identify objects. We aim not to map our taxonomy onto the SGAM, but to use it as a boundary to define and describe each specific interoperability layer and, as a result, our LFM solution.

3.2. Taxonomy building method

Traditionally, taxonomies are means of classification using empirical observations of identified objects [73]. However, given the rapid evolution of LFMs and regulations, relying solely on empirical data may result in an outdated taxonomy. Therefore, we incorporated conceptual information to enhance and strengthen our taxonomy. We selected the extended taxonomy design process (ETDP) method proposed by Kundisch et al. [74] as it builds from Nickerson et al. [75] and extends the evaluation step (see Appendix A–Fig. A.1 for convenience).

The process of building a taxonomy involves several steps. Researchers start by specifying the observed phenomena (i.e., the matter of research), the target groups, and the intention of the research. Next, they determine the meta-characteristics of the taxonomy, which provide the essence of the classification. Then, researchers need to determine their ending conditions and evaluation goals. Succeeding steps then focus on the main building blocks of the taxonomy through a step-oriented method that involves empirical (E-2-C) and/or conceptual (C-2-E) iterations to drive the dimensions and characteristics of the taxonomy. In our case, we used a mixed approach that combines both iterations. The taxonomy is defined by a set of dimensions, each consisting of mutually exclusive characteristics. Dimensions can be considered variables, while characteristics can be considered possible values of these variables [75]. Taxonomies can be multi-layered to increase comprehension and readability [74]. In our case, we use the term “category” instead of “layer” to avoid naming convention problems with the SGAM interoperability layers. After each iteration, researchers revise the taxonomy and check their ending conditions. If they meet their ending conditions, they continue by configuring and performing the evaluation. Once the researchers meet their evaluation goals, they can consider that they have finalized the taxonomy and can then report it.

To develop our taxonomy, we focused on observing the phenomenon of local flexibility market platforms and identified three user target groups: (1) Academic, (2) Industrial, and (3) Regulatory. The taxonomy serves as a foundation from which to describe, understand, classify, and analyze LFM platforms in a harmonized fashion. Therefore, the established meta-characteristic is: *“Design characteristics of local flexibility market platforms focused on congestion management at distribution level in the EU”*.

We assumed four objective ending conditions. Objective conditions provide a clear and straightforward means for researchers to check their stopping conditions. The first condition is to cover a representative sample of objects, in our case, commercial solutions and EU projects. To do so, we analyzed commercial and development solutions available such as Piclo [63], NODES [64], OMIE [76], GOPACS [60],[1] which are

[1] It is not considered a local flexibility market per-se, but we considered it nonetheless, as it can help with the evaluation process and is an experiment for the usefulness of the taxonomy.

the leading commercial solutions. We also analyzed the details of the main EU projects targeting LFM selected from our literature analysis (see Section 2.3). The second condition is to stop iterating if we do not perform any merge or split operations in the previous iteration (see [74]). The third condition is that every dimension and characteristic must be unique for each interoperability layer. The fourth condition is that the combination of characteristics is unique and not repeated. In a similar fashion, as authors from the same discipline [36,77] or other disciplines have done [78,79], we incorporated an additional mutually exclusive marker as a new column in our taxonomy. This mutually exclusive marker delineates whether characteristics are unique or if multiple characteristics can apply within a single dimension. Moreover, the mutually exclusive clause facilitates a reduction in the number of characteristics, as it prevents the need to specify their combinations.

We assumed five subjective ending conditions. Subjective ending conditions are more complex to check. This is because they depend, to a large extent, on each researcher's point of view. First, the taxonomy must be concise. Consequently, we aimed to limit the number of dimensions and characteristics in each dimension to locate and capture abstraction and conciseness. Second, the taxonomy must be sufficiently robust to provide differentiation between objects based on the dimensions and characteristics of the taxonomy. Third, it has to be comprehensive to enable a (random) sample of objects within the domain to be classified. Fourth, it has to be extendable so that new dimensions or characteristics can be added easily. Fifth, it has to be largely self-explanatory; in other words, the naming convention has to be intuitive.

3.3. Iterations

We required a total of sixteen iterations as collected in Table 3. The first iteration, $I = 1$, was a C-2-E iteration focused on reviewing existing literature on topics related to our taxonomy. We used search strings that included *congestion management, local flexibility markets, local energy markets, taxonomy, and smart grid architecture*. We conducted our review using online libraries such as *IEEE Xplore* [80], *Science Direct* [81], and *Semantic Scholar* [82]. We also utilized our professional and academic knowledge, as well as the projects we reviewed (see Section 2.3). The initial outcome of $I = 1$ was the initial version, $V1$, which we further enhanced through subsequent revisions.

Subsequent versions of the taxonomy resulted from E-2-C approach iterations. In our E-2-C iterations, we used the latest version of the taxonomy and conducted interviews to enhance the taxonomy. In total, we interviewed twenty-eight experts from different backgrounds. We selected our pool of candidates based on their experience in the context of LFMs and, if possible, knowledge in the SGAM domain. We provide details from our expert interviews in Table 4. We employed a semi-structured interview format and used the drama model as our guiding framework [83]. We conducted the interviews in Spanish and English. Before initiating each interview, we obtained consent from our experts to record and transcribe the conversation. We could record all the interviews and analyze the transcription to complete, modify, or adapt them. In each interview, we introduced our motivations and objectives, explained our research approach, provided an overview of our taxonomy per SGAM interoperability layer, discussed the taxonomy, and concluded by asking for their feedback. We collected their feedback on the taxonomy and literature recommendations, allowing us to build upon refined versions, as well as cross-checking comments from all interviewees.

After iteration $I = 4$, we introduced the *category* "layer" in our taxonomy to provide a better context for the dimensions and their characteristics, following interviewee recommendations and analyzing similar approaches in the literature [77–79].

Subsequent iterations, $I = 12$ and $I = 14$ incorporated cross-national use cases (Netherlands (NL), Spain (ES), and the UK), with iteration $I = 12$ emphasizing interview-based insights and iteration $I = 14$ scrutinizing extant documentation. The shift was because interviewees from $I = 13$ recommended instantiating the taxonomy to (1) check its completeness, (2) determine its ability to distinguish real-world objects, and (3) analyze any potential constraints when populating it. After two more iterations, we met all the ending conditions considered and performed the evaluation.

3.4. Evaluation

We evaluated our taxonomy in a two-stage process. The first stage involved mid-term feedback from interviewees at the end of the interviews and the instantiation of the taxonomy in iterations $I = 12$ and $I = 14$ to identify areas for improvement and refinement of the taxonomy, ensuring its practical relevance and alignment with real-world expectations.

The second stage occurred post-completion, after iteration $I = 16$. We used a qualitative question-based method, drawing from the guidelines of Kundisch et al. [74], March et al. [84], and Prat et al. [85], to assess various dimensions including completeness, ease of use, and robustness. We developed a set of open-ended questions to evaluate the *completeness*, *ease of use*, *simplicity*, *understandability*, *fidelity with the real world*, *consistency*, *level of detail*, and *robustness* of our taxonomy. At the same time, we invited all the interviewees from the taxonomy-building process by email (Bcc) to share their feedback and answer

Table 3
Overview of iterations carried out to complete the taxonomy.

Overview				Categories	Dimension[a]					Characteristics[a]				
Iteration	Version	Type	Data (i = interviewee)	Number	B	F	I	C	Comp	B	F	I	C	Comp
1	V1	C-2-E	Own, literature and project documentation	–	19	3	2	6	9	63	15	7	18	23
2	V2	E-2-C	V1 + i_1	–	16	2	2	6	8	53	13	7	20	22
3	V3	E-2-C	V2 + i_2	–	17	2	2	6	8	57	14	7	20	21
4	V4	E-2-C	V3 + i_3	18	17	7	3	6	7	44	20	11	16	18
5	V5	E-2-C	V4 + i_4	18	17	7	3	6	7	44	20	11	15	18
6	V6	E-2-C	V5 + i_5 + i_6 + i_7	21	23	7	3	6	7	53	20	11	16	18
7	V7	E-2-C	V6 + i_8	21	23	7	3	6	7	53	20	11	15	18
8	V8	E-2-C	V7 + i_9	23	20	7	3	8	7	50	20	11	16	19
9	V9	E-2-C	V8 + i_{10} + i_{11}	23	21	7	3	8	7	54	20	11	16	19
10	V10	E-2-C	V9 + i_{12} + i_{13} + i_{14} + i_{15} + i_{16}	23	21	7	3	8	7	57	20	11	16	19
11	V11	E-2-C	V10 + i_{17} + i_{18} + i_{19}	24	21	7	3	8	7	59	20	11	16	19
12	V12	E-2-C	V11 + i_{20} + i_{21} + UC (NL)	24	21	7	3	8	7	53	21	11	16	18
13	V13	E-2-C	V12 + i_{22} + i_{23} + i_{24} + i_{25} + i_{26}	23	21	6	3	8	6	52	18	11	16	16
14	V14	C-2-E	V13 + UC (ES, UK)	25	24	6	3	8	6	62	18	11	16	16
15	V15	E-2-C	V14 + i_{27}	23	22	7	3	8	6	52	21	11	16	16
16	V16	E-2-C	V15 + i_{28}	24	21	7	3	8	6	50	20	11	16	16

[a] B = Business, F = Function, I = Information, C = Communication, Comp = Component.

Table 4
Interview details.

ID	Country of activity	Sector	Position	Topic expertise	SGAM expertise[a]	Duration (min)	Interview setup	
1	Spain	University	Researcher	LFM and SGAM	B, F	103	Physical	Individual
2	Spain	University	Research assistant	LFM and SGAM	B	102	Physical	Individual
3	Spain	University	Research professor	LFM	B	82	Physical	Individual
4	Spain	University	Professor	LFM	B	76	Physical	Individual
5	Spain	University	Research assistant	LFM and SGAM	I, C, Comp	100	Physical	Group
6	Spain	University	Professor	SGAM	I, C, Comp	100	Physical	Group
7	Spain	University	Assistant Professor	LFM and SGAM	I, C, Comp	100	Physical	Group
8	Spain	Industry	DSO role	LFM and SGAM	B, Comp	102	Online	Individual
9	The Netherlands	Industry	Senior consultant	LFM	B	100	Online	Individual
10	Austria	Research	Head of research unit	LFM and SGAM	All	72	Online	Individual
11	Germany	Industry	Senior project manager	LFM	B	86	Online	Individual
12	Austria	Research	Head of research unit	LFM and SGAM	F, I, C, Comp	68	Physical	Individual
13	Austria	Research	Researcher	LFM and SGAM	F, I, C, Comp	71	Online	Individual
14	N-W & central Europe	Industry	Manager business development	LFM	B	83	Online	Individual
15	Spain	Industry	Senior developer	LFM	B	93	Online	Group
16	Spain	Industry	Senior developer	LFM	B	93	Online	Group
17	Austria	Research	Researcher	LFM and SGAM	F, I, C, Comp	74	Physical	Group
18	Austria	Research	Researcher	LFM and SGAM	All	74	Physical	Group
19	Portugal	Research	Head of research unit	LFM and SGAM	All	54	Online	Individual
20	The Netherlands	Industry	Project manager (DSO)	LFM and SGAM	B	80	Physical	Group
21	The Netherlands	Industry	Product owner flexibility systems (DSO)	LFM and SGAM	B	80	Physical	Group
22	Belgium	Policy	Policy advisor	LFM	B	76	Online	Group
23	Belgium	Policy	Management, Lead & Advisor	LFM	B	76	Online	Group
24	Norway	Policy	Senior Engineer	LFM	B	86	Online	Individual
25	United Kingdom	Industry	Economic Consultant	LFM	B	84	Online	Individual
26	Greece	Policy	Policy freelancer	LFM and SGAM	All	146	Online	Individual
27	Belgium	Policy	Head of research	LFM and SGAM	B	66	Online	Individual
28	Belgium/EU	Industry	Flexibility Manager	LFM and SGAM	B	89	Online	Individual

[a] B = Business, F = Function, I = Information, C = Communication, Comp = Component.

our questions. Table B.1 collects these questions in Appendix B. All twenty-eight experts interviewed responded positively, although three also shared minor comments.

On the one hand, these experts acknowledged that the taxonomy effectively bridges the gap between diverse terminologies and facilitates accurate, holistic understanding. They also appreciated its completeness, which covers the entire perspective of these solutions and provides a solid foundation. Additionally, they noted the balanced abstraction level, which helps avoid the taxonomy becoming quickly outdated.

On the other hand, the experts expressed the following minor concerns. First, they recognized that the taxonomy, although complete, well-structured, and detailed, requires a certain level of expertise to understand. This is because it encompasses intricate elements that may necessitate prior knowledge or supplementary information for non-experts. Second, periodic updates to the taxonomy may be necessary, particularly in response to regulatory changes. However, they also acknowledged that such changes would require minimal work due to the logical structure of the taxonomy and the followed method. Thus, the expressed concern in reality aligns with the inherent nature of taxonomies, which, as suggested by Nickerson et al. [75], should be extensible, dynamic, and not merely static to adapt to changes. Finally, some respondents noted that they could provide a more detailed answer regarding the ease of use once they used the multi-layer taxonomy, although it seems straightforward at first glance.

As final remark, during a presentation at a doctoral workshop [86], we received positive feedback on the elegance of the taxonomy. This was principally due to the way it incorporates the SGAM's structure, thus contributing to a well-organized taxonomy.

4. Taxonomy

In the following section, we introduce our taxonomy, organized into five SGAM interoperability layers detailed in subsequent subsections. In each taxonomy, the extra column indicates whether characteristics are mutually exclusive (ME)—"yes" for unique characteristics and "no" for combinable ones.

4.1. Business interoperability layer

In Table 5, we present our proposed taxonomy for the business interoperability layer, featuring nine categories, 21 dimensions, and 50 characteristics. The nomenclature aligns with the latest frameworks from ACER [29], universal smart energy framework (USEF) [87], and ENTSO-E [88].

The first category in our taxonomy focuses on congestion management needs (CM needs), which are classified into planned and unplanned origins. Planned needs are predictable and stem from network expansion plans, allowing the SO to prepare accordingly. Unplanned needs arise from sudden or post-fault scenarios, making it uncertain if corrective measures will be needed, as seen in cases from Spain [76] and the UK [89].

The second category in our taxonomy identifies the primary players in an LFM: flexibility buyers, FSPs, and the market operator. Our taxonomy focuses on DSOs, or a combination of DSOs and TSOs, as the main flexibility buyers for congestion management at the distribution level. We have identified two types of market designs for this in Section 2.3. In the first design, one or multiple DSOs can act as buyers in an LFM. In the second design, both DSOs and TSOs can purchase flexibility through market-based coordination, with an LFM serving as the initial stage. We identified two key types of FSPs: aggregators and individual providers. Aggregators can be further classified into traditional and independent models according to [90,91], but this taxonomy does not cover it.

The role of market operators in LFM is a subject of debate as remarked in [92,93]. While some DSOs may operate the market, upcoming EU regulations and frameworks [29] suggest multiple operator options, including independent entities like Piclo or regulated ones as NEMOs. LFM operators have similar responsibilities to traditional market operators but may take on additional tasks when an SO assumes this role, such as resource prequalification or flexibility activation [94].

The third category, market scope, contains three dimensions: negotiation time frame, grid level location of flexibility needs, and location organization of offers. The negotiation time frame concerns the "gate" opening and "gate" closure for customers to participate in flexibility

Table 5
Taxonomy based on the business interoperability layer for congestion management service.

Category	Dimension	Characteristic				ME
CM need	Origin	Planned	Unplanned			Yes
Participants	Flexibility buyer	DSO/s	DSO + TSO			Yes
	Flexibility service provider	Aggregator/s	Individual provider/s			Yes
	Market operator	System operator/s	Third-party commercial	Third-party regulated		No
Market scope	Negotiation time frame	Real-time	Short-term	Mid-term	Long-term	Yes
	Flexibility need – grid level	DSO HV	DSO MV	DSO LV		No
	Offer organization	Congestion point/s	Congestion zone/s			No
Market access	Prerequisites	Technical	Market			No
Product	Attributes(Parameters)	Not standardized	Standardized for UC/BC only	Standardized at country level		No
	Transactional object	Energy (Activation)	Capacity (Availability)			No
	Power	Active Power	Reactive Power			No
	Direction	Upwards	Downwards			Yes
Clearing	Matching	Continuous market	Call market			Yes
	Demand/Supply formation	One side Market	Two side Market			Yes
	Grid constraint representation	Bid limitation	Partial grid data	Comprehensive grid data		Yes
	Pricing rule	Pay-as-clear	Pay-as-bid			Yes
Metering verification	Flexibility unit metering	Portfolio	Asset			No
	Baseline method	Historical data	Real-time data	Alternative data		No
Integration	External coordination	Implements MO/s coordination	Does not implement coordination			Yes
	Existing market interaction	Defined	Undefined			Yes
Economic	Fees	Fixed	Variable			No

markets with their bids (flexibility offers). Customers can participate in flexibility markets, ranging from real-time to long-term. Real-time encompasses same-day market negotiations, short-term refers to hours to a day, mid-term includes weeks to months, and long-term extends over years. The grid level location is crucial for distribution networks as it dictates the effectiveness of congestion solutions. Here, we adhere to the EN 50160 and E.DSO (European DSOs association) guidelines [95, 96] and consider high voltage (HV), MV, and LV levels excluding Extra-HV because of our distribution-level focus. The offer location organization dimension contains two main characteristics: congestion points and congestion zones, which may dynamically change over time according to real projects [97]. These dimensions incorporate insights from various studies and guidelines, such as EN 50160, E.DSO reports, and practices in countries like Spain, the Netherlands, and the UK (see Section 4).

The fourth category, market access, outlines the prerequisites that FSP must meet to enter the market. These prerequisites can be technical (such as prequalification of assets and communication with assets) or market-specific. Market-specific prerequisites may involve providing company information, collateral for participation, or declaring responsibility for balancing.

The fifth category refers to the product. Our research found that companies and research projects may use various attributes to describe a congestion management product. For example, the OneNet project [98] introduces a framework that categorizes product attributes in two different levels: technical attributes (e.g., traded commodity, location of delivery, level of availability, ramping period, required mode of activation, etc.); and bid related attributes (e.g., divisibility, granularity, availability and activation prices, aggregation allowed, etc.). Similarly, the Open Networks project in the UK [99], outlines specific attributes for active power products, including minimum flexible capacity, maximum ramping period, minimum activation capability, availability agreement period, among others, mixing the technical and bid related attributes. Such a classification into technical and bid-related (similar to OneNet project) provides a simple structure but lacks depth. In order to provide depth into the taxonomy, we incorporate several dimensions to provide insights at a technical level and later at a market level. Thus, from a technical perspective in the product, to provide a concise set of parameters – rather than an extensive and dynamic list that may change due to upcoming regulations in the EU (e.g., ACER's demand response framework guidelines [29]) – we focused on how standard or common these characteristics are in the operational context. We segmented them into three levels of standardization: non-standardized, standardized for the use case/business case, and standardized at the country level. The non-standardized characteristic offer customization at the cost of complexity and are specific to individual contracts or flexibility needs. Standardized for the use case/business, like those in NODES, balance customization and efficiency and are specific to congestion management as they can be replicated across countries since they are use case dependent. Lastly, *standardized at the country level* aims to provide a cohesive framework for all market participants within a country, as seen, for example, in the UK. Future guidelines from ACER may encourage but not enforce this level of standardization. The transactional object dimension describes the traded commodity: energy (activation or utilization as known in the UK) or capacity (availability). It is essential to emphasize that our taxonomy acknowledges the possibility of combining these characteristics to create specific and unique variations. Additionally, depending on the design and the product at hand, capacity products may introduce further nuances, such as traditional capacity or capacity limitation (e.g., dispatch limitation), as highlighted in the framework guidelines [29] or in proposed designs as in [100]. Nevertheless, from an abstract perspective, these still revolve around capacity. The power dimension refers to the product's nature, which can be active or reactive power. While most congestion markets emphasize active power, recent EU projects like Coordinet [46] and EUniversal [47] explore the use of reactive power. The direction dimension distinguishes between upwards (increasing generation or reducing consumption) and downwards (decreasing generation or increasing consumption). Even though limiting power direction could constrain market liquidity, it can also offer clarity and simplification for both flexibility buyers and FSPs, thus influencing the LFM's overall effectiveness.

The sixth category refers to market clearing, which is crucial in any market-based procurement system. It outlines the operational and management aspects of the market. The clearing matching dimension, in its abstraction, can be either a continuous market (e.g., intraday continuous), or a call market approach for procuring services. The call market – which includes tenders, bilateral contracts, or various types of auctions [17,101,102] – has been the subject of much discussion during interviews. The key distinction is that while the continuous market clears frequently, the call market has an opening and closure period for FSPs to submit their offers. The demand/supply formation dimension in market clearing refers to either one-side or two-side markets. In one-sided markets, the focus is mainly on meeting the buyer's needs, often selecting bids based on criteria like the lowest price. In contrast, two-sided markets balance both buyer and seller offers, determining the market-clearing point where demand and supply intersect. The grid constraint representation dimension distinguishes between bid limitation, partial grid data, and comprehensive grid data. Bid limitation relies solely on bid information for market clearing. Partial and comprehensive grid data involve varying degrees of network information to address location-based congestion needs as indicated in [54]. The pricing rule dimension identifies if the market operates under pay-as-clear or pay-as-bid mechanisms [103].

During the taxonomy development process, two additional potential dimensions emerged: price capping and the organization responsible for clearing. The issue of price capping was considered outside the scope of the business layer. It can be included in the information taxonomy interoperability layer as market information (see Section 4.3). As a side note, DSOs might use budgets instead of price caps for purchasing flexibility. The second dimension, which pertains to the entity in charge of clearing, was found to overlap with the functional taxonomy. As such, we restricted it to the functional layer, focusing on the managerial responsibilities associated with each function (see Section 4.2).

The seventh category focuses on metering verification. It significantly influences the settlement process and, thus, the service payment. We focus on two key dimensions: flexibility unit metering and baseline methods. Flexibility unit metering can be portfolio-based or centered on individual assets, using either main metering or specialized submetering. Baseline methods are categorized into three main types: based on historical data (where any previous data helps infer the baseline); real-time data (as monitoring or nowcasting (prediction in a very short time ahead) provides); or any alternative data (such as schedules or nominations). These examples are non-exhaustive as pointed out in [24,45,104].

The eighth category focuses on market integration. We split it into two main dimensions: external coordination and existing market interaction. External coordination pertains to whether the LFM interfaces with other network operators (DSO-DSO, TSO-DSO) or market operators or remains isolated. Existing market interaction investigates the relationship between the LFM and existing markets like day-ahead or intraday. For example, OMIE in Spain plans to leverage day-ahead market data in their developing LFM. The OneNet project also explores how LFMs interact using primarily bid forwarding with established energy and ancillary markets [54].

We dedicate the last category in our business taxonomy to the economic aspect, which considers the LFM fees that can be fixed or variable. LFM platform solutions might include many different fees and might only be equal to some participants. For example, fixed fees could refer to the cost of the LFM solution in terms of infrastructure, with participants facing a fixed fee to use it paid once or by subscription or even mutualized by all end-customers. Variable fees may refer to trading fees based on total volume or penalties or price reductions FSP might face upon non-delivery of their product.

4.2. Function interoperability layer

Table 6 collects the taxonomy for the function interoperability layer consisting of three categories, seven dimensions, and twenty characteristics. It aims to classify the functions required to perform in an LFM. The number of functions to classify may vary depending on the description and complexity of the LFM use case. We recommend the following steps to use the proposed function interoperability layer taxonomy effectively:

1. Identify all functions present in the LFM solution by selecting the best representative characteristics of the Scope dimension.
2. For each identified function and its scope, describe the other two categories (Management and Computation) by selecting one characteristic per dimension.

Aligned with studies by ENTSO-E [28] and Office of Gas and Electricity Markets (OFGEM) [105], our taxonomy for the function interoperability layer of LFM includes:

1. Assessment Functions: Cover activities such as monitoring and forecasting for flexibility management.
2. Trading Functions: Focus primarily on bid selection and market processes.
3. Communication Functions: Facilitate coordination and information sharing, exemplified in H2020 projects like InteGrid [69] and EUniversal [106].
4. Dispatch Functions: Relay selected offers to FSPs for subsequent asset operation.
5. Activation Functions: Initiate the operation of flexibility assets based on specific parameters.
6. Validation and Settlement Functions: Interlinked functions that verify and finalize contracts and deliveries, also triggering payment processes.

The differentiation between dispatch and activation emerged from the interviews and research [31]. While they might appear synonymous or often treated together in some contexts, they serve distinct roles in many scenarios. For example, a DSO may issue a dispatch order well in advance, specifying the flexibility requirements. However, the actual activation, which puts these requirements into effect, is typically carried out by the FSP at a designated later time. This separation underscores the nuanced roles these functions can play in operating an LFM.

The responsibility for performing specific functions in an LFM impacts system architecture, device prequalification, and market design [107]. Our taxonomy distinguishes between the flexibility platform operator and third-party operators for this responsibility. This clarity is crucial, especially for functions like activation, where ambiguity can result in task failure. Currently, no set approach for activation exists; it can be market-based (via the market operator (MO)) or directly controlled (via the SO) [8]. This may change with the forthcoming EU demand response framework, specifying the SO's role in bid selection, activation, and service control (see paragraph (62) in [29]).

We outline five dimensions in the computation category. The first, the input dimension, considers whether a function requires single or multiple information sources. This affects architecture and scalability [72,108]. The second, the trigger dimension, categorizes functions as manual or automatic, noting that semi-automatic functions are considered manual. The third dimension deals with time constraints on computations, which we classify broadly as defined or undefined. The fourth, execution, examines whether the function operates in real-time, near real-time (e.g., within 15 min), or batch (e.g., for payment) mode. Lastly, the resource dimension qualitatively identifies resource consumption as low, medium, or high, given the fast-changing nature of technology and the prior author's experience with quantification [108].

Table 6
Taxonomy based on the function interoperability layer.

Category	Dimension	Characteristic						ME
Objective	Scope	Assessment	Trading	Communication	Dispatch	Activation	Validation & settlement	Yes
Management	Responsible	System operator			Third-party operator			Yes
Computation	Input	Single			Multiple			Yes
	Trigger	Manually			Automatically			Yes
	Time limitation	Defined			Undefined			Yes
	Execution	Real-time		Near real-time		Batch		Yes
	Resources	Low demanding		Medium demanding		High demanding		Yes

4.3. Information interoperability layer

Table 7 describes the taxonomy for the information interoperability layer. The information taxonomy has three categories, three dimensions, and eleven characteristics, making it the shortest of all five interoperability layers taxonomies. Even though its relatively short aspect, it complies with the recommendations from [74,75]. The taxonomy provides relevant insights concerning the information, structure, contents, and how to use it. We recommend that practitioners consider the following steps when utilizing the taxonomy:

1. identify each link,
2. classify each link using the taxonomy.

In other words, we propose to describe each link, with each representing a connection between different nodes (components), thus being similar to the function taxonomy. The complexity of this exercise reduces when using a SGAM mapping as the primary input for the taxonomy. Authors in [108] provide examples of identified link descriptions for the information interoperability layer.

We identify three main categories for the information interoperability layer taxonomy, each having a single dimension. The first category concerns the data model employed, which refers to how the data was wrapped. Examples include asset metering models like IEC 62056 [109], flexibility models such as energy flexibility data model (EFDM) [110], and market data models like USEF's USEF Flex Trading protocol (UFTP) [111]. Given the diversity of data models, we include general characteristics for resilience in our taxonomy. The second category, content, differentiates among three characteristics: technical–electrical (e.g., power, voltage, holding duration), market (e.g., price, bid size, price cap, contract duration) [112], and support information (e.g., grid data via common information model (CIM)). Our approach aligns with the framework in [113]. The third category focuses on data treatment. The interviewees emphasized the role of cyber security in LFM solutions, underscoring its importance in the context of data exchange and general data protection regulation (GDPR) [114]. Our taxonomy addresses this by including a data sensitivity category, guided by National Institute of Standards and Technology (NIST) and Confidentiality, Integrity and Availability (CIA) frameworks [115,116].

4.4. Communication interoperability layer

Table 8 provides a communication interoperability taxonomy inspired by selective layers of the Open Systems Interconnection (OSI) model [117]. This selection emerged from targeted interviews. Although resembling the Transmission Control Protocol/Internet Protocol (TCP)/Internet Protocol (IP) model [118] and Enhanced Performance Architecture (EPA), our taxonomy accommodates smart grid-specific protocols like S0 used for Remote Terminal Unit (RTU) communication [108]. Similar to the function and information layer, we recommend practitioners should:

1. identify each link,
2. classify each link using the taxonomy.

For the data transport category, we focus on the end-to-end reliability dimension and distinguish between two key characteristics: acknowledgment, exemplified by TCP, and no acknowledgment, exemplified by User Datagram Protocol (UDP).

For the network infrastructure category, we identify two dimensions: management and coverage. Management is further categorized into public and private networks, while the coverage dimension follows the Smart Grid Coordination Group classification, aligning with SGAM concept (see Figure 16 — Mapping of communication networks on the SGAM. [20]).

For the communication technologies category, we identify three descriptive dimensions: Latency, divided into time-sensitive, which refers to the time limit for communication as crucial, and non-time-sensitive; Medium, representing either wireless or wired technologies; and Raw Data Rate, described qualitatively as low, medium, or high. Given the rapid pace of technological change, we opt for a qualitative approach (low, medium, or high). This approach allows practitioners to describe their systems within the context of this taxonomy effectively.

For the application protocol category, we focus on one dimension: message-coupling. We identify two characteristics: client–server and publish–subscribe. The client–server model features a hierarchical structure where information flows directly from server to client. In contrast, the publish–subscribe model is non-hierarchical, involving a broker to mediate information exchange between publishers and subscribers.

Lastly, we considered interoperability as a category, given its importance in smart grids [119]. To simplify such a complex category, we hone in on protocol standardization, addressing the core issue of technical interoperability [120]. We differentiate between open protocols that allow user implementation and proprietary ones that restrict usage and conceal internal details.

4.5. Component interoperability layer

Table 9 presents a taxonomy for the LFM component interoperability layer, blending power components like electrical networks with devices or tools. We recommend practitioners use it as an overarching solution description, aligned with SGAM, rather than isolating each component for LFM use cases. We advise practitioners to follow these steps:

1. select the characteristic for the electrical network category;
2. identify each component for classification;
3. classify each tool identified based on the tools category.

However, we suggest choosing only the relevant categories for those who wish to apply the taxonomy to individual components, excluding the electrical network.

The first category is the electrical network. Electrical location matters for flexibility provision as it influences power flow and line conditions. We categorize network structures into meshed, radial interconnected, and radial. Meshed networks offer multiple paths for reliability. We consider ring structures to be simplified mesh networks. Radial interconnected structures are hierarchical but have reconfiguration devices for some merging. Radial networks are common and straightforward, with all elements stemming from a substation.

Flexibility assets are the sources of flexibility. They are units capable of changing their operation following a signal. They play a central role in LFM, as congestion problems are location-specific, and solving congestion could require a specific flexibility source (load, generation, or storage) and a specific voltage connection level (LV, MV, HV). We do not distinguish between market roles (such as generation, consumer,

Table 7
Taxonomy based on the information interoperability layer.

Category	Dimension	Characteristic					ME
Container	Data model	Asset metering	Flexibility	Market	Asset control	Not specified	Yes
Content	Focus	Technical-Electrical		Market information		Support information	Yes
Data treatment	Sensitivity	Public		Confidential/Private		Restricted	Yes

Table 8
Taxonomy based on the communication interoperability layer.

Category	Dimension	Characteristic			ME
Data transport	Reliability	Acknowledgment	No acknowledgment		Yes
Network infrastructure	Management	Public	Private		Yes
	Coverage	SGAM – List			Yes
Communication technologies	Latency	Time sensitive	Non time sensitive		Yes
	Medium	Wireless	Wired		Yes
	Raw data rate	Low	Medium	High	Yes
Application protocol	Message-coupling	Client-Server	Publish-Subscribe		Yes
Interoperability	Protocol standardization	Open	Proprietary		Yes

Table 9
Taxonomy based on the component interoperability layer.

Category	Dimension	Characteristic			ME
Electrical network	Structure	Meshed	Radial interconnected	Radial	Yes
Flexibility asset	Flexibility source	Load	Generation	Storage	No
	Voltage connection	LV	MV	HV	No
Metering & Control	Device	Smart meter	IED - Off the shelf	IED - Specific	No
Tools	Computational location	On-premise (Local)	Cloud based (Third-party)		Yes
	Data storage	Centralized	Decentralized		Yes

or prosumer) as we only focus on the asset type for the component interoperability taxonomy.

In LFM, device measurement and control are key aspects, as highlighted in Sections 4.1 and 4.2. We categorize this under a single abstract dimension: the device. We split it into two categories: smart meters, intelligent electrical device (IED)-off-the-shelf or IED-specific. Smart meters are essential for data collection and validation but not for all flexibility assets. Some solutions use custom devices (IED-specific), while others opt for off-the-shelf to improve technical interoperability.

Finally, our taxonomy highlights tools as essential components for task execution, focusing on two primary dimensions: computational location and data storage. Computational location can be either on-premise or cloud-based. When computational power is provided by internal servers belonging to the tool's owning organization, we categorize it as on-premise. This distinction is important for assessing varying physical and cyber security requirements. Data storage is another crucial dimension, particularly given the rise in data sensitivity issues. We identify two types of storage: centralized and decentralized. In centralized storage, the data remains within the organization. In contrast, decentralized storage involves external systems like third-party cloud services or Distributed Ledger Technologies (DLTs) [121]. This is relevant for practitioners considering data storage options and their associated technological challenges.

5. Taxonomy examples

This section showcases the practical application of the taxonomy through various use cases, including a detailed one involving the DSO Electricity North West Ltd. (ENWL) and Piclo's LFM solution. Three more use cases are in Appendix C, covering diverse contexts like different countries, market platforms, and regulations. These additional examples include a UK case with NGED's Flexible Power, a Dutch case focusing on Grid Operators Platform for Congestion Spreads (GOPACS) and local DSO Enexis, and a Spanish case featuring an LFM solution by OMIE.

5.1. United Kingdom - electricity north west - Piclo

ENWL, a UK DNO transitioning to a DSO [122,123], oversees 57,000 km of power lines and runs biannual Invitation to Tender (ITT) for local flexibility services. Their current tenders (so-called competitions) aim to procure local flexibility through a three-stage process: pre-tender, tender, and post-tender [124]. These are hosted on the Piclo Flex platform, an online marketplace for energy flexibility [63]. The latest ITT for Spring 2023 targets 1097 MW of flexibility across 32 locations with a £ 10.1 m budget spanning 2023–2028 [125]. Subsequent sections will focus on this specific tender.

Our analysis centers on three specific competitions: ENWL-229, ENWL-230, and ENWL-238, omitting new developments by Piclo [126]. The first two target Dynamic and Restore services in Alston, while the latter focuses on Secure service in Bolton By Bowland. We examine a representative contract for each area to elucidate the taxonomy.

1. ENWL-229/Alston (Dynamic) W23/24 - All Day,
2. ENWL-230/Alston (Restore) FY24 - All Day,
3. ENWL-238 Bolton By Bowland (Secure) W27/28 - All Day.

The details of site-specific requirements and service parameters are available in [127] and the flexibility map of the Piclo Flex platform [128].

5.1.1. Business interoperability layer taxonomy

Table 10 presents a business taxonomy for each selected competition, noting that all deal with unplanned congestion management needs. Specifically, ENWL-238 targets pre-fault needs, while ENWL-229 and ENWL-230 focus on post-fault needs. The primary difference between the latter two is that ENWL-230 emphasizes flexibility during network re-energization caused by abnormalities.

In each competition, the DSO is the flexibility buyer, with FSPs participating individually or in aggregated units. The market operator is Piclo, an independent entity. The bidding window runs from July 10 to 21, 2023, for service delivery between November 2023 and March 2028. In our taxonomy, ENWL-238 is categorized as "long-term" due to its October 2027 delivery, while the other contracts start in November 2023. The DSO seeks at the MV (11 kV) and LV (0.24 kV) levels. FSPs must first pass the market and then the technical prequalification steps on the Piclo platform to participate. The market requires FSPs to register on the Dynamic Procurement System (DPS), a company qualification assessment [129], while for the technical, they need to fill in a Prequalification Questionnaire on the Piclo platform.

The three competitions have similar product attributes, as standardized by the Energy Networks Association (ENA). These attributes include not exclusive: minimum flexibility capacity, frequency of use, and ramping period. All competitions seek upward active power and share the same market-clearing design, operating in a one-sided market with DSO as the single buyer. The competitions differ mainly in their remuneration structure: ENWL-229 favors higher energy payments, ENWL-238 emphasizes capacity payments, and ENWL-230 offers only

Table 10
Business interoperability layer taxonomy for the three service products in the UK Electricity North West offers in Piclo.

Category	Dimension	NWL-238/Bolton By Bowland (Secure)		ENWL-229/Alston (Dynamic)		ENWL-230/Alston (Restore)	
CM need	Origin	Unplanned (pre-fault)		Unplanned (post-fault)		Unplanned (restoration)	
Participants	Flexibility buyer	DSO		DSO		DSO	
	Flexibility service provider	Aggregator	Individual provider	Aggregator	Individual provider	Aggregator	Individual provider
	Market operator	Independent commercial		Independent commercial		Independent commercial	
Market scope	Negotiation time frame	Long-term		Mid-term		Mid-term	
	Flexibility need (grid level)	DSO MV	DSO LV	DSO MV	DSO LV	DSO MV	DSO LV
	Offer organization	Congestion zone/s		Congestion zone/s		Congestion zone/s	
Market access	Prerequisites	Technical	Market	Technical	Market	Technical	Market
Product	Attributes (Parameters)	Standardized at country level		Standardized at country level		Standardized at country level	
	Transactional object	Energy (Activation)	Capacity (Availability)	Energy (Activation)	Capacity (Availability)	Energy (Activation)	
	Power	Active Power		Active Power		Active Power	
	Direction	Upwards		Upwards		Upwards	
Clearing	Matching	Call market (Tender)		Call market (Tender)		Call market (Tender)	
	Demand/Supply formation	One side Market		One side Market		One side Market	
	Grid constraint representation	Bid limitation		Bid limitation		Bid limitation	
	Pricing rule	Pay-as-bid		Pay-as-bid		Pay-as-bid	
Metering verification	Flexibility unit metering	Asset	Portfolio	Asset	Portfolio	Asset	Portfolio
	Baseline method	Historical data	Alternative data	Historical data	Alternative data	Historical data	Alternative data
Integration	External coordination	Does not implement coordination		Does not implement coordination		Does not implement coordination	
	Existing market interaction	Undefined		Undefined		Undefined	
Economic	Fees	Fixed	Variable	Fixed	Variable	Fixed	Variable

Table 11
Function taxonomy for the flexibility assessment and clearing functions.

Category	Dimension	Characteristic - Flexibility Assessment	Characteristic - Clearing
Objective	Scope	Assessment	Trading
Management	Responsible	System operator	Third party operator
Computation	Input	Multiple	Multiple
	Trigger	Manually	Automatically
	Time limitation	Undefined	Undefined
	Execution	Batch	Batch
	Resources	High demanding	Medium demanding

a premium energy payment. The Piclo Flex platform clears the market based solely on FSPs bids, with no grid information considered. Payments follow a pay-as-bid system until the DSO meets its requirements or reaches the area's budget limit.

ENWL measures at the point of supply, requiring each FSP to offer minute-by-minute asset data. ENWL uses various baseline methods like Mid 8-in-10 (uses data from the middle of the last 8 of 10 days); Mid 8-in-10 with Same Day Adjustment; Mid X-in-Y (the user can choose how many days to consider and the length of same day adjustment), Nominated (self-declared baseline of the asset in advance of the flexibility dispatch event) and Zero (assumes that the asset is not operating except for when providing a flexible service). Consequently, our taxonomy includes historical and alternative data as characteristics of the baseline dimension.

The Piclo platform is an independent marketplace without external market coordination or links to existing markets like intraday or day-ahead. Both the DSO and FSP incur fixed platform fees, and FSPs may face variable fees for partial or non-fulfillment of contracts.

5.1.2. Function interoperability layer taxonomy

From a functional point of view, we focus on three key functions: flexibility assessment, clearing, and order dispatch, selected based on interview insights and remarks by authors in [31]. These functions operate consistently across different products and competitions. Table 11 and Table 12 provide a taxonomy tailored for classifying these functions.

The flexibility assessment function, managed by ENWL, identifies and quantifies areas requiring flexibility to alleviate congestion. This involves gathering data, including forecasts and substation data. Typically executed in a resource-intensive batch process, this function is manually triggered without a set time frame (batch process).

The clearing function, managed by the Piclo platform, matches FSPs offers with DSO flexibility needs specified in the tender. After clearing, Piclo informs the DSO of the matched bids, although the final bid selection is a two-stage and two-company process inherited from their design. The clearing is an automated process with multiple inputs, executed after post-bidding, and operates in a batch mode without real-time constraints, requiring medium-level resources.

The dispatch activation function in Table 12, handled by the DSO on the Piclo platform, sends dispatch signals of winning bids to FSPs for all power products and competitions. We assume the following: it is a manual process with a single input—the output from the clearing stage. Time-sensitive and critical, it varies in execution: "secure" products are dispatched in batches a week ahead, while "dynamic" and "restore" are near real-time, triggered as needed. This function requires low resources, primarily for communication.

5.1.3. Information interoperability layer taxonomy

We used a dispatch signal as an example for our information taxonomy represented in Table 13. We assume after speaking with Piclo managers that the DSO sends the dispatch signal to the FSP through the Piclo platform using a JavaScript Object Notation (JSON) schema known as an "obligation". We considered it as "asset control" in our taxonomy; this signal includes both technical and support details. Technical information covers start/end times, capacity, and direction. Support information includes identifiers for both DSO and FSP, obligation ID, request for response, and signature. Given that it contains sensitive identifiers, the dispatch signal is considered confidential.

5.1.4. Communication interoperability layer taxonomy

Likewise, we examined the communication link between the DSO and FSP for dispatching signals in Table 14. The link uses Internet-based webhooks triggered by events and follows the standard TCP/IP

Table 12
Function taxonomy for the dispatch function.

Category	Dimension	Characteristic - Secure	Characteristic - Dynamic	Characteristic - Restore
Objective	Scope	Dispatch	Dispatch	Dispatch
Management	Responsible	System operator	System operator	System operator
Computation	Input	Single	Single	Single
	Trigger	Manually	Manually	Manually
	Time limitation	Defined	Defined	Defined
	Execution	Near real-time	Near real-time	Near real-time
	Resources	Low demanding	Low demanding	Low demanding

Table 13
Information taxonomy for the dispatch signal.

Category	Dimension	Characteristic	
Container	Data model	Asset control	
Content	Focus	Technical-Electrical	Support
Data treatment	Sensitivity	Confidential/Private	

Table 14
Communication taxonomy for the dispatch signal communication link.

Category	Dimension	Characteristic	
Data transport	Reliability (end-to-end)	Acknowledgment	
Network infrastructure	Management	Public	
	Coverage	DSO market backhaul	FSP market backhaul
Communication technologies	Latency	Time sensitive	
	Medium	Wire	
	Raw data rate	Low	
Application protocol	Message-coupling	Client-Server	
Interoperability	Protocol standardization	Open	

Table 15
Component taxonomy.

Category	Dimension	Characteristic	
Electrical network	Structure	Radial	
Flexibility asset	Flexibility source	Load	Generation
	Voltage connection	LV	MV
Metering & Control	Device	Smart meter	IED - Off the shelf
Tools - Dispatch	Computational location	Cloud based (Third-party)	
	Data storage	Decentralized	

model. Acknowledgment is required for data transport. Given its use of the Internet, the link has extensive coverage, referred to as the backhaul connection. We assume it is a wired link with a low data rate. The dispatch signals are time-sensitive, requiring low latency. The communication uses a client–server architecture with message coupling.

5.1.5. Component interoperability layer taxonomy

Table 15 presents the taxonomy for the component interoperability layer. We assumed a radial electrical LV and MV network, commonly found in Europe [130]. ENWL seeks flexibility from load and generation sources at these voltage levels. We excluded storage systems due to uncertainty. Smart meters and IEDs are essential for metering and control. The dispatch tool from Piclo, which uses a third-party cloud. According to Piclo's engineers (whom we approached), the data is decentralized across several servers.

6. Discussion and recommendations

This section synthesizes key insights and recommendations. These are drawn from the work conducted in this paper: literature and project review and analysis, expert interview comments, and the taxonomy instantiation over various LFM design solutions across Europe.

6.1. Taxonomy insights

First, the approach of organizing the taxonomy into five layers, aligned with the SGAM framework, streamlines the interpretation of LFM solutions from multiple perspectives. This approach not only highlights market-specific considerations but also reveals these solutions' intrinsic nuance differences in their characteristics. We observe that this approach has four key advantages: (1) it provides a holistic overview of the solutions, (2) it facilitates the rapid identification of pertinent discussion topics across academic, industrial, and regulatory stakeholders, and (3) it allows for the mapping of design principles to specific layers within the multi-tiered taxonomy. For example, market neutrality and product design principles are closely linked with the business layer, operational responsibilities correspond with the function layer, and issues of data clarity and interoperability resonate with the ICT layers of the taxonomy.

Second, while all the LFMs solutions analyzed in Section 5 and Appendix C operate under a common conceptual framework and aim to develop and use a platform-based LFM solution, our taxonomy unveils subtle yet impactful differences, as earlier inferred. These distinctions often arise from a similar congestion management challenge that SOs face, but they implement different solutions to solve it. We found this diversity even within the same jurisdiction, such as the UK, where competing solutions adopt similar but nuanced approaches. For instance, some solutions employ distinct remuneration schemes for energy and capacity to address specific grid congestion issues, thereby influencing their overall design. Another salient example is the disparate management of the market-clearing function: one solution employs a third-party operator, while the other utilizes a SO. These observed variances underscore the necessity for a holistic taxonomy that highlights and contextualizes these nuances in a harmonized format applicable to these solutions.

Third, the choice of MO significantly shapes the governance dynamics of these LFMs solutions. Opting for either a third-party entity or the SO as the MO brings its own set of advantages and drawbacks. A third-party operator may strengthen market neutrality but necessitates intricate coordination mechanisms for effective data sharing among stakeholders, particularly regarding network-related information, in a highly network-location-dependent problem. Contrariwise, designating the SO as both MO and flexibility buyer allows for the seamless integration of network constraints into the LFM market clearing system. It enhances the coordination and efficiency in procuring and operating flexible resources but opens the market question of market neutrality.

Fourth, the design of these LFMs solutions can be viewed as either restrictive or liberating depending on the vantage point, whether it be the FSP, SO, or any third-party. For example, unrestricted technical market access may be favorable for attracting more FSPs. However, it could counterproductively diffuse the SO's efforts to resolve specific grid congestion challenges. The instantiated taxonomies also enlighten the delicate balance required in formulating market penalties that can discourage FSP participation while ensuring grid security from the SO's perspective. Additionally, certain design choices, such as the directionality of power flexibility, may be regulatory constraints that limit market participation. Yet, the necessity of such directionality is contingent on the actual needs of the flexibility buyer. Another aspect warranting attention is the impact of pricing rules on DSO. Typically, DSO revenues are a function of customer count and regulated network tariffs. Design characteristics like utilizing a pay-as-clear market pricing rule may result in uniform payments across FSPs, despite variances in their technical impact on the network, thus potentially escalating costs for the DSO. Nevertheless, the comprehensiveness of the taxonomy can aid stakeholders in recognizing and articulating these inherent design trade-offs, reinforcing that no stakeholder is unduly favored in the LFM solution design.

Fifth, a notable concern is that many LFMs currently operate isolated and detached from existing power markets, which poses potential risks to market liquidity and long-term viability. To mitigate these challenges, some regions have pursued unique strategies. For example, in Spain, there is a natural integration with pre-established electricity markets due to shared operational agents (OMIE). Another avenue is to build interconnections within internal LFM markets, as demonstrated by Flexible Power, where non-fulfillment of long-term contracts automatically activates shorter-term agreements. Nonetheless, the full efficacy of these approaches can only be validated through analysis in the coming years as they operate.

Sixth, the product definition is central to the architecture of LFM solutions. Standardization of well-defined products has been observed to accelerate the evolution of LFM markets, as exemplified by operational markets in the United Kingdom and the Netherlands.

Finally, our last insight underscores the potential need to periodically review the taxonomy as policies and specific characteristics of LFM solutions become more defined through forthcoming guidelines and national regulations.

6.2. Recommendations

We propose the following recommendations from the previously derived observations and insights that can guide practitioners.

1. Theoretical framework limitations: While the SGAM framework has been instrumental in structuring our taxonomy, it has certain limitations, especially in accommodating market-driven elements in only one unique layer (i.e., business), aligning with observations by Paustian et al. [131]. Both our study and theirs advocate for revising the SGAM to better accommodate market-driven paradigms.
2. Unique taxonomy layer design: Our multi-layered taxonomy can serve as a foundational structure that could be adapted for other taxonomies-oriented services, other taxonomies (i.e., local electricity markets), or ontologies of congestion management services. A single-layered taxonomy might not be practical or optimal due to the numerous design characteristics inherent in LFM solutions.
3. Addressing information gaps: We found a notable lack of information outside the business taxonomy layer, such as communication protocols and device requirements. To mitigate this, we recommend utilizing the comprehensive taxonomy to enhance the depth of documentation, thereby augmenting the transparency and accessibility of LFM solutions.
4. Consideration of several design principles: Given the power system structures and many different points of view, we recommend considering these points of view to collect the market design principles for developing solutions as otherwise solutions that do not feature these principles may face challenges and a lack of support from other stakeholders. For instance, Europex is a power exchange association that advocates for facilitating transparent and neutral market operations, openness to different flexibility resources, straightforward product design, adaptability to local needs, integration with existing markets, and responsibility and incentive schemes for cost-effective system management principles to be included in LFM solutions [132].
5. Clarification of Governance and Operational Models: Upcoming regulations should clarify both high-level and granular roles and responsibilities. This would offer guidelines applicable to both SO-managed and third-party-managed LFMs.
6. Push for market integration and liquidity: We recommend the development of mechanisms that allow cross-platform integration and multi-service provisioning in LFMs as one additional solution to the currents previously explored. This approach is likely to enhance market liquidity and is congruent with broader energy market objectives, albeit it necessitates comprehensive research, validation, and investment.
7. Product Definition and Standardization: A minimum set of attributes should be defined as a template for all products, allowing ad-hoc attributes to be added as specific needs arise.
8. Periodic Update: Taxonomies should be dynamic, not static, adapting to emerging new objects [75]. Hence, our final recommendation is to review the taxonomy in the coming years. Since our recommendations are based on a period where LFM solutions, with a focus on congestion management, are still in development — and considering guidelines like those from ACER — it would be prudent to revisit the taxonomy after a few years, especially after the demand response framework guidelines and the appearance of regulation from different jurisdictions.

7. Conclusion

The development of local flexibility markets platform solutions is a rapidly growing and complex area within smart grid solutions. We have created a comprehensive, multi-layer taxonomy to understand better and analyze these solutions. Our multi-layer taxonomy contribution strives to describe, classify, and analyze local flexibility market platforms, explicitly focusing on congestion management at the distribution layer and consequently reducing the information fragmentation of information to be used when describing these solutions.

We developed the multi-layer taxonomy following an iterative process involving sixteen iterations. We considered a range of projects, online documentation, expert opinions, and academic literature to ensure that our multi-layer taxonomy was comprehensive and accurate. The result is a five-layer taxonomy that aligns with the Smart Grid Architecture Model framework. This multi-layer taxonomy provides a complete classification of local flexibility market platforms, facilitating a deeper understanding of their design characteristics.

To demonstrate the applicability of our multi-layer taxonomy, we have provided a complete example, focused on the Piclo local flexibility market platform solution currently operating in the United Kingdom. Additionally, we have included three additional examples of use cases from the United Kingdom, the Netherlands, and Spain. These examples highlight the versatility and relevance of our taxonomy in capturing the complexity of local flexibility market platform solutions. This is particularly the case in the context of congestion management at the distribution level.

As highlighted in the discussion section, local flexibility markets solutions evolve continually, and our taxonomy serves as a foundational block for further exploration and analysis. As the landscape of local flexibility markets expands in the future to include other services, our taxonomy provides a solid basis to accommodate the increased complexity that may arise. By offering a structured and comprehensive approach, our taxonomy contributes to advancing knowledge and understanding of local flexibility market solutions. This will support informed decision-making, and foster innovation in the pursuit of efficient and reliable smart grid systems.

CRediT authorship contribution statement

Sergio Potenciano Menci: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Orlando Valarezo:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgments

The authors would like to acknowledge Dr. Alex Rieger and Dr. Ivan Pavic for their valuable feedback on the first draft of this paper.

This work has been supported by the Kopernikus-project "SynErgie" by the German Federal Ministry of Education and Research (BMBF), by the Luxembourg National Research Fund (FNR) and PayPal, PEARL grant reference 13342933/Gilbert Fridgen. The authors would like to express their gratitude for the project supervision by the project management organization Projektträger Jülich (PtJ). For the purpose of open access, and in fulfillment of the obligations arising from the grant agreement, the author has applied a Creative Commons Attribution 4.0 International (CC BY 4.0) license to any Author Accepted Manuscript version arising from this submission.

Appendix A. Taxonomy-building method steps

For clarity and convenience, we include Fig. A.1 in our appendix. We have taken it from [74], and it illustrates the sequential process necessary for constructing a taxonomy.

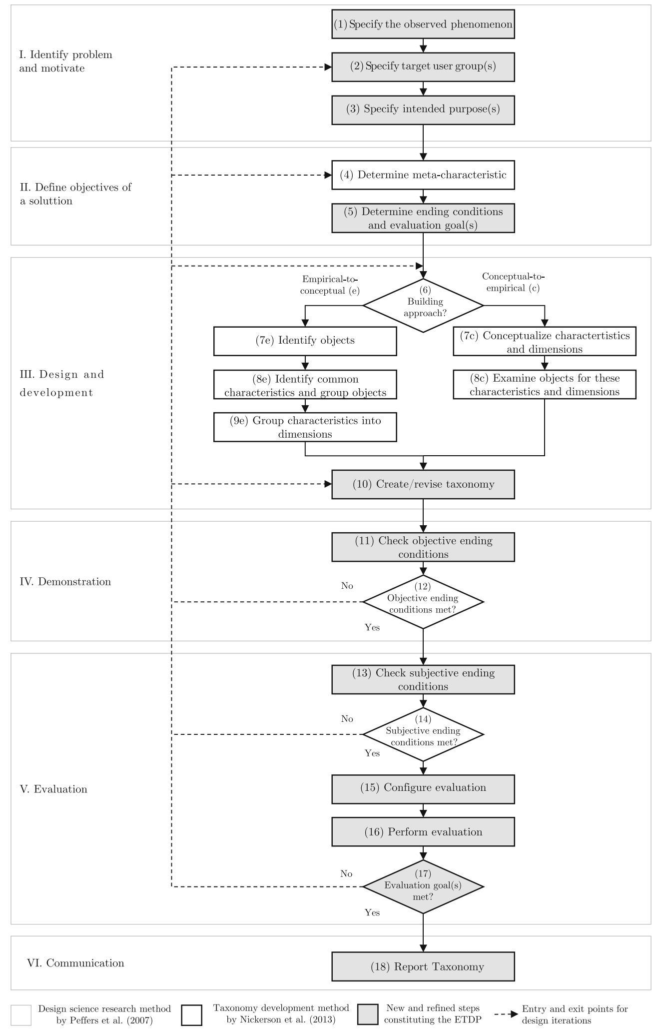


Fig. A.1. Extended taxonomy design process (ETDP) taken from [74].

Appendix B. Evaluation questions

See Table B.1.

Appendix C. Additional taxonomy examples

C.1. United Kingdom - national grid - flexible power

NGED, rebranded from Western Power Distribution in September 2022, operates as both a DNO and DSO in various regions. In 2018, they began procuring flexibility services through bi-annual tenders. We examined their 2022 s cycle tender, which ran from June 27 to October 3, 2022, and aimed to procure 297.69 MW of flexibility across 47 locations for contracts lasting one to four years. From these locations and contracts, we analyzed in detail the following two:

1. Grassmoor - Chesterfield (Secure),
2. Aberaeron - Ceredigion (Dynamic)

C.1.1. Business taxonomy

We provide in Table C.2 the business layer taxonomy for the 2022 tendering process second cycle.

NGED uses their tender process to address potential network congestion issues, targeting both winter and summer constraints up to 2027. While the Grassmoor-Chesterfield area focuses on pre-fault needs,

Table B.1
Overview of the battery of questions for the evaluation criteria.

Criteria [84,85]	Questions	Definition of evaluation criteria [74]
Completeness	Do you believe the taxonomy is now complete?	The degree to which the structure of the artifact contains all necessary elements and relationships between elements.
Ease of use	Is the taxonomy easy to use?	The degree to which the use of the artifact by individuals is free of effort.
Simplicity	Does it cover the essentials?	The degree to which the structure of the artifact contains the minimal number of elements and relationships between elements.
Understandability	Is it understandable?	The degree to which the artifact can be comprehended, both at a global level and at the detailed level of the elements and relationships inside the artifact.
Fidelity with real-world	Can it help analyze LFM solutions focused on congestion management in the EU?	The degree to which the structure of the artifact corresponds to the modeled reality.
Consistency	Can it help to describe, understand, and classify real-world and upcoming solutions?	Results from the ratio of completeness and simplicity.
Level of detail?	Does it cover a sufficient degree of detail	Results from the ratio of completeness and simplicity.
Robustness	Is it robust enough for you to allocate information across the layers?	The ability of the artifact to handle invalid inputs or stressful environmental conditions.

Table C.2
Two service products business taxonomy from NGED in the UK.

Category	Dimension	Characteristic - Grassmoor - Chesterfield (Secure)		Characteristic -Aberaeron - Ceredigion (Dynamic)	
CM need	Origin	Unplanned (pre-fault)		Unplanned (post-fault)	
Participants	Flexibility buyer	DSO		DSO	
	Flexibility service provider	Aggregator	Individual provider	Aggregator	Individual provider
	Market operator	Network operator		Network operator	
Market scope	Negotiation time frame	Long-term		Long-term	
	Flexibility need (grid level)	DSO MV		DSO MV	
	Offer organization	Congestion zone/s		Congestion zone/s	
Market access	Prerequisites	Technical	Market	Technical	Market
Product	Attributes (Parameters)	Standardized at country level		Standardized at country level	
	Transactional object	Energy (Activation)	Capacity (Availability)	Energy (Activation)	
	Power	Active Power		Active Power	
	Direction	Upwards		Upwards	
Clearing	Matching	Call market (Tender)		Call market (Tender)	
	Demand/Supply formation	One side Market		One side Market	
	Grid constraint representation	Bid limitation		Bid limitation	
	Pricing rule	Pay-as-clear		Pay-as-clear	
Metering verification	Flexibility unit metering	Portfolio	Asset	Portfolio	Asset
	Baseline method	Historical data	Alternative data	Historical data	Alternative data
Integration	External coordination	Does not implement coordination		Does not implement coordination	
	Existing market interaction	Undefined		Undefined	
Economic	Fees	Variable		Variable	

Aberaeron-Ceredigion deals with post-fault scenarios. Both rely on NGED as the DSO, market operators and flexibility buyers, working with aggregators and individual providers through the Flexible Power platform. Our focus was on long-term contracts for Secure and Dynamic services in 2022, but NGED plans to fulfill remaining needs through shorter-term products. For example, they require 2.73 MW in Grassmoor-Chesterfield and 0.74 MW in Aberaeron-Ceredigion. Unmet longer-term needs will trigger a short-term market. The flexibility grid level varies by area but both analyzed locations require DSO MV flexibility. NGED has specific technical and market criteria for FSPs to participate in their flexibility tenders. At the same time, they share similarities with ENWL's taxonomy (Section 4), NGED like DPS, it employs adapted terms, like Pre-Qualification Questionnaire (PQQ).

Concerning the product, the taxonomy is the same as ENWL's business taxonomy in Section 5.1. In the UK, the attributes are standardized at the country level, with the technicality that NGED uses adapted terminology for the same concepts. Both competitions seek upward active power using a call market approach for long-term contracts, driven by the DSO (one-sided market). In these cases, the grid representation is also limited to the bid information following a pay-as-clear pricing rule. However, it is necessary to note that NGED also has maximum selling prices for each product type and area. For example, for 2023 the Grassmoor (Secure) area and their long-term flexibility has a capacity (availability) selling price of £1252/MWh and an energy (activation or utilization) ceiling price of £1753/MWh.

For metering and verification, NGED utilizes Flexible Power, requiring FSPs to form dispatch groups with one or multiple meterable units per congestion area. These units can be single or aggregated assets. In our taxonomy, we categorize these as either *portfolio* or *asset*. NGED mainly uses historical data for baselines, calculating average demand from the past month's first three weeks and using the last 75 h for generators.

Regarding integration and fees, like ENWL, NGED operates in isolation with no external market interaction. Fees are variable and act as penalties; FSPs see payment reductions based on delivery accuracy.

C.1.2. Function taxonomy

Regarding the function taxonomy, we provide three examples of different functions in Table C.3. The classification applies to any of the 47 locations where the tender process occurs, including the area of Grassmoor - Chesterfield (Secure) and Aberaeron - Ceredigion (Dynamic).

The flexibility assessment function, conducted by the DSO, involves multiple internal steps, including network impact assessments and cost–benefit analyses, as detailed in [133]. We assume it to be manually triggered and resource-intensive, requiring various scenarios for optimal operation.

The clearing function, managed by the DSO, we assume to have multiple inputs and automatically triggers as competitions close, given the limited online information available. Furthermore, we assume it places medium resource demands by comparing and ranking bids based on price and that there is no specified time limit for its execution.

NGED manages the order dispatch function consistently across all competition types and time frames. We assume, an operator manually triggers this function and has a single input. It has a 15-minute time limit for execution ahead of activation. Due to its near-real-time requirement, it places low demands on resources.

C.2. The Netherlands - Enexis

Enexis, one of the seven primary DSOs in the Netherlands, uses two solutions for local flexibility: their own Grid and Management Service (GMS) [19] and the widely-used GOPACS [60]. The latter is not technically a market platform as remarked in [31,134] but is significant for short-term congestion management in the Dutch market. We included a taxonomy for Enexis for two reasons: to test if our taxonomy can apply to solutions not traditionally considered as LFM, and to help Enexis align (prescription) its GMS or the GOPACS solution with upcoming demand-response frameworks from ACER.

C.2.1. Business - GOPACS

In the Enexis case study using GOPACS, we outline a business taxonomy in Table C.4. GOPACS serves as a short-term, unplanned congestion management solution involving Enexis, aggregators, and flexibility providers. Despite lacking a traditional market operator, GOPACS relies on ENERGY TRADING PLATFORM AMSTERDAM (ETPA) [135] or potentially EPEX SPOT in the future [136], leading us to categorize the market operator dimension as *independent regulated*.

In the case of GOPACS, the short-term negotiation focuses on unplanned flexibility needs. FSPs must meet technical and market prerequisites to participate. Technically, they must obtain a Congestion management Service Provider (CSP) approval from Tennet, the TSO, and undergo a DSO-led pre-qualification for each congestion point. Unlike other systems, no physical tests (ex-ante) are required in prequalification. Market-wise, FSPs must register with Energie Data Services Nederland (EDSN) and sign the intra-day congestion spreads (IDCONS) participation agreement, providing a list of 18-digit European article numbering (EAN) codes that identify electrical connections. They must also have an agreement with a market connected to GOPACS, currently ETPA.

In GOPACS, the only available product is IDCONS, which is not standardized at a national level, unlike in the UK. An IDCONS must specify power, time of use, price, and, importantly, the EAN code. It remunerates solely based on declared energy. An IDCONS comprises an order and a contra-order, which balances the system. The price difference between these orders is termed "the spread", covered by

Table C.3
Function taxonomy for three different functions from NGED in the UK.

Category	Dimension	Characteristic - Flexibility Assessment	Characteristic - Clearing	Characteristic - Order dispatch
Objective	Scope	Assessment	Trading	Dispatch
Management	Manager	System operator	System operator	System operator
Computation	Input	Multiple	Multiple	Single
	Trigger	Manually	Automatically	Manually
	Time limitation	Undefined	Defined	Defined
	Execution	Batch	Batch	Near real-time
	Resources	High demanding	Medium demanding	Low demanding

Table C.4
Short-term service LFMs business taxonomy from Enexis in the Netherlands.

Category	Dimension	Characteristic – GOPACS Short-term	
CM need	Origin	Unplanned	
Participants	Flexibility buyer	DSO	
	Flexibility service provider	Aggregator	Individual provider
	Market operator	Independent regulated	
Market scope	Negotiation time frame	Short-term	
	Flexibility need (grid level)	DSO HV	
	Offer organization	Congestion zone/s	
Market access	Prerequisites	Technical	Market
Product	Attributes (Parameters)	Standardized at UC/BC only	
	Transactional object	Energy (Activation)	
	Power	Active Power	
	Direction	Upwards	Downwards
Clearing	Matching	Continuous	
	Demand/Supply formation	One side Market	
	Grid constraint representation	Bid limitation	
	Pricing rule	Pay-as-bid	
Metering verification	Flexibility unit metering	Asset	
	Baseline method	Alternative data	
Integration	External coordination	Implements MO/s coordination	
	Existing market interaction	Defined	
Economic	Fees	Fixed	

the DSO. When congestion occurs, the DSO can request flexibility from GOPACS. FSPs then submit offers in either buy or sell orders, depending on the specific needs of the congested area. A buy order aims to reduce generation or increase consumption, while a sell order aims to increase generation or reduce consumption. The order direction will depend on the flexibility required in the area the DSO faces congestion.

In GOPACS, the bid-matching is conducted in tender mode with opening and closing times set by the DSO. While not a market, GOPACS collaborates with market operators like ETPA and the forthcoming EPEX Spot for market clearing. The system gathers all buy and sell orders, matches them, and then passes the results to the DSO. Enexis, the DSO, ultimately selects the offer with the lowest spread price. We categorize this arrangement as a one-sided market, where Enexis drives the final offer selection. The algorithm focuses solely on bid information, making *bid limitation* a key characteristic. The pricing rule is *pay-as-bid*, but with the nuance that the DSO pays only the spread. In the short-term market, the FSP gets their bid price for the offer, while in the contra-area, they receive both the market price and the spread.

In GOPACS, metering is asset-specific, as indicated by the requirement for an EAN from the FSP. The DSO, Enexis, relies on T-prognosis data for generation and consumption, which aligns with Dutch regulation — Article 5.1; par.5.1.1.1 and 5.1.1.2 [137]. Although other baselines can be agreed upon with the FSP, Enexis uses T-prognosis as its data source. Therefore, we categorize this as *alternative data*.

The integration feature of GOPACS sets it apart as it not only addresses local congestion issues but also considers the broader market impact. It coordinates with market operators and is currently integrated with ETPA, with plans to include EPEX SPOT. In terms of our taxonomy, this is classified as *market operator coordination* for external coordination and *defined* for existing market interaction. Economically, the platform operates on a subscription-based model with fixed annual fees. Currently, there are no variable fees involved.

C.2.2. Potential future design for longer negotiation time frames

In a follow-up interview, we suggest a possible market design (prescription) to help Enexis select or design a new market to complement the current GOPACS solution. Given the trend among DSOs, particularly in the UK, to incorporate long-term flexibility procurement into their network planning, our proposed market design aims to meet this need for Enexis as collected in Table C.5.

To adapt the current GOPACS system to future needs, we propose four main changes across different categories: congestion management, market scope, product, and economics.

1. Congestion Management: We recommend shifting the characteristic in the *origin* dimension from *unplanned* to *planned*. This aligns with the concept of integrating flexibility procurement into network planning, thereby allowing for better foresight and preparation.
2. Market Scope: In the *negotiation time frame* dimension, we suggest moving from a *short-term* to a *long-term* focus. This aligns with the overall shift toward more strategic, planned approaches.
3. Product: We recommend standardization for the *attributes* dimension. A nationally standardized product can streamline the market and provide guarantees, benefiting Enexis and other Dutch DSOs.
4. Economics: Regarding fees, penalties are crucial for DSOs to ensure compliance. However, they must be balanced carefully to avoid deterring participation, especially in markets dependent on network situations that vary widely in stress levels. Therefore, DSOs must find a balance that encourages FSPs to participate, even if flexibility provision is not their primary business.

C.3. Spain - OIME's local flexibility solution

OMIE is the NEMO for the Iberian Peninsula's (Spain and Portugal) day-ahead and intraday electricity markets. They are actively developing an integrated LFM solution. Although the platform is still in development and subject to changes due to evolving regulations, we have included it in our analysis based on the most recent data from October 2022. The solution's integration with other markets makes it particularly relevant to our study.

C.3.1. Business taxonomy

To condense, OMIE traditionally recognizes only day-ahead and intraday markets. However, for our analysis, we have divided their platform into four distinct market designs to capture its inherent complexities. We present these in two business taxonomies: one for their long-term and mid-term markets (Table C.6), and another for their day-ahead and intraday markets (Table C.7). This differentiation allows us to analyze OMIE's LFM in a more nuanced manner, and our taxonomies are based on available data and consultations with OMIE experts.

These four market designs differ in four critical dimensions:

1. Origin of Congestion Management: Long-term and mid-term markets focus on planned flexibility, aiding DSOs in long-term planning and DER integration. Short-term markets target unplanned, immediate congestion scenarios.

Table C.5
Potential design for long-term flexibility procurement solution for Enexis in the Netherlands.

Category	Dimension	Characteristic – Potential LFM Long-term	
CM need	Origin	Planned	
Participants	Flexibility buyer	DSO	
	Flexibility service provider	Aggregator	Individual provider
	Market operator	Independent regulated	
Market scope	Negotiation time frame	Long-term	
	Flexibility need (grid level)	DSO HV	
	Offer organization	Congestion zone/s	
Market access	Prerequisites	Technical	Market
Product	Attributes (Parameters)	Standardized at country level	
	Transactional object	Energy (Activation)	Capacity (Availability)
	Power	Active Power	
	Direction	Upwards	Downwards
Clearing	Matching	Call market (Tender)	
	Demand/Supply formation	One side Market	
	Grid constraint representation	Bid limitation	
	Pricing rule	Pay-as-bid	
Metering verification	Flexibility unit metering	Asset	
	Baseline method	Alternative data	
Integration	External coordination	Implements MO/s coordination	
	Existing market interaction	Defined	
Economic	Fees	Fixed	Variable

2. Negotiation Time Frame: The long-term market deals with years-ahead planning, the mid-term market focuses on monthly planning, the day-ahead is for next-day procurement, and the intraday market is for same-day needs, targeting isolated systems.
3. Transactional Object: Long-term and mid-term markets compensate for both energy and capacity, with an emphasis on capacity. The short-term markets only pay for the energy.
4. Market Clearing Matching: All markets except the intraday market are tender-based, initiated by the DSO's specific needs. The intraday market uses a continuous market clearing algorithm.

These designs offer DSOs a range of options to manage both planned and unplanned congestion, from long-term strategies to immediate same-day actions.

In turn, these markets share several similarities across various dimensions. These markets primarily serve the needs of DSOs in managing congestion. Participants can include both aggregators and individual providers, with OMIE acting as an independently regulated market operator. These markets focus on assets connected to a DSO's medium voltage grid, specifically those in designated congestion zones. To participate, assets must meet technical and market pre-conditions. For technical criteria, assets undergo a prequalification process, typically initiated by the DSO [62,76]. On the market side, FSPs must have a trading account on OMIE's platform and meet document requirements. We assumed that the attributes are standardized at the country level, and all markets focus on trading active power in either direction. The markets operate under a one-sided model driven by the DSO and utilize a pay-as-bid pricing mechanism for market clearing with limited bid information.

OMIE allows FSPs to offer either a collection or individual assets for metering and verification. Baselines can be historical data, forecasts, or real-time nominations from short-term markets. A distinctive feature is the integration of short-term LFMs with OMIE's existing platform, which also serves European markets in the Iberian Peninsula. Therefore, we categorized it as *MO coordination* and *defined* for existing market interaction based on [62,76]. Economically, the solution involves both fixed and variable fees. Fixed fees cover platform connectivity for DSO and FSPs, while variable fees pertain to penalties for non-fulfillment [62]. However, it is important to remark that these current designs might evolve as new regulations emerge.

Table C.6
Long-term and mid-term LFMs business taxonomy from OMIE in Spain.

Category	Dimension	Characteristic - Long-term		Characteristic - Mid-term	
CM need	Origin	Planned		Planned	
Participants	Flexibility buyer	DSO		DSO	
	Flexibility service provider	Aggregator	Individual provider	Aggregator	Individual provider
	Market operator	Independent regulated		Independent regulated	
Market scope	Negotiation time frame	Long-term		Mid-term	
	Flexibility need (grid level)	DSO MV		DSO MV	
	Offer organization	Congestion zone/s		Congestion zone/s	
Market access	Prerequisites	Technical	Market	Technical	Market
Product	Attributes (Parameters)	Standardized at country level		Standardized at country level	
	Transactional object	Energy (Activation)	Capacity (Availability)	Energy (Activation)	Capacity (Availability)
	Power	Active Power		Active Power	
	Direction	Upwards	Downwards	Upwards	Downwards
Clearing	Matching	Call market (Tender)		Call market (Tender)	
	Demand/Supply formation	One side Market		One side Market	
	Grid constraint representation	Bid limitation		Bid limitation	
	Pricing rule	Pay-as-bid		Pay-as-bid	
Metering verification	Flexibility unit metering	Portfolio	Asset	Portfolio	Asset
	Baseline method	Historical data	Alternative data	Historical data	Alternative data
Integration	External coordination	Implements NO/s coordination		Implements NO/s coordination	
	Existing market interaction	Defined		Defined	
Economic	Fees	Fixed	Variable	Fixed	Variable

Table C.7
Short-term day-ahead and intraday LFMs taxonomy from OMIE in Spain.

Category	Dimension	Characteristic - Short-term DA		Characteristic - Short-term ID	
CM need	Origin	Unplanned		Unplanned	
Participants	Flexibility buyer	DSO		DSO	
	Flexibility service provider	Aggregator	Individual provider	Aggregator	Individual provider
	Market operator	Independent regulated		Independent regulated	
Market scope	Negotiation time frame	Short-term		Real-time	
	Flexibility need (grid level)	DSO MV		DSO MV	
	Offer organization	Congestion zone/s		Congestion zone/s	
Market access	Prerequisites	Technical	Market	Technical	Market
Product	Attributes (Parameters)	Standardized at country level		Standardized at country level	
	Transactional object	Energy (Activation)		Energy (Activation)	
	Power	Active Power		Active Power	
	Direction	Upwards	Downwards	Upwards	Downwards
Clearing	Matching	Call market (Tender)		Call market (Tender)	
	Demand/Supply formation	One side Market		One side Market	
	Grid constraint representation	Bid limitation		Bid limitation	
	Pricing rule	Pay-as-bid		Pay-as-bid	
Metering verification	Flexibility unit metering	Portfolio	Asset	Portfolio	Asset
	Baseline method	Historical data	Alternative data	Historical data	Alternative data
Integration	External coordination	Implements MO coordination		Implements MO coordination	
	Existing market interaction	Defined		Defined	
Economic	Fees	Fixed	Variable		

References

[1] Lopes JA, Madureira A, Matos M, Bessa R, Monteiro V, Afonso J, et al. The future of power systems: Challenges, trends, and upcoming paradigms. Wiley Interdiscip Rev: Energy Environ 2019;9:e368. http://dx.doi.org/10.1002/wene.368.

[2] Zhang Q, Yan J, Gao HO, You F. A systematic review on power systems planning and operations management with grid integration of transportation electrification at scale. Adv Appl Energy 2023;11:100147. http://dx.doi.org/10.1016/j.adapen.2023.100147, URL https://www.sciencedirect.com/science/article/pii/S2666792423000264.

[3] Verzijlbergh RA, De Vries LJ, Lukszo Z. Renewable energy sources and responsive demand, do we need congestion management in the distribution grid? IEEE Trans Power Syst 2014;29(5):2119–28. http://dx.doi.org/10.1109/TPWRS.2014.2300941.

[4] Ardian F, Concettini S, Creti A. Renewable generation and network congestion: An empirical analysis of the Italian power market. Energy J 2018;39(01). http://dx.doi.org/10.5547/01956574.39.si2.fard.

[5] Villar J, Bessa R, Matos M. Flexibility products and markets: Literature review. Electr Power Syst Res 2018;154:329–40. http://dx.doi.org/10.1016/j.epsr.2017.09.005, URL https://www.sciencedirect.com/science/article/pii/S0378779617303723.

[6] Babatunde O, Munda J, Hamam Y. Power system flexibility: A review. Energy Rep 2020;6:101–6. http://dx.doi.org/10.1016/j.egyr.2019.11.048, URL https://www.sciencedirect.com/science/article/pii/S2352484719309242, the 6th International Conference on Power and Energy Systems Engineering.

[7] Heggarty T, Bourmaud J-Y, Girard R, Kariniotakis G. Quantifying power system flexibility provision. Appl Energy 2020;279:115852. http://dx.doi.org/10.1016/j.apenergy.2020.115852, URL https://www.sciencedirect.com/science/article/pii/S030626192031326X.

[8] Kupzog F, Genest O, Ahmadifar A, Berthomé F, Cupelli M, Kazmi J, et al. Sgam-based comparative study of interoperability challenges in European flexibility demonstrators: methodology and results. In: 2018 IEEE 16th international conference on industrial informatics. IEEE; 2018, p. 692–7.

[9] The European Parliament and the Council of the European Union. Regulation (EU) 2019/943 of the European parliament and of the council of 5 June 2019 on the internal market for electricity. Off J Eur Union L 2019;158:54–124.

[10] The European Parliament and the Council of the European Union. Directive (EU) 2019/944 of the European parliament and of the council of 5 June 2019 on common rules for the internal market for electricity and amending directive 2012/27/EU. Off J Eur Union L 2019;158:125–99.

[11] Valarezo O, Gómez T, Chaves-Avila JP, Lind L, Correa M, Ulrich Ziegler D, Escobar R. Analysis of new flexibility market models in Europe. Energies 2021;14(12). http://dx.doi.org/10.3390/en14123521, URL https://www.mdpi.com/1996-1073/14/12/3521.

[12] Ramos A, De Jonghe C, Gómez V, Belmans R. Realizing the smart grid's potential: Defining local markets for flexibility. Util Policy 2016;40:26–35. http://dx.doi.org/10.1016/j.jup.2016.03.006.

[13] Radecke J, Hefele J, Hirth L. Markets for local flexibility in distribution networks. Tech. rep., Kiel, Hamburg: ZBW – Leibniz Information Centre for Economics; 2019, URL http://hdl.handle.net/10419/204559.

[14] Fonteijn R, Van Cuijk T, Nguyen PH, Morren J, Slootweg JG. Flexibility for congestion management: A demonstration of a multi-mechanism approach. In: Proceedings - 2018 IEEE PES innovative smart grid technologies conference Europe, ISGT-Europe 2018. 2018, http://dx.doi.org/10.1109/ISGTEurope.2018.8571896.

[15] Bouloumpasis I, Steen D, Tuan LA. Congestion management using local flexibility markets: Recent development and challenges. In: 2019 IEEE PES innovative smart grid technologies Europe. 2019, p. 1–5. http://dx.doi.org/10.1109/ISGTEurope.2019.8905489.

[16] Minniti S, Haque N, Nguyen P, Pemen G. Local markets for flexibility trading: Key stages and enablers. Energies 2018;11(11). http://dx.doi.org/10.3390/en11113074.

[17] Jin X, Wu Q, Jia H. Local flexibility markets: Literature review on concepts, models and clearing methods. Appl Energy 2020;261. http://dx.doi.org/10.1016/j.apenergy.2019.114387.

[18] Olivella-Rosell P, Bullich-Massagué E, Aragüés-Peñalba M, Sumper A, Ottesen SØ, Vidal-Clos J-A, et al. Optimization problem for meeting distribution system operator requests in local flexibility markets with distributed energy resources. Appl Energy 2018;210:881–95. http://dx.doi.org/10.1016/j.apenergy.2017.08.136, URL https://www.sciencedirect.com/science/article/pii/S0306261917311522.

[19] Potenciano Menci S, Herndler B, Kupzog F, Zweistra M, Steegh R, Willems M. Scalability and replicability analysis of grid management services in low voltage networks in local flexibility markets: an interflex analysis. In: 2021 IEEE Madrid powertech. 2021, p. 1–6. http://dx.doi.org/10.1109/PowerTech46648.2021.9495061.

[20] CEN-CENELEC-ETSI. CEN-CENELEC-ETSI smart grid coordination group. Smart grid reference architecture. 2012, URL https://www.cencenelec.eu/media/CEN-CENELEC/AreasOfWork/CEN-CENELEC_Topics/Smart%20Grids%20and%20Meters/Smart%20Grids/4_sgcg_methodology_sgamusermanual.pdf. [Accessed: 09 October 2023].

[21] Delnooz A, Vanschoenwinkel J, Rivero E, Madina C. Coordinet deliverable d1.3 - definition of scenarios and products for the demonstration campaigns. Tech. rep., CoordiNet Project; 2019, URL https://private.coordinet-project.eu//files/documentos/5d72415ced279Coordinet_Deliverable_1.3.pdf.

[22] Eurelectric. Flexibility and aggregation requirements for their interaction in the market. Tech. rep., Eurelectric; 2014, URL https://www.usef.energy/app/uploads/2016/12/EURELECTRIC-Flexibility-and-Aggregation-jan-2014.pdf.

[23] Correa-Florez CA, Michiorri A, Kariniotakis G. Optimal participation of residential aggregators in energy and local flexibility markets. IEEE Trans Smart Grid 2020;11(2):1644–56. http://dx.doi.org/10.1109/TSG.2019.2941687.

[24] Ziras C, Heinrich C, Bindner HW. Why baselines are not suited for local flexibility markets. Renew Sustain Energy Rev 2021;135:110357. http://dx.doi.org/10.1016/j.rser.2020.110357, URL https://www.sciencedirect.com/science/article/pii/S1364032120306456.

[25] Dronne T, Roques F, Saguan M. Local flexibility markets for distribution network congestion-management in center-western Europe: Which design for which needs? Energies 2021;14(14). http://dx.doi.org/10.3390/en14144113, URL https://www.mdpi.com/1996-1073/14/14/4113.

[26] Färegård S, Miletic M. A Swedish Perspective on aggregators and local flexibility markets: considerations and barriers for aggregators and sthlmflex together with their potential to manage grid congestions in stockholm [Master's thesis], KTH - Kungliga Tekniska högskolan; 2021.

[27] Singh R, Vijay R, Mathuria P, Bhakar R. Local flexibility markets in the context of reactive power provision by distributed energy resources. In: 2022 4th international conference on energy, power and environment. 2022, p. 1–6. http://dx.doi.org/10.1109/ICEPE55035.2022.9798333.

[28] Charbonnier V, Dikaiakos C, Foresti M, Appleman N, Cooper M, Hussein A, et al. Review of flexibility platforms. Tech. rep., ENTSO-E and Frontier Economics Ltd; 2021.

[29] European Union Agency for the Cooperation of Energy Regulators (ACER). Framework guideline on demand response. 2022, URL https://acer.europa.eu/Official_documents/Acts_of_the_Agency/Framework_Guidelines/Framework%20Guidelines/FG_DemandResponse.pdf. [Accessed: 09 October 2023].

[30] Valarezo O, Chaves-Ávila J, Gómez T. Exploring the interaction between electricity distribution network reconfiguration and local flexibility markets. Curr Sustain/Renew Energy Rep 2023. http://dx.doi.org/10.1007/s40518-023-00221-6.

[31] Chondrogiannis S, Vasiljevska J, Marinopoulos A, Papaioannou I, Flego G. Local electricity flexibility markets in Europe, publications office of the European union (KJ-NA-31-194-EN-N (online)). 2022, http://dx.doi.org/10.2760/9977.

[32] Troncia M, Chaves Ávila JP, Damas Silva C, Gerard H, Willeghems G. Market-based TSO-DSO coordination: A comprehensive theoretical market framework and lessons from real-world implementations. Energies 2023;16(19). http://dx.doi.org/10.3390/en16196939, URL https://www.mdpi.com/1996-1073/16/19/6939.

[33] Acosta RR, Lehnhoff S, Gomez JM. An electricity market categorization based on morphological analysis for smart grid development. In: 2022 18th international conference on the European energy market. 2022, p. 1–7. http://dx.doi.org/10.1109/EEM54602.2022.9921038.

[34] Teske F, Funk F, Fehrle A, Franke J. Evaluation of market designs for local energy markets to support the distribution grid. In: 2022 IEEE PES transactive energy systems conference. 2022, p. 1–5. http://dx.doi.org/10.1109/TESC53336.2022.9917255.

[35] Møller Sneum D. Barriers to flexibility in the district energy-electricity system interface – A taxonomy. Renew Sustain Energy Rev 2021;145:111007. http://dx.doi.org/10.1016/j.rser.2021.111007, URL https://www.sciencedirect.com/science/article/pii/S1364032121002975.

[36] Mengelkamp E, Schlund D, Weinhardt C. Development and real-world application of a taxonomy for business models in local energy markets. Appl Energy 2019;256:113913. http://dx.doi.org/10.1016/j.apenergy.2019.113913, URL https://www.sciencedirect.com/science/article/pii/S0306261919316009.

[37] Di Silvestre ML, Favuzza S, Riva Sanseverino E, Zizzo G. How decarbonization, digitalization and decentralization are changing key power infrastructures. Renew Sustain Energy Rev 2018;93:483–98. http://dx.doi.org/10.1016/j.rser.2018.05.068, URL https://www.sciencedirect.com/science/article/pii/S1364032118304283.

[38] European Commission. Delivering the European green deal. 2022, URL https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en#documents. [Accessed: 09 October 2023].

[39] European Commission. Framework guideline on demand response. 2023, URL https://energy.ec.europa.eu/topics/energy-systems-integration/eu-strategy-energy-system-integration_en. [Accessed: 09 October 2023].

[40] European Commission, Directorate-General for Informatics. Strategic Plan 2020-2024. Tech. rep., European Commission; 2020, URL https://commission.europa.eu/system/files/2020-10/ener_sp_2020_2024_en.pdf. [Accessed: 09 October 2023].
[41] European Commission. Proposal for a directive of the European parliament and of the council amending directive (EU) 2018/2001 of the European parliament and of the council, regulation (EU) 2018/1999 of the European parliament and of the council and directive 98/70/ec of the European parliament and of the council as regards the promotion of energy from renewable sources, and repealing council directive (EU) 2015/652. 2018, URL https://eur-lex.europa.eu/resource.html?uri=cellar:dbb7eb9c-e575-11eb-a1a5-01aa75ed71a1.0001.02/DOC_1&format=PDF. [Accessed: 09 October 2023].
[42] European Commission. Commission proposes new energy efficiency directive. 2021, URL https://commission.europa.eu/news/commission-proposes-new-energy-efficiency-directive-2021-07-14_en. [Accessed: 09 October 2023].
[43] European Commission. Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions 'fit for 55': delivering the eu's 2030 climate target on the way to climate neutrality. 2021, URL https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC0550. [Accessed: 09 October 2023].
[44] The European Parliament and the Council of the European Union. Communication from the commission to the European parliament, the European council, the council, the European economic and social committee and the committee of the regions repowereu plan (2022-05-18). 2022.
[45] Stevens N, Merckx K, Crucifix P, Gómez I, Santos-Mugica M, Díaz Ángel, et al. Coordinet deliverable d2.1 - markets for dso and tso procurement of innovative grid services: specification of the architecture, operation and clearing algorithms. Tech. rep., CoordiNet Project; 2020, URL https://private.coordinet-project.eu//files/documentos/6033b5fe475cdCoordiNet_WP2_D2.1_Markets%20for%20DSO%20and%20TSO%20procurement%20of%20innovative%20grid%20services_V1.0_20.02.2021.pdf.
[46] H2020 Project CoordiNet. 2019, https://coordinet-project.eu/, [Accessed: 09 October 2023].
[47] H2020 Project EUniversal. 2020, https://euniversal.eu/, [Accessed: 09 October 2023].
[48] Valarezo O, Cossent R, Beckstedde E, Meeus L. Deliverable D10.2 - Methodology and scenarios for the euniversal scalability and replicability analysis. Tech. rep., EUniversal Project; 2022, URL https://euniversal.eu/wp-content/uploads/2022/01/EUniversal_D10.2_Methodology-and-scenarios-for-the-EUniversal-SRA.pdf.
[49] Effantin C, Loevenbruck P. EU-SysFlex D3.3: T3.3 business use cases for innovative system services. Tech. rep., EU-SysFlex Project; 2018, URL http://eu-sysflex.com/wp-content/uploads/2019/03/D3.3_Business-Use-Cases-for-Innovative-System-Services.pdf.
[50] H2020 Project EU-SysFlex. 2018, https://eu-sysflex.com/, [Accessed: 09 October 2023].
[51] H2020 Project InterFlex. 2018, https://interflex-h2020.com/, [Accessed: 09 October 2023].
[52] van Cuijk T, Fonteijn R, Geelen D, Laarakkers J, Rademakers P, Ran B, et al. InterFlex D7.3 Innovative Solutions To Be Tested in the Use Cases, Version 1.0. Tech. rep., InterFlex Project; 2018, URL https://interflex-h2020.com/wp-content/uploads/2020/02/D7.3-Enexis-DEMO-innovative-solutions-to-be-tested-in-the-use-cases_Enexis_InterFlex.pdf.
[53] H2020 Project OneNet. 2020, https://onenet-project.eu/, [Accessed: 09 October 2023].
[54] Chaves JP, Troncia M, Silva CD, Willeghems G. OneNet D3.1 - overview of market designs for the procurement of system services by DSOs and TSOs. Tech. rep., OneNet Project; 2021, URL https://onenet-project.eu/wp-content/uploads/2022/10/D31-Overview-of-market-designs-for-the-procurement-of-system-services-by-DSOs-and-TSOs.pdf.
[55] Sommer H, Lahmar E, Gertje J, Wilken J, Jebens J, Neumann C, et al. Using enera's experience to complement the upcoming redispatch regime with flexibility from load & other non-regulated assets. Tech. rep., Enera Project; 2020, URL https://projekt-enera.de/wp-content/uploads/enera-Improving-redispatch-thanks-to-flexibility-platform-experience.pdf.
[56] Heussen K. Use cases for the ecogrid flexibility ecosystem - EcoGrid 2.0, D4.0. Tech. rep. DTU, 2018.
[57] Cornwall Local Energy Market project. 2018, https://www.centrica.com/innovation/cornwall-local-energy-market, [Accessed: 09 October 2023].
[58] Flexible Power, flexible power trademark. 2021, https://www.flexiblepower.co.uk/, [Accessed: 09 October 2023].
[59] ENEDIS Request for Information (RFI) platform. 2021, https://flexibilites-enedis.fr/, [Accessed: 09 October 2023].
[60] GOPACS, gopacs the platform to solve congestion in the electricity grid. 2023, https://en.gopacs.eu/, [Accessed: 09 October 2023].
[61] OMIE. Local flexibility markets: Contribution to ders penetration. 2022, URL https://www.dres2market.eu/wp-content/uploads/2023/02/OMIE-Local-Flexibility-Markets.pdf.
[62] OMIE. Modelo de funcionamiento de los mercados locales de electricidad. Tech. rep., OMIE; 2019, URL https://www.omie.es/sites/default/files/2019-12/modelo_de_funcionamiento_mercados_locales_electricidad_v2_0.pdf.
[63] Piclo. The leading independent marketplace for flexibility services. 2023, https://www.piclo.energy/, [Accessed: 09 October 2023].
[64] Nodes. Nodes - marketplace. 2023, https://nodesmarket.com/, [Accessed: 09 October 2023].
[65] Engelbrecht D, Schweer A, Gehrcke R, Lauen E, Deuchert B, Wilczek J, et al. Demonstration of a market-based congestion management using a flexibility market in distribution networks. In: ETG-Kongress 2019 - das gesamtsystem im fokusder energiewende. 2019, p. 306–11.
[66] Abusdal GM, Hagen H, Pedersen J, Kazemi S. Norflex: Accommodating e-mobility in the distribution grid utilising a flexibility market to manage grid congestions. In: CIRED workshop on e-mobility and power distribution systems. 2022, http://dx.doi.org/10.1049/icp.2022.0794.
[67] Smart Senjab. Smart senja project. 2019, https://smartsenja.no/en/, [Accessed: 09 October 2023].
[68] Sthlmflex. Sthlmflex project. 2023, https://www.svk.se/sthlmflex, [Accessed: 09 October 2023].
[69] H2020 Project InteGrid. 2017, https://cordis.europa.eu/project/id/731218, [Accessed: 09 October 2023].
[70] on Data Format Working Group, under the Expert Group 1 Procedures. Towards interoperability within the eu for electricity and gas data access & exchange. Tech. rep., European Commission; 2019.
[71] Lambert E, Boultadakis G, Kukk K, Kotsalos K, Bilidis N, et al. European energy data exchange reference architecture, data management working group. Tech. rep., European Commission; 2019.
[72] Potenciano Menci S, Bessa RJ, Herndler B, Korner C, Rao B-V, Leimgruber F, et al. Functional scalability and replicability analysis for smart grid functions: The Integrid project approach. Energies 2021;14(18). http://dx.doi.org/10.3390/en14185685, URL https://www.mdpi.com/1996-1073/14/18/5685.
[73] Bailey KD. Typologies and taxonomies, quantitative applications in the social sciences. Thousand Oaks, CA: SAGE Publications; 1994.
[74] Kundisch D, Muntermann J, Oberläer A, Rau D, Roeglinger M, Schoormann T, et al. An update for taxonomy designers - methodological guidance from information systems research. Bus Inf Syst Eng 2021. http://dx.doi.org/10.1007/s12599-021-00723-x.
[75] Nickerson RC, Varshney U, Muntermann J. A method for taxonomy development and its application in information systems. Eur J Inf Syst 2013;22(3):336–59. http://dx.doi.org/10.1057/ejis.2012.26.
[76] Operador del Mercado Ibérico de Energía (OMIE). Modelo de funcionamiento de los mercados locales de electricidad, proyecto iremel (integración de recursos energéticos a través de mercados locales de electricidad). Tech. rep., OMIE; 2022, URL https://www.omie.es/sites/default/files/2019-12/modelo_de_funcionamiento_mercados_locales_electricidad_v2_0.pdf.
[77] Charbonnier F, Morstyn T, McCulloch MD. Coordination of resources at the edge of the electricity grid: Systematic review and taxonomy. Appl Energy 2022;318:119188. http://dx.doi.org/10.1016/j.apenergy.2022.119188, URL https://www.sciencedirect.com/science/article/pii/S030626192200558X.
[78] Hartwich E, Ollig P, Fridgen G, Rieger A. Probably something: A multi-layer taxonomy of non-fungible tokens. Internet Res 2023. http://dx.doi.org/10.1108/INTR-08-2022-0666.
[79] Püschel L, Roeglinger M, Schlott H. What's in a smart thing? development of a multi-layer taxonomy. In: ICIS 2016 proceedings. 2016.
[80] IEEE Xplore. 2023, https://ieeexplore.ieee.org/Xplore/home.jsp, [Accessed: 09 October 2023].
[81] Science direct. 2023, https://www.sciencedirect.com/, [Accessed: 09 October 2023].
[82] Semantic scholar. 2023, https://interflex-h2020.com/, [Accessed: 09 October 2023].
[83] Myers MD, Newman M. The qualitative interview in is research: Examining the craft. Inf Organ 2007;17(1):2–26. http://dx.doi.org/10.1016/j.infoandorg.2006.11.001, URL https://www.sciencedirect.com/science/article/pii/S1471772706000352.
[84] March ST, Smith GF. Design and natural science research on information technology. Decis Support Syst 1995;15(4):251–66. http://dx.doi.org/10.1016/0167-9236(94)00041-2, URL https://www.sciencedirect.com/science/article/pii/0167923694000412.
[85] Prat N, Comyn-Wattiau I, Akoka J. A taxonomy of evaluation methods for information systems artifacts. J Manage Inf Syst 2015;32(3):229–67. http://dx.doi.org/10.1080/07421222.2015.1099390.
[86] Potenciano Menci S. Abstracts of the 11th DACH+ conference on energy informatics (S53-taxonomy of local flexibility markets). Energy Inf 2022;5.
[87] de Heer M, van der Laan H, Armenteros A Sáez. Usef: the framework explained: the framework explained, update 25 May 2021. Framework report, USEF; 2021.
[88] EFET and ebIX. The harmonised electricity market role model. Tech. rep., European Network of Transmission System Operators for Electricity; 2017, URL https://eepublicdownloads.entsoe.eu/clean-documents/EDI/Library/HRM/Harmonised_Role_Model_2017-01.pdf.

[89] Energy networks association. Active power services implementation plan. Tech. rep., ENA; 2020, URL https://www.energynetworks.org/industry-hub/resource-library/open-networks-2020-ws1a-p3-final-implementation-plan.pdf.

[90] Sáez Armenteros A, de Heer H, Bjørndalen J. The regulation of independent aggregators: with a focus on compensation mechanisms. Tech. rep., DNV-GL; 2022.

[91] Poplavskaya K, de Vries L. Chapter 5 - aggregators today and tomorrow: from intermediaries to local orchestrators? In: Sioshansi F, editor. Behind and beyond the meter. Academic Press; 2020, p. 105–35. http://dx.doi.org/10.1016/B978-0-12-819951-0.00005-0, URL https://www.sciencedirect.com/science/article/pii/B9780128199510000050.

[92] Lopes F. From wholesale energy markets to local flexibility markets: structure, models and operation. In: Local electricity markets. Elsevier; 2021, p. 37–61.

[93] Gazafroudi AS, Khajeh H, Shafie-khah M, Laaksonen H, Corchado JM. Chapter 5 - local market models. In: Pinto T, Vale Z, Widergren S, editors. Local electricity markets. Academic Press; 2021, p. 79–90. http://dx.doi.org/10.1016/B978-0-12-820074-2.00010-1, URL https://www.sciencedirect.com/science/article/pii/B9780128200742000101.

[94] Valarezo O, Chaves-Avila JP, Rossi J, Hillberg E, Baron M. Survey results on local markets to enable societal value. In: 2021 IEEE Madrid PowerTech. 2021;1. http://dx.doi.org/10.1109/PowerTech46648.2021.9495089.

[95] Markiewicz H, Klajn A. Voltage Disturbances Standard En 50160 - Voltage Characteristics in Public Distribution Systems. Standard EN 50160, 2004.

[96] Mataczyńska E, Rodríguez JM, van der Heijden S, Kula J, Voumvoulakis M. Grid Observability for Flexibility. Tech. rep., E.DSO – European Distribution System Operators; 2022, URL https://www.edsoforsmartgrids.eu/images/20220513_TF1_ANM_-_Go4Flex_Report.pdf.

[97] Piclo. Adding and managing competitions. 2023, URL https://support.picloflex.com/article/53-competitions. [accessed on 10 March 2023].

[98] Dominguez F, Willeghems G, Gerard H, Tzoumpas A, Drivakou K, Villar J, et al. OneNet D2.2 - a Set of standardised products for system services in the tsodso-consumer value chain. Tech. rep., OneNet Project; 2021, URL https://onenet-project.eu/wp-content/uploads/2022/10/D22-A-set-of-standardised-products-for-system-services-in-the-TSO-DSO-consumer-value-chain.pdf.

[99] Association Energy Networks. Active Power Products Review. Tech. rep., ENA; 2022, URL https://www.energynetworks.org/assets/images/Resource%20library/ON22-WS1A-P6%20Active%20Power%20Product%20Review%20-%20Draft%20V3%20(2).pdf.

[100] Heinrich C, Ziras C, Jensen TV, Bindner HW, Kazempour J. A local flexibility market mechanism with capacity limitation services. Energy Policy 2021;156:112335. http://dx.doi.org/10.1016/j.enpol.2021.112335, URL https://www.sciencedirect.com/science/article/pii/S0301421521002056.

[101] Zade M, Lumpp SD, Tzscheutschler P, Wagner U. Satisfying user preferences in community-based local energy markets — auction-based clearing approaches. Appl Energy 2022;306:118004. http://dx.doi.org/10.1016/j.apenergy.2021.118004, URL https://www.sciencedirect.com/science/article/pii/S0306261921013003.

[102] Khorasany M, Mishra Y, Ledwich G. Market framework for local energy trading: a review of potential designs and market clearing approaches. IET Generation, Transmission & Distribution 2018;12(22):5899–908. http://dx.doi.org/10.1049/iet-gtd.2018.5309, arXiv:https://ietresearch.onlinelibrary.wiley.com/doi/pdf/10.1049/iet-gtd.2018.5309 URL https://ietresearch.onlinelibrary.wiley.com/doi/abs/10.1049/iet-gtd.2018.5309.

[103] Kiesling LL. Chapter 16 - An economic analysis of market design: Local energy markets for energy and grid services. In: Pinto T, Vale Z, Widergren S, editors. Local electricity markets. Academic Press; 2021, p. 279–93. http://dx.doi.org/10.1016/B978-0-12-820074-2.00001-0, URL https://www.sciencedirect.com/science/article/pii/B9780128200742000010.

[104] Sáez Armenteros A, de Heer H, et al. Baseline methodology assessment. Tech. rep., DNV-GL; 2020.

[105] Ofem. Ofgem's future insights series flexibility platforms in electricity markets. resreport, OFEM; 2019.

[106] Silva C, Marques P, Milzer G, Sætre N, Eide Øystein Dyvik, Crucifix P, Debray A, et al. UMEI API management and documentation. Tech. rep., EUniversal Project; 2022, URL https://euniversal.eu/wp-content/uploads/2022/08/EUniversal_D2.6_UMEI.pdf.

[107] Heilmann E, Klempp N, Wetzel H. [Design of regional flexibility markets for electricity: A product classification framework for and application to german pilot projects]. Util Policy 2020;67:101133. http://dx.doi.org/10.1016/j.jup.2020.101133, URL https://www.sciencedirect.com/science/article/pii/S0957178720301272.

[108] Potenciano Menci S, Le Baut J, Matanza Domingo J, López López G, Cossent Arín R, Pio Silva M. A novel methodology for the scalability analysis of ict systems for smart grids based on sgam: The integrid project approach. Energies 2020;13(15). http://dx.doi.org/10.3390/en13153818, URL https://www.mdpi.com/1996-1073/13/15/3818.

[109] International Electrotechnical Commission, et al. Electricity metering data exchange—the DLMS/COSEM suite—part 5-3: DLMS/COSEM application layer. 2017.

[110] Fridgen G, Potenciano Menci S, van Stiphoudt C, Schilp J, Köberlein J, Bauernhansl T, et al. Referenzarchitektur der energiesynchronisationsplattform: Teil der reihe diskussionspapiere v4 konzept der energiesynchronisationsplattform. Tech. rep., Fraunhofer; 2021, URL https://orbilu.uni.lu/handle/10993/49557.

[111] USEF Foundation. Usef flexibility trading protocol specifications. Tech. rep., USEF; 2021, URL https://www.usef.energy/app/uploads/2020/01/USEF-Flex-Trading-Protocol-Specifications-1.01.pdf.

[112] Attar M, Repo S, Mann P. Congestion management market design- approach for the nordics and central Europe. Appl Energy 2022;313:118905. http://dx.doi.org/10.1016/j.apenergy.2022.118905, URL https://www.sciencedirect.com/science/article/pii/S0306261922003300.

[113] Bouloumpasis I, Mirzaei Alavijeh N, Steen D, Le AT. Local flexibility market framework for grid support services to distribution networks. Electr Eng 2021;1–19.

[114] European Commission. [Regulation (EU)] 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC (General Data Protection Regulation) (Text with EEA relevance). 2016, URL https://eur-lex.europa.eu/eli/reg/2016/679/oj.

[115] Nieles M, Dempsey K, Pillitteri VY. An introduction to information security. Tech. rep., NIST; 2017, URL https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1800-26.pdf.

[116] Cawthra J, Ekstrom M, Lusty L, Sexton J, Sweetnam J. Data integrity: detecting and responding to ransomware and other destructive events. Tech. rep., NIST; 2020, URL https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1800-26.pdf.

[117] Zimmermann H. Osi reference model-the iso model of architecture for open systems interconnection. IEEE Trans Commun 1980;28(4):425–32.

[118] Baker F. Core protocols in the internet protocol suite, draft-baker-ietf-core-03. Tech. rep. txt., internet draft; 2009, (2009).

[119] Van Steen M, Tanenbaum AS. Distributed systems. The Netherlands: Maarten van Steen Leiden; 2017.

[120] European Commission. Annex to the communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions. 2017, URL https://eur-lex.europa.eu/resource.html?uri=cellar:2c2f2554-0faf-11e7-8a35-01aa75ed71a1.0017.02/DOC_3&format=PDF. [accessed on 10 April 2023].

[121] Benisi NZ, Aminian M, Javadi B. Blockchain-based decentralized storage networks: A survey. J Netw Comput Appl 2020;162:102656.

[122] Shaw S. Distribution system operator (DSO) update. 2018, URL https://www.enwl.co.uk/globalassets/innovation/innovation-event-documents/lcni-presentations-2018/distribution-system-operator-update.pdf.

[123] ENA. Open networks project opening markets for network flexibility 2017 achievements and future direction. Tech. rep., ENA; 2017, URL https://www.energynetworks.org/industry-hub/resource-library/open-networks-2017-prj-end-of-year-report.pdf.

[124] Electricity North West. Distribution flexibility services procurement report. Tech. rep., ENW; 2023, URL https://www.enwl.co.uk/globalassets/go-net-zero/flexible-services/document-library/ofgem-dfp-reporting/distribution-flexibility-services-procurement-report---april-2023.pdf.

[125] Electricity North West. Spring 2023 flexibility requirement. 2023, URL https://www.enwl.co.uk/future-energy/flexibility-hub/previous-requirements/spring-2023/.

[126] Piclo. Piclo to support national grid eso's new local constraint market in Scotland. 2022, URL https://www.piclo.energy/press-releases/piclo-to-support-national-grid-esos-new-local-constraint-market-in-scotland.

[127] Electricity North West. Appendix 3 - site requirements, flexible service requirement spring 2023. Tech. rep., ENW; 2023, URL https://www.enwl.co.uk/globalassets/go-net-zero/flexible-services/previous-requirements/spring-2023/spring-23-itt-appendices/tt111027---flexibility-services-spring-2023---appendix-3---site-requirements.pdf.

[128] Piclo. Piclo flex flexibility map. 2023, https://picloflex.com/dashboard, [Accessed: 09 October 2023].

[129] Piclo. Company qualification / Dynamic Procurement System (DPS). 2023, URL https://support.picloflex.com/article/138-dps-company-qualification.

[130] Vasiljevska J, Gangale F, Covrig L, Mengolini A. Smart grids and beyond? an Eu research and innovation perspective, scientific analysis Or Review KJ-NA-30786-EN-N (Online). Luxembourg (Luxembourg: Joint Research Center; 2021, http://dx.doi.org/10.2760/705655, (online).

[131] Paustian S, Köhlke J, Mattes J, Lehnhoff S. The (still unexplored) social side of smart grid development: Towards a social layer for the smart grid architecture model (sgam). In: Proceedings of the thirteenth ACM international conference on future energy systems. e-Energy '22, New York, NY, USA: Association for Computing Machinery; 2022, p. 521–31. http://dx.doi.org/10.1145/3538637.3539585.

[132] Europex. A market-based approach to local flexibility – design principles. position paper. 2020, URL https://www.europex.org/wp-content/uploads/2020/02/20200212_A-market-based-approach-to-local-flexibility-design-principles_final-2.pdf.

[133] National Grid Electricity Distribution. Distribution flexibility services procurement statement December 2022 update. Tech. rep., NG; 2023, URL https://www.nationalgrid.co.uk/downloads-view-reciteme/621958.
[134] Schittekatte T, Meeus L. Flexibility markets: Q & A with project pioneers. Util Policy 2020;63:101017. http://dx.doi.org/10.1016/j.jup.2020.101017, URL https://www.sciencedirect.com/science/article/pii/S0957178720300126.
[135] GOPCAS. Idcons product terms & conditions. 2023, URL https://en.gopacs.eu/wpcms/wp-content/uploads/General-terms-and-conditions-GOPACS.pdf.
[136] EXPEX SPOT. Cooperation between epex spot and gopacs enables significant growth in flexible capacity activation for congestion management. 2022, URL https://www.epexspot.com/en/news/cooperation-between-epex-spot-and-gopacs-enables-significant-growth-flexible-capacity.
[137] Netherlands Authority for Consumers and Markets (ACM). Electricity grid code. 1998, URL https://wetten.overheid.nl/BWBR0037940/2023-04-01#Hoofdstuk5. [Accessed: 11 May 2023].

A.3.2 Research Paper 2 – *Energy synchronization platform to enable and streamline automated industrial demand response*

Energy Synchronization Platform Concept to Enable and Streamline Automated Industrial Demand Response#

Christine van Stiphoudt[1], Sergio Potenciano Menci[1], Can Kaymakci[2], Simon Wenninger[3], Dennis Bauer[2], Sebastian Duda[4], Gilbert Fridgen[1], and Alexander Sauer[2]

[1]Interdisciplinary Centre for Security, Reliability and Trust - SnT, University of Luxembourg
[2]Fraunhofer IPA, University of Stuttgart
[3]Applied University of Augsburg
[4]Fraunhofer FIT, University of Bayreuth

ABSTRACT

The industrial sector consumes a large amount of electricity, making it an ideal candidate for Demand response (DR) flexibility in modern power systems. However, current solutions for industrial DR are limited to individual cases, services and platforms, preventing companies from exploring their complete flexibility potential. Addressing this, we introduce the Energy synchronization platform (ESP), a digital integration platform concept to enable and streamline automated industrial DR. This paper outlines the ESP's conceptual architecture, components, and operational interactions, highlighting the benefits and challenges faced in a small-scale demonstrator consisting of three industrial companies.

Keywords: automated industrial demand response, digital energy platform, energy services, generic flexibility description.

NOMENCLATURE

Abbreviations	
API	Application programming interface
CP	Company-side platform
DR	Demand response
DSO	Distribution system operator
EFDM	Energy flexibility data model
EFMS	Energy flexibility management service
ERP	Enterprise resource planning
ESP	Energy synchronization platform
GUI	Graphical user interface
IaaS	Infrastructure as a service
IAM	Identity and Access Management
IoT	Internet of Things
IT	Information technology
JSON	JavaScript Object Notation
LFM	Local flexibility market
MES	Manufacturing execution systems
MIBS	Market information retrieval service
MP	Market-side platform
MSB	Manufacturing service bus
OTC	Over-the-counter
PaaS	Platform as a service
PLC	Programmable logic controller
PPC	Production Planning and Control
S-DB	Service database
SaaS	Software as a service
SC	Smart connector
SO	System operator
XaaS	X-as-a service

1. INTRODUCTION

The energy landscape, especially the power system, is rapidly changing due to three key trends: (1) the rise of renewable energy and electrification, (2) advances in digital technology, and (3) a shift towards decentralized power systems. While these trends introduce complexities, they also introduce opportunities [1].

The growing adoption of renewable energy sources like solar and wind creates fluctuations in power supply, leading to congestion and balancing challenges for the power grid. Additionally, the increased electrification of various sectors, including residential, industrial, and transportation, adds another layer of complexity to the stability of the power grid. In response to these challenges, System operators (SOs) are increasingly leveraging market-based strategies such as DR seeking additional flexibility [2]. These strategies not only help balance the variable energy supply but also turn the electrification trend into an advantage. By treating electrified sectors as potential sources of flexibility, DR can align demand with fluctuating supply.

The advent of digital technologies, coupled with the move towards decentralized power systems, adds complexity to an already intricate power grid by increasing the effort required for coordination and operation. Yet, this complexity spawns new business opportunities, from aggregation and forecasting services to real-time

This is a paper for the 15^{th} International Conference on Applied Energy - ICAE2023, Dec. 3-7, 2023, Doha, Qatar.

monitoring and virtual power plants. As a result, a diverse array of platforms and businesses have emerged to capitalize on these new service opportunities [3].

Within this context, the industrial sector can have a critical role in the rapidly evolving power system, given its significant energy consumption. For example, in 2019, the European Union and Germany's industrial sectors accounted for about a quarter of the total final energy use [4, 5]. This makes them prime candidates for DR programs, which can provide much-needed flexibility to SOs and other market players like aggregators.

A host of specialized platforms have emerged to facilitate such programs [6]. However, implementing industrial DR is not without challenges. These platforms often require substantial technical investment and coordination. They also tend to focus on specific types of services, such as ancillary services or load management, advocating for industrial companies to a handful of services and potential vendor lock-in and interoperability problems [7]. The platform specialization is particularly evident in Germany [8], as it strongly pushes for Industry 4.0 digitalization [9].

Given these challenges in reducing technical constraints to reduce costs and allow any industrial company to participate in industrial DR, avoiding unique service specialization and fostering interoperability, we derive the following research question: How can a digital platform concept facilitate the integration of various services for automated, interoperable and agnostic industrial energy management? To answer this, we introduce the ESP, a digital integration platform concept to enable and streamline automated DR.

This paper substantiates our approach and findings as follows: Section 2 outlines related work, from industrial DR to digital platforms in the energy sector and design principles. Section 3 elaborates on the research approach that guided the ESP's development. Section 4 offers a detailed look at the ESP's conceptual architecture, while Section 5 focuses on the ESP's internal interactions to delineate its functionality. Section 6 discusses the benefits and challenges of the architecture based on a small-scale demonstrator of the of the ESP concept consisting of three industrial companies. The paper concludes with Section 7, which synthesizes our contributions and outlines future steps.

2. RELATED WORK

For the design and concept development of the ESP, this paper analyzes the domain of industrial DR as well as supporting digital energy platforms and design principles for guidance.

2.1 Industrial demand response

The European Union defines DR as "*a tariff or program established to incentivize changes in electric consumption patterns by end-use consumers in response to changes in the price of electricity over time, or to incentivize payments designed to induce lower electricity use at times of high market prices or when power grid reliability is jeopardized*" [10]. In other words, end-use customers, like industrial companies, modify their operation plans based on incoming signals like electricity or market prices. Furthermore, the European Union distinguishes between two DR categories [10]. On the one hand, implicit DR – so-called price-based – refers to customers' reaction to price signals (electricity prices and/ or network tariffs) through automation or personal actions. However, implicit DR is provided as part of the customer's supply contract and does not include participation in electricity markets. On the other hand, explicit DR – so-called incentive-driven – refers to demand traded at different electricity markets (e.g., wholesale, balancing power, and ancillary service) through aggregator services or single large customers. This latter category of DR provides SOs with a solution to adjust consumers' load to tackle operational issues [10, 11]. However, these two DR categories are not a replacement for each other as they are interconnected and complementary given their different scopes [10].

Notably, industrial DR can leverage both DR categories, although it needs to fulfill technical and timescales requirements [12]. Shoreh et al. [12] further clarify that not all industries are suitable for all DR programs, given that their processes, production, and planning differ, in addition to the technical requirements to participate.

Furthermore, Shoreh et al. [12] identify barriers industrial DR faces. One of the main barriers to its widespread adoption is the lack of interoperability and standardization given the different technologies companies use for DR provision. Although standards such as Open ADR [13] and Green button [14] exist, the lack of a complete solution that enables the communication between different actors and devices limits its adoption [15].

2.2 Energy-related digital platforms

In recent years, the rise of digital platforms has had a transformative effect across various business sectors, following a platformization trend [16]. To comprehend this phenomenon in the energy domain, numerous studies have offered valuable insights. Kloppenburg and Boekelo [17] categorize platforms based on their integration with energy infrastructure and user scope. The typology includes platforms focused on *provenance* (e.g., energy flow tracking), *community* (e.g., virtual power plants or energy management services), and *access* (e.g., access to consumer investment platforms).

Expanding on this, Duda et al. [18] conducted a comprehensive review of 46 energy European platforms, proposing a multi-layer taxonomy. The taxonomy has three distinct layers: (1) general, (2) data-centric, and (3) transaction-centric, each with five dimensions. Furthermore, Duda et al. [19] using the taxonomy, identified four primary platform archetypes: (1) Research-driven Energy Platforms, (2) Energy Flexibility Platforms, (3) Software as a service (SaaS)-Aggregators/Virtual Power Plants, and (4) (Manufacturing) Internet of Things (IoT)-Platforms. One key implication of their work is the need for a digital platform that combines features from all four archetypes to streamline automated DR offerings. This is because typically, digital platforms use proprietary interfaces, limiting interoperability across digital platforms [15] and data exchange [19].

Within the German landscape, Singh et al. [8] examined 240 start-ups offering X-as-a service (XaaS) models that emerged between the years 2014 and 2020. Their survey highlighted various services, from data analytics software and charging network stations to peer-to-peer energy trading and DR solutions. The diversity in services underlines the innovative potential of digital platforms in the energy sector. Moreover, the rise of XaaS models emphasizes the potential for multi-sided platforms that can connect various user groups and overcome existing limitations, aligning closely with the objectives of this paper.

2.3 Design principles for digital platforms

The literature on platform development is expansive, covering a diverse array of considerations ranging from development approaches to design principles.

In the context of development approaches, Drewel et al. [20] categorize the existing scientific literature into three principal methodologies: (1) canvas-based approaches, which utilize tools for strategic planning and construction; (2) expert-specific approaches, relying on specialized expert advice, and (3) pattern-based approaches, employing frameworks that address recurring challenges across multiple domains.

As for design principles, Göbel and Cronholm [21] propose three pivotal principles: (1) designing for dynamic processes that integrate actors within service ecosystems, (2) fostering an iterative co-innovation process, and (3) encouraging co-problematization, where problems are conceived and tackled from different actors' point of view. Blaschke et al. [22] contribute an additional set of four principles, which include (1) ecosystem-oriented design, (2) technology-oriented design, (3) mobilization-oriented design, and (4) interaction-oriented design. Fischer et al. [23] further derives four design requirement categories from these insights for developing digital platforms. These are (1) facilitating service innovation, (2) supporting co-creation, (3) identifying mutual problems and needs, and (4) easing the entry for actors to engage service innovation and value co-creation. Furthermore, Fischer et al. [23] map 20 specific design requirements that they identified in the literature as well as the seven design principles elucidated by Göbel and Cronholm [21] and Blaschke et al. [22] to these four design requirement categories providing insightful guidance for the design of digital platforms.

3. RESEARCH APPROACH

Our approach to designing and developing the ESP follows the design science research methodology and design science paradigms [24]. We drew insights from three key areas - industrial DR, digital energy platforms, and design principles - to create a digital integration platform concept for automated industrial DR. We followed an iterative design cycle that involved continual development and internal evaluation. It is worth noting that this work was part of a larger research project called the "Kopernikus-project SynErgie", and not just the authors' contribution. Given the project's scale and the diverse expertise, we followed an expert-specific approach. To ensure the success of digital platform development, we considered four essential core design requirement categories, as suggested by Fischer et al. [23].

The first design requirement category is to facilitate service innovation in the solution. Thus, we designed the ESP as a multi-sided digital integration platform, fostering competition among diverse services, from forecasting to aggregators services.

The second design requirement category is to embrace co-creation in the design process. We use iterative design cycles involving multi-disciplinary experts in expert discussion rounds. These discussion rounds took place almost every month (the holiday season limited the frequency); on average, eighteen experts participated, from which we maintained clear internal documentation and protocols to provide a well-structured backdrop for collaborative efforts.

The third design requirement category is to identify common challenges and requirements. The expert discussion rounds also revealed barriers and needs across the industrial and energy sectors. We identified the complexities of initial DR adoption, issues of vendor lock-in, and the need for interoperable, agnostic solutions. Based on these findings, we made crucial design decisions that led to the implementation of modular components in our digital platforms and services conceptions.

The last design requirement category is to ease the entry of new actors to the solution. We developed audio-visual guides and a beginner-friendly guidance service to alleviate entry barriers. In connection with the previous requirement, we used standardized and open interfaces to ease the integration complexity.

4. ENERGY SYNCHRONIZATION PLATFORM

We introduce a novel digital integration platform concept called the ESP to enable and streamline automated industrial DR. This concept platform addresses the challenges outlined in Section 2.2, such as the lack of interoperability and integration among different digital platforms and the energy ecosystem, such as services, users, and data exchanges. Through ESP, we facilitate seamless communication and data exchange between energy actors (such as energy suppliers, aggregators, and SOs) and industrial consumers by utilizing a standardized data model as underlined in Section 4.1. To ensure effective coordination and usage, we have defined specific stakeholders, technical interfaces, data flows, and platform management or organizational protocols [25].

The architecture of the ESP comprises two primary types of digital platforms: the Company-side platform (CP) and the Market-side platform (MP), as depicted in Figure 1. Thus, there can only be one ESP with many CPs but only one MP that can offer access to external services. The division between the CP and the MP is deliberate, isolating specific domain knowledge, technologies, and methods in each digital platform to ensure they do not adversely affect the overall system's operation and performance. The CP, geared towards industrial companies, offers a service-oriented infrastructure digital platform for the technological connection and control of manufacturing processes. Whereas the MP is a digital meta-platform that serves as a connectivity hub for offering access to external market-side services that support DR provision. In other words, the MP does not operate any external services. Its primary role is to serve as the initial point of contact for industrial companies and service providers. The MP facilitates the booking of services by industrial companies and allows external service providers to register their services on the MP.

We further clarify the ESP concept and its digital platforms based on the taxonomy of Duda et al. [19] in Table 1. Due to their inherent characteristics, the CP and MP share the same "General Dimension" characteristics. For instance, the platform operator can be either a company or a consortium, the access can be Web-App and still have specific interfaces. However, they differ in their specialized dimensions: the CP aligns with "Data-Centric Dimensions", while the MP and its market-side external services correspond to "Transaction-Centric Dimensions". The highlighted fields in Table 1 mark the specific characteristics of the CP and MP.

4.1 *Generic industrial flexibility data model*

The Energy flexibility data model (EFDM) is a generic and standardized data model to describe energy flexibility. We consider energy flexibility in the manufacturing industry as "industrial flexibility". The EFDM consists of two classes: *flexibility space* and *flexible load measure* [25, 26]. We depict its logical structure in Figure 2.

The industrial *flexibility space* describes the possibilities (potential) of a flexible industrial energy system to deviate from its energy consumption (increase, decrease) compared to a reference operation. Meanwhile,

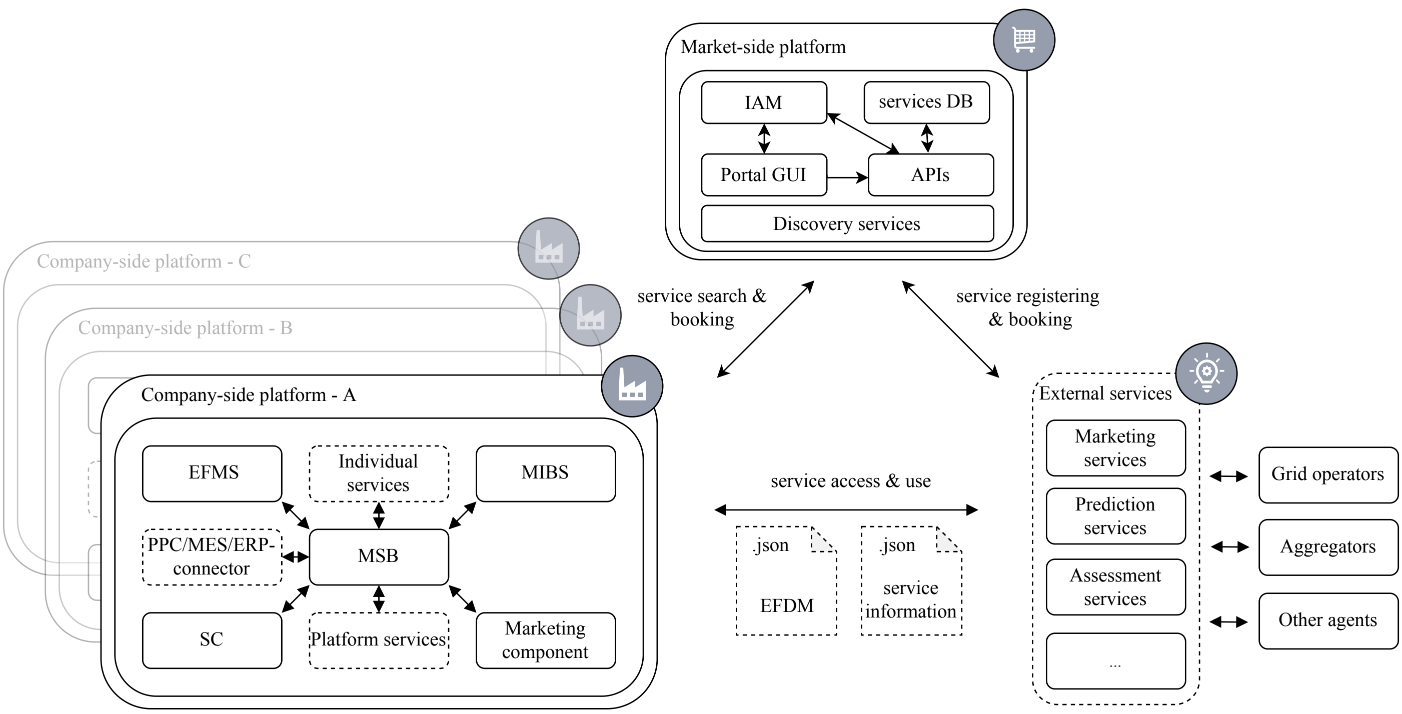


Fig. 1 Simplified architecture of the Energy Synchronization Platform.

Table 1 Characteristics of the ESP mapped to the taxonomy of Duda et al. [19].

	Dimensions	Characteristics				Ex*
General dimensions	Platform operator	Company	Consortium	Aggregator		E
	Access	Web-App	Native-App	Specific interface		NE
	Operational concept	On-Premise	Cloud	Hybrid		NE
	Access requirements	Free Access	Certain criteria to fulfil	Certain devices necessary		NE
	Platform structure	Fixed structure	Modular structure without external interfaces	Modular structure with external interfaces		E
Data-centric dimensions	Platform type	SaaS		Platform as a service (PaaS)		E
	Communication	One-to-Many		Many-to-Many		E
	Data flow	Unidirectional		Bidirectional		E
	Data processing	Transactional	Visual analysis	Data-driven analysis		NE
	Data source	Device		Cloud		NE
Transaction-centric dimensions	Main function	Electricity trading	Energy flexibility trading	Virtual power plant		E
	Trading venue	Stock exchange	Markets for systems ervices	Over-the-counter (OTC)		NE
	Flexibility type	Market flexibility	System flexibility	Grid flexibility		NE
	Market design	Open		Closed		E
	Pricing	Free	Regulated	Free with regulating elements	No pricing	NE

* Ex: Exclusivity E: exclusive; NE: non-exclusive.

the *flexible load measure* describes a specific load activation profile (schedule), one of the potentials described in the *flexibility space*. Thus, the EFDM enables automated communication internally in the CP and between the CP and flexibility services offered through the MP. We specify both EFDM classes in a JavaScript Object Notation (JSON) schema available in [27].

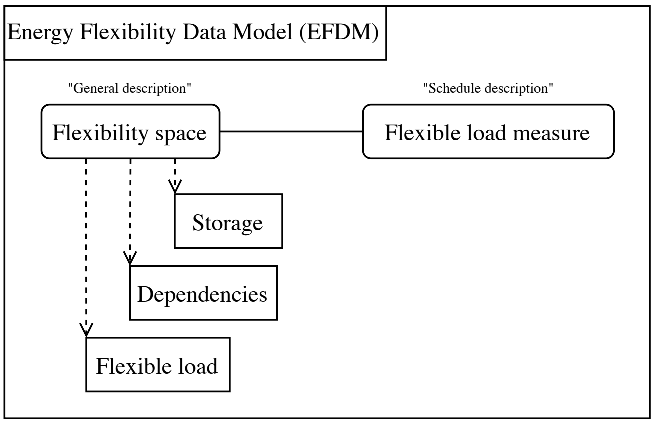


Fig. 2 Logical structure of the EFDM.

The schema for the *flexibility space* comprises three sub-classes as depicted in Figure 2. Each sub-class defines internal parameters with key/value pairs. The first class is the ”flexible load”. It describes the core of the *flexibility space* of an industrial load. For example, including but not limited to, it contains the potential power points of operation deviating from a reference operation, the start and end time, the activation and deactivation gradient, the voltage level, and the price. The second class represents the ”dependencies” industrial machines might have. Industrial flexibility can get highly complex as many production systems involve several machines and follow a certain logic for their operation which creates dependencies as expressed in [28]. For instance, some key/value pairs include but are not limited to the trigger flexibility and the amount of times it can be activated. The third class is the description and definition of energy ”storage”. Industrial processes can use internal energy storages (e.g., thermal or material), increasing the complexity of industrial flexibility. Thus, this subclass contains key/value pairs relevant to storage systems including but not limited to the drain, the cost, and the energy loss. Combining the three categories enables a holistic and accurate description of industrial *flexibility space*.

The schema for the *flexible load measure* does not consist of any sub-class as represented in Figure 2. It describes one of the possibilities defined in the *flexibility space* and contains all the information necessary for an activation signal. Thus, it includes load profiles/schedules that the machines and storages must follow when providing industrial flexibility.

4.2 *Company-side platform overview*

The CP is an open and modular digital platform that enables industrial companies to participate in automated bidirectional flexibility services, i.e., market and control of flexibilities [25]. The CP has five core components: the Manufacturing service bus (MSB), Smart connector (SC), Energy flexibility management service (EFMS), Market information retrieval service (MIBS), and marketing component. It primarily utilizes EFDM instances for communication purposes [25].

The MSB is the central component for information distribution, facilitating service orchestration. All components and services in the CP connect to the MSB. The MSB supports various industrial and standardized communication and network protocols [25]. Nevertheless, to address the integration challenge raised by experts when using proprietary industrial protocols, such as Siemens S7 for Programmable logic controllers (PLCs), we developed the SC. It acts as a software integration component translating communication and network protocols. However, it requires extensive configuration of the SC to generate and execute EFDM instances. The EFMS functions as a repository for storing EFDM instances and acts as a broker to communicate requested EFDM instances through the MSB. Two core components facilitate the CP's connection with external services registered in the MP. The MIBS enables retrieval of information from market-sided flexibility services, such as weather data, electricity and gas prices, and their forecasts. The marketing component allows the CP to communicate the industrial flexibility potential to external services using EFDM instances and receive activation signals. These signals are translated into EFDM instances and distributed within the CP using the MSB.

Optional components include individual services (i.e., tailored optimization services), a connector for systems like Production Planning and Control (PPC), Manufacturing execution systems (MES), and Enterprise resource planning (ERP), and Platform Services for business management. We developed an Infrastructure as a service (IaaS) interface to enable independent IaaS providers to connect to the CP, with support for Java, Python, and C# programming languages [29].

The CP offers three modes of operation based on company size, budget, and industrial plants and processes. The default option (1) is private operation, where each company runs its own CP. Another option (2) is to operate separate CPs for individual business units or locations, which can be superordinated to a company-wide platform or operated by a service provider. In the third option (3), a service provider operates the CP. This flexible approach, especially the third option, lowers barriers to participation in industrial DR, particularly for small and medium-sized companies with lower energy consumption or limited Information technology (IT) infrastructure.

4.3 *Market-side platform overview*

To streamline industrial DR activities in energy markets, the MP serves as a digital platform connecting flexibility providers, such as industrial companies, market players like aggregators and SOs, and ancillary information services (e.g., forecasting). Unlike existing solutions that focus primarily on service operations, the MP emphasizes the integration of information about these services. It is a marketplace where service providers can list their services and industrial companies search and book them [30].

The platform already incorporates a range of services, including price forecasting, market-side optimizations, information services, and Local flexibility markets (LFMs) for Distribution system operators (DSOs) that can serve as blueprints for other competing services [25]. Importantly, it's designed to be future-proof, easily accommodating for new services and actors as well as those already available through other platforms. This fosters market transparency and encourages competition [7, 25, 26].

To prevent vendor lock-in, the MP employs standardized communication interfaces, allowing for seamless integration of services from various providers, pending approval [25, 31].

The MP consists of five core internal components. The first is the Identity and access management (IAM) component. It is responsible for identity validation, authorization, and ensuring trust and security. Next is the Service database (S-DB). It stores metadata related to individual services, including properties, descriptions, technical specifications, contact information, and life cycle data. The third is the Application programming interface (API), offering APIs for search, booking, and service administration that interact with the S-DB. Fourth is Discovery Services, which allows companies to locate, compare, and access services using protocols like UDDI or JAXR to minimize human intervention. Lastly, the Graphical user interface (GUI) component complements the API by providing a user-friendly interface for interaction.

To further clarify the interaction dynamics between the CP, the MP, and any external services, consider that when an industrial company identifies a service that meets its needs and books it, subsequent interactions with the chosen service provider bypass the MP. This design choice is deliberate and accomplishes three key objectives: (1) increase operational efficiency by routing direct service communications away from the MP and mitigate the risk of the platform becoming a bottleneck in the provision of services; (2) simplify regulatory compliance as this configuration avoids categorizing the MP as a critical infrastructure; and (3) increase governance flexibility by decoupling the service interactions from the MP. The management of the MP can be undertaken by either a single entity or a multi-organizational consortium, thus offering governance agility.

5. INTERACTIONS IN THE ENERGY SYNCHRONIZATION PLATFORM

We provide an illustrative example of the operation of the ESP. Following the expert-guided design approach, this illustrative example has been evaluated and validated during our design process by experts from research and industry with backgrounds including production processes, software architectures, electricity markets, and smart grids. We limit our example to the following main steps to exemplify the interactions between the different ESP components. These steps are, 5.1 Registering a service at the MP, 5.2 Finding a service, 5.3 Booking a service, 5.4 Using a service. It is important to note that this example focuses on the main steps for simplicity and does not cover all the internal processes involved in the services offered through the MP or the IAM of the MP.

5.1 *Registering a service: External service - MP interaction*

In this step, an external service provider registered in the MP registers its service with the MP. The service provider provides service information through the service-administration-API, which stores it in the S-DB. They provide relevant service information, including the service description, technical specifications, and contact details. Once stored, it enables other ESP users, mainly industrial companies, to easily find the newly registered service in the MP.

5.2 *Finding a service: CP - MP interaction*

In this step, an industrial company wants to market its flexibility with the assistance of an external service provider. For this step, we consider as an example one industrial company with one CP. We illustrate the simplified process in Figure 3 as a sequence diagram with the *getServiceInfo* frame. The industrial company requests information about flexibility marketing services. The MIBS in the CP sends a request to the Search-API of the MP. The Search-API queries the S-DB, selects suitable services, and returns their information to the MIBS. Based on this information, the industrial company can choose the service they prefer for marketing their flexibility.

5.3 *Booking a service: CP - MP - external service interaction*

In our example, once the industrial company decides on a service it wishes to book — in this case, the LFM service to market its industrial flexibility — it takes the following steps as visualized in the simplified process represented in Figure 3, under the *bookService* frame. It is

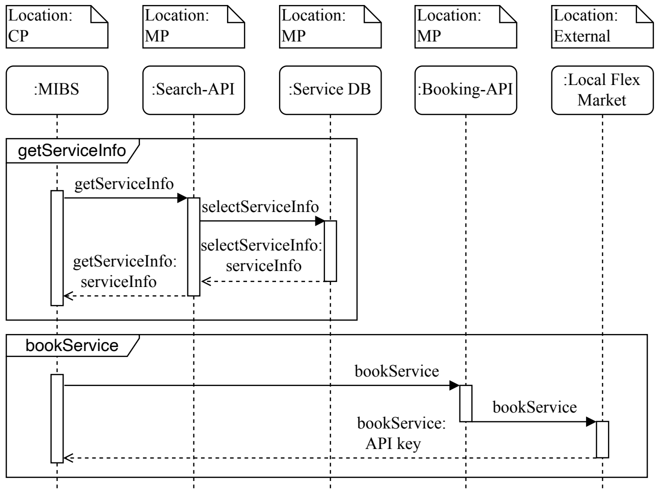


Fig. 3 Simplified service search and booking sequence diagram in the ESP.

important to reiterate that the LFM service is not operated by the MP itself. Instead, a third-party company runs the service and utilizes the MP as a marketplace to offer it.

To initiate the booking, the industrial company sends a booking request from its own MIBS, which is part of its CP, to the MP. This is done through the booking-API provided by the MP. Upon receiving the request, the MP forwards it to the LFM service provider.

The LFM service provider then generates a unique API key tailored explicitly for the industrial company. This key is directly sent back to the company's CP. Equipped with this API key, the industrial company now has all it needs to successfully access and utilize the LFM service.

5.4 *Using a service: CP - external service interaction*

After confirming the booking, the industrial company is set to utilize the selected service, which could involve various activities such as data exchange, energy market transactions, or other specific interactions, depending on what the service entails. To illustrate, we consider an industrial company that operates multiple machines under one CP and aims to market its energy flexibility through an external service provider. In this scenario, the company has chosen the LFM service for this purpose.

The sequence diagram in Figure 4 provides a simplified depiction of the process. It illustrates how the company markets its industrial flexibility, from the shop-floor level to its interaction with the LFM service. The diagram outlines the series of actions and communications that enable the industrial company to fully leverage the LFM service for marketing its energy flexibility effectively.

The process starts within the CP, where the SCs generate EFDM flexibility potential instances. They register them with the EFMS. The industrial company uses a

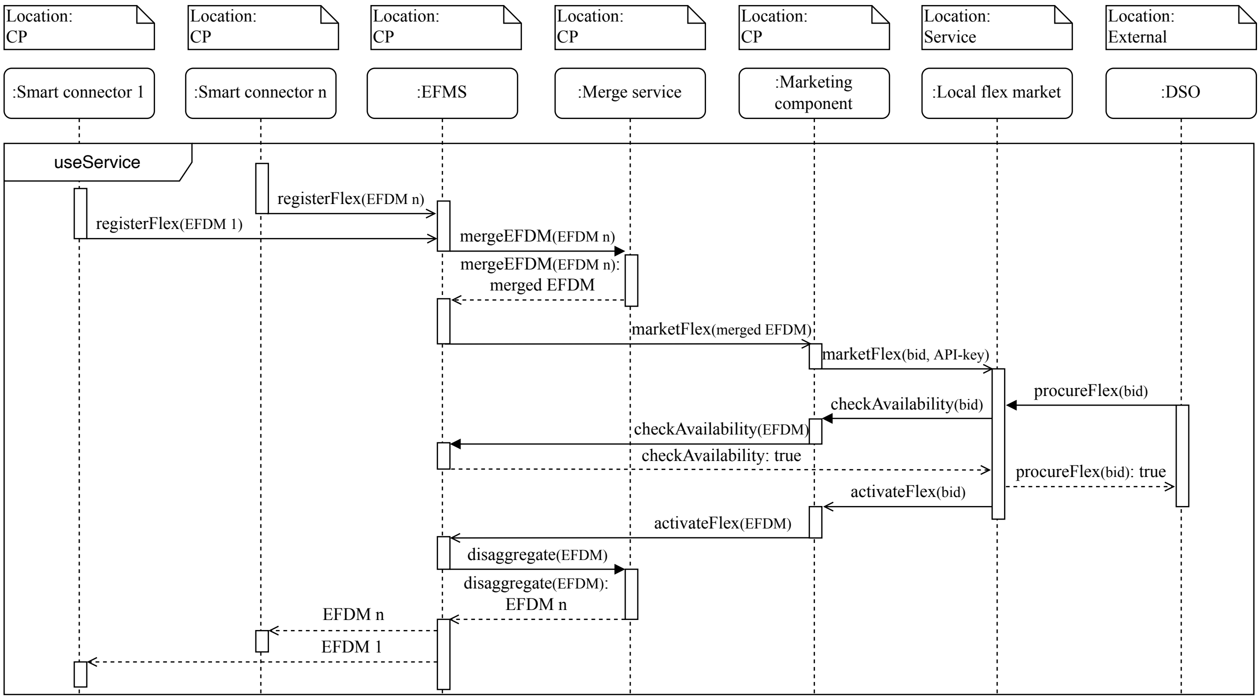


Fig. 4 Simplified industrial flexibility marketing sequence diagram in the ESP.

specialized merge service within the CP to optimize its flexibility potential. This service combines the individual EFDM flexibility instances, thereby creating an aggregate flexibility potential.

With its flexibility offering consolidated, the industrial company uses a marketing component to interface with the LFM. This component takes the information from the EFDM flexibility instances and converts them into offers compatible with the LFM. Then, it forwards them with a specific API key to the LFM.

The DSO, another LFM user, selects the most suitable offer to solve their problem, for example, a congestion problem. Once the DSO confirms the selection, the LFM sends a flexibility activation signal to the CP targetting the marketing component. This component then translates the LFM signal into a corresponding EFDM flexibility load measure instance, which is registered in the EFMS for further action.

Finally, the merge service within the CP receives this new EFDM flexibility load measure instance. It disaggregates the measure into individual components and registers them back in the EFMS. The EFMS, in turn, forwards these disaggregated measures to the relevant SCs, enabling them to implement the control actions required to activate the marketed flexibility requested from the DSO.

6. BENEFITS AND CHALLENGES OF THE ENERGY SYNCHRONIZATION PLATFORM

We implemented the ESP as a small-scale demonstrator to test and gather feedback on the CP and MP design choices and functionalities. Three industrial companies across the Augsburg county in Germany participated. One used the LFM service for explicit DR, while another leveraged an aggregator service for similar purposes. In contrast, the remaining used an industrial flexibility market optimization tool service for implicit DR. This section provides a comprehensive analysis of the advantages and challenges unearthed through the results of the small-scale demonstrator.

6.1 *Benefits of the open architecture*

To achieve the ESP's goal of automated and interoperable industrial energy management, we adopted an open architecture aligned with the four core design requirement categories outlined by Fischer et al. [23] (see Section 2).

The MP's design is inherently flexible, supporting integrating existing and future services. During the demonstration phase, one of the services registered was already pre-existing and used by industrial companies. This openness to integrate even existing services encourages service innovation and market competition, benefiting users by elevating service quality, value, and diversity [31, 32].

The CP's design is equally adaptable, compatible with various industry standards and interfaces, and even accommodates proprietary software not initially designed for energy flexibility. This versatility makes for cost-efficient automated energy management and lowers the barriers for companies to adopt the ESP.

Additionally, our standardized interface between the CP, MP, and external services eliminates the need for company-specific interfaces with service providers, thus preventing long-term vendor lock-in. Given that the cost of re-implementing interfaces is a known issue among participating companies, this feature was particularly well-received during the demonstration phase.

6.2 Benefits following platform adoption

Industrial companies actively engaging with the ESP and its various components and services have reported additional benefits. For instance, by utilizing the EFDM to identify their flexibility potential, these companies gained an in-depth understanding of the interconnectedness of their industrial processes, infrastructure, and energy use. This newfound transparency offers multifaceted advantages:

First, it enables process optimization, peak shaving, precise production cost calculation, and facilitates flexibility marketing as Rösch et al. [31] reports. Second, it aids in sustainable manufacturing. Companies can adjust their energy consumption to align with the availability of renewable energy, thereby reducing CO_2 emissions. Moreover, they can manage fluctuating electricity prices for optimal cost efficiency using the service created by Bahmani et al. [28].

6.3 Challenges in the operation

While the ESP offers various advantages, it is not without challenges, as identified during the demonstration phase.

First, the participating industrial companies noted the investment of time and resources needed to integrate the ESP into their operations, which includes adapting their equipment and gaining proficiency in the new system. Second, the long-term operation of the CP will necessitate ongoing maintenance. Operators must allocate time and resources to update software components, ensuring they remain compatible with evolving industrial standards and interfaces. Lastly, the MP design also presents its own set of challenges. Changes in regulatory frameworks or the entrance of new stakeholders in DR could necessitate updates to management structures or data security protocols.

7. CONCLUSION & OUTLOOK

Industrial flexibility holds significant potential in the evolving energy landscape as a DR resource. However, it faces hurdles such as specialized service requirements, technical limitations, and the need for standardized data models for flexibility information sharing. Addressing these issues, we propose the ESP. This concept comprises two interconnected digital platforms: the CP and the MP, supplemented by the EFDM as a standard data model to articulate industrial flexibility. Our paper delineates the functionalities of each platform and offers an example to illustrate their combined interactions. We also provide insights on the benefits and challenges of a small-scale, practical implementation.

The ESP stands out from existing solutions through its open, service-oriented, and modular architecture, which enables a seamless flow of information from industrial machines to energy market stakeholders. Thus, to further contribute, the following steps will focus on testing a broader implementation of the ESP with several CP and a collection of external services available at the MP with an analysis of specific user interactions and performance.

AKNOWLEDGEMENT

This work has been supported by the Kopernikus-project “SynErgie” by the German Federal Ministry of Education and Research (BMBF) and by the Luxembourg National Research Fund (FNR) and PayPal, PEARL grant reference 13342933/Gilbert Fridgen. The authors gratefully would like to acknowledge the project supervision by the project management organization Projektträger Jülich (PtJ).

REFERENCES

[1] Lopes JA, Madureira A, Matos M, Bessa R, Monteiro V, Afonso J, Santos S, Catalão J, Antunes C, and Magalhães P. The Future of Power Systems: Challenges, Trends, and Upcoming Paradigms. Wiley Interdisciplinary Reviews: Energy and Environment 2019; 9:e368. DOI: 10.1002/wene.368

[2] Dumbs C, Jarry G, Willems M, Gross T, Larsen A, and Wagner T. Market models for local flexibility procurement: InterFlex' experience and main challenges. 2019

[3] Heymann F and Galus MD. Digital platforms in the energy sector – A menu of regulatory options for policy makers. 2022 IEEE 21st Mediterranean Electrotechnical Conference (MELECON). 2022 :1045–9. DOI: 10.1109/MELECON53508.2022.9843059

[4] Eurostat. Energy Statistics - an Overview. 2022

[5] International Energy Agency. Germany. 2022

[6] Siddiquee SS, Howard B, Bruton K, Brem A, and O'Sullivan DT. Progress in demand response and it's industrial applications. Frontiers in Energy Research 2021; 9:673176

[7] Bauer D, Abele E, Ahrens R, Bauernhansl T, Fridgen G, Jarke M, Keller F, Keller R, Pullmann J, Reiners R, Reinhart G, Schel D, Schöpf M, Schraml P, and Simon P. Flexible IT-platform to Synchronize Energy Demands with Volatile Markets. Procedia CIRP. Ed. by Tseng MM, Tsai HY, and Wang Y. Vol. 63. 2017 :318–23. DOI: 10.1016/j.procir.2017.03.088

[8] Singh M, Jiao J, Klobasa M, and Frietsch R. Emergence of digital and X-as-a-service (XAAS) platforms in German energy sector. IAEE International Online Conference. 2021

[9] Bhagwan N and Evans M. A review of industry 4.0 technologies used in the production of energy in China, Germany, and South Africa. Renewable and Sustainable Energy Reviews 2023; 173:113075

[10] Zancanella P, Bertoldi P, and Kiss B. Demand Response Status in EU Member States. Policy Assessment. Luxembourg (Luxembourg): Publications Office of the European Union, 2016

[11] Murthy Balijepalli V, Pradhan V, and Khaparde S. Review of Demand Response under Smart Grid Paradigm. ISGT2011-India. IEEE, 2011 :236–43. DOI: 10.1109/ISET-India.2011.6145388

[12] Shoreh MH, Siano P, Shafie-khah M, Loia V, and Catalão JPS. A Survey of Industrial Applications of Demand Response. Electric Power Systems Research 2016; 141:31–49. DOI: 10.1016/j.epsr.2016.07.008

[13] The OpenADR Alliance. OpenADR - Connecting Smart Energy to the Grid. Accessed 20/02/2023. 2002. Available from: https://www.openadr.org/

[14] The Green Button Alliance. Green Button - Open Energy Data. Accessed 27/02/2023. 2011. Available from: https://www.energy.gov/data/green-button

[15] Panetto H, Zdravkovic M, Jardim-Goncalves R, Romero D, Cecil J, and Mezgár I. New Perspectives for the Future Interoperable Enterprise Systems. Computers in Industry 2016; 79:47–63. DOI: 10.1016/j.compind.2015.08.001

[16] Constantinides P, Henfridsson O, and Parker G. Platforms and Infrastructures in the Digital Age. Information Systems Research 2018 May; 29. DOI: 10.1287/isre.2018.0794

[17] Kloppenburg S and Boekelo M. Digital platforms and the future of energy provisioning: Promises and perils for the next phase of the energy transition. Energy Research & Social Science 2019; 49:68–73

[18] Duda S, Kaymakci C, Köberlein J, Wenninger S, Haubner T, Sauer A, and Schilp J. Structuring the Digital Energy Platform Jungle: Development of a Multi-Layer Taxonomy and Implications for Practice. Proceedings of the Conference on Production Systems and Logistics: CPSL 2022. Hannover: publish-Ing. 2022 :42–51

[19] Duda S, Fabri L, Kaymakci C, Wenninger S, and Sauer A. Deriving Digital Energy Platform Archetypes for Manufacturing – A Data-Driven Clustering Approach. Proceedings of the Conference on Production Systems and Logistics: CPSL 2023 - 1. Ed. by Herberger D, Hübner M, and Stich V. publish-Ing., 2023 :54–64. DOI: 10.15488/13424

[20] Drewel M, Özcan L, Gausemeier J, and Dumitrescu R. Platform patterns—using proven principles to develop digital platforms. Journal of the Knowledge Economy 2021; 12:519–43

[21] Göbel H and Cronholm S. Nascent Design Principles Enabling Digital Service Platforms. Vol. 9661. 2016 May :52–67. DOI: 10.1007/978-3-319-39294-3_4

[22] Blaschke M, Riss U, Haki K, and Aier S. Design principles for digital value co-creation networks: a service-dominant logic perspective. Electronic Markets 2019; 29:443–72

[23] Fischer S, Lohrenz L, Lattemann C, and Robra-Bissantz S. Critical Design Factors for Digital Service Platforms -A Literature Review. ECIS 2020 Research Papers. 2020 May

[24] Hevner A, March S, Park J, and Ram S. Design Science in Information Systems Research. Management Information Systems Quarterly 2004; 28:75–105. DOI: 10.2307/25148625

[25] Schilp J, Bank L, Köberlein J, Bauernhansl T, Sauer A, Schlereth A, Fridgen G, Potenciano Menci S, Weigold M, Lindner M, and Oeder A. Konzept der Energiesynchronisationsplattform. Diskussionspapiere V4. Executive Summary [Concept of the Energy Synchronization Platform. Discussion Papers v4. Executive Summary]. Discussion Paper. 2021. DOI: 10.24406/IGCV-N-642368

[26] Schott P, Sedlmeir J, Strobel N, Weber T, Fridgen G, and Abele E. A Generic Data Model for Describing Flexibility in Power Markets. Energies 2019; 12:1893. DOI: 10.3390/en12101893

[27] EFDM development team. EFDM - Project Repository. 2023. Available from: https://git.ptw.maschinenbau.tu-darmstadt.de/eta-fabrik/public/energy_flexibility_data_model

[28] Bahmani R, van Stiphoudt C, Menci SP, Schöpf M, and Fridgen G. Optimal Industrial Flexibility Scheduling Based on Generic Data Format. Energy Informatics 2022; 5:26. DOI: 10.1186/s42162-022-00198-4

[29] VFK development team. Virtual Fort Knox Research Repository. 2019

[30] Sauer A, Buhl H, Mitsos A, and Weigold M, eds. Energieflexibilität in der deutschen Industrie. Band 2: Markt- und Stromsystem, Managementsysteme und Technologien energieflexibler Fabriken [Energy flexibility in German industry. Volume 2: Market and power systems, management systems and technologies of energy flexible factories]. Fraunhofer Verlag, 2022

[31] Rösch M, Bauer D, Haupt L, Keller R, Bauernhansl T, Fridgen G, Reinhart G, and Sauer A. Harnessing the Full Potential of Industrial Demand-Side Flexibility: An End-to-End Approach Connecting Machines with Markets through Service-Oriented IT Platforms. Applied Sciences 2019; 9:3796. DOI: 10.3390/app9183796

[32] Evans D and Schmalensee R. Failure to Launch: Critical Mass in Platform Businesses. Review of Network Economics 2010; 9. DOI: 10.2202/1446-9022.1256

A.3.3 Research Paper 3 – *Scalability and replicability analysis of grid management services in low voltage networks in local flexibility markets: an Interflex analysis*

Scalability and Replicability Analysis of Grid Management Services in Low Voltage Networks in Local Flexibility Markets: an InterFlex analysis

Sergio Potenciano Menci* §, Barbara Herndler*, Friederich Kupzog*, Marisca Zweistra†, Robert Steegh‡ and Marcel Willems‡

*Electrical Energy Systems, Austrian Institute of Technology (AIT), Vienna, Austria
Email: [Barbara.Herndler, Friederich.Kupzog]@ait.ac.at

†Elaad, Arnhem, Netherlands, Email: marisca.zweistra@elaad.nl

‡Smart Grid, Enexis, Eindhoven, Netherlands, Email: [Robert.Steegh, Marcel.Willems]@enexis.nl

§SnT - Interdisciplinary Center for Security, Reliability and Trust, University of Luxembourg, Luxembourg, Luxembourg, Email: sergio.potenciano-menci@uni.lu

***Abstract*—The numerous changes in the power grid, due to the current and foreseeable increase of Renewable Energy Sources (RES) within the electrical network has resulted in a new perception of the modern distribution network. A key aspect in this regard is the efficient utilisation of flexibility in demand and generation. This paper focuses on the impact of RES when used to provide flexibility for grid management services. In the European project InterFlex, grid management services were offered in local flexibility markets in distribution networks. The results of the Scalability and Replicability Analysis (SRA) of the smart grid Dutch demonstration is presented. Furthermore, the challenges of replicating and analysing a real system based on a high number of interconnected tools, where seasonality effects and realistic large scale deployments which are to be forecasted, are considered and discussed.**

***Index Terms*—Aggregation, Grid Management, Flexibility impact, Smart Grid, Scalability, Replicability**

I. Introduction

The continuous rise of integration of renewable energy resources (RES) in the distribution grid [1]–[3] has also caused an increase in the number of challenges within the network, such as (under or over) voltage violation, hosting capacity restrictions, network congestion or reverse power flows. The occurrence of these problems is expected to become more frequent and accentuated as more RES are integrated across the distribution system. This scaling effect of network devices nonetheless, has paved way for the opportunity for the incorporation of new business models, such as virtual power plants (VPP) to be used for a wider variety of services [4]. One of these services includes the provision of flexibility, control and steering of the source/s as and when they are required by the distribution system operator (DSO) or the transmission system operator (TSO). This provides network operators with the necessary tools for network operation using smart grid functions, without resorting to traditional network reinforcement methods. Hence, it is important to remark that the main issues in the distribution system, both currently and in the future, are a problem of scaling, since more devices are to be integrated within the system. This topic, in addition to the replication analysis, has been analyzed over several European projects, such as InteGrid [5] and InterFlex [6]. The latter one, InterFlex, is a Horizon 2020 project which aims to ease the integration of renewables into the distribution grid and promote their use as local flexibility sources to provide support services to the DSO through aggregation, autonomous functions or direct control means of flexibilities. The different control types and source integration were demonstrated across six demonstrations, located in five countries. Within this scope, this paper aims to present an analysis of the scaling and replication impact and lessons learnt based on the outcomes of the smart grid demonstration conducted in the Netherlands [7], where a local flexibility market is created for aggregators to provide their energy sources, photo-voltaic (PV), electric vehicles (EVs), and a smart storage unit (SSU) to the DSO for congestion management [8] in low voltage networks. It uses as a foundation the Universal Smart Energy Framework (USEF) [9]. The basis of this framework is to exchange the operation schedules of the different aggregators with the DSO to ensure that there is no future congestion in the distribution grid. In the case that network congestion exists, this framework is used to quantify the volume of flexibility the DSO would require to alleviate such constraints.

This paper is structured as follows. Section I provides the context and aim of the paper. Section II exposes the methodology used for the SRA and the system architecture. This includes a brief description of the different simulation tools used. Section III provides an in-depth view of the internal simulation functions, through the different modules and scenarios considered. Section IV exposes the combination

Funding - The research leading to this work is being carried out as a part of the ÎnterFlex project, which received funding from the European Union's Horizon 2020 Framework Programme for Research and Innovation under grant agreement No. 731289

978-1-6654-3597-0/21/$31.00 ©2021 IEEE

of scalability and replicability results obtained. Lastly, section V provides a general conclusion and lessons learnt.

II. Methodology

The SRA methodology used for the analysis is based on a five step process adjusted according to the specific DSO requirements. The necessary assumptions are made to define relevant future scenarios, based on an increase of DER implementation in the network. In order to conduct the SRA, the real system (demo site) needs to be replicated into a simulation-testing environment, as the system itself is in production and deals with real operation. The first step, therefore, is to develop a representation of the system architecture to understand the data flow and the main components, shown in Figure 1.

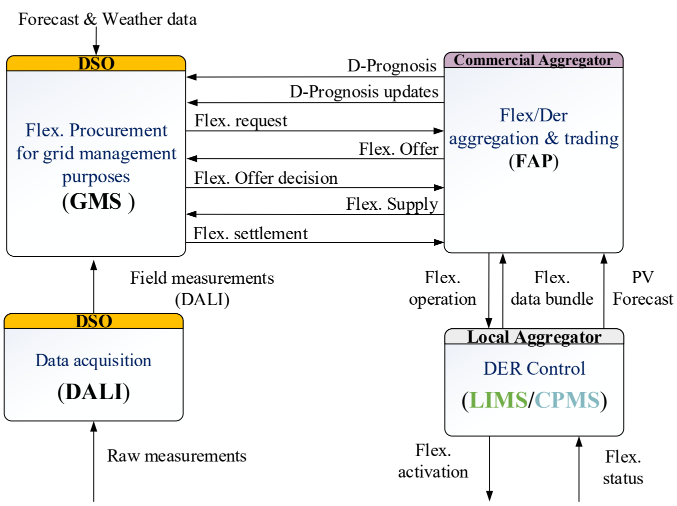


Fig. 1. NL demo architecture and data flows.

Based on the architecture, four main components are required. The Distribution Automation Light (DALI) are the field devices which are used to collect the raw measurements (voltages, power, current, etc.). The DSO saves these measurements and uses them as input for the Grid Management System (GMS). The GMS is able to provide management schemes within both the intra-day market as well as day-ahead operation, the latter being the most often used smart function. The aim of this tool is to provide flex procurement with the aggregators for congestion management purposes. This tool consists of several internal modules which are interconnected and calculates the process according to the received data. The aggregators are, likewise, aggregated. The flexibility sources such as the PV, EV and SSU are locally aggregated according to type. The Local Infrastructure Management System (LIMS) is responsible for the aggregation of any non-EV flexibility, whereas the Charging Point Management System (CPMS) is specialized in EV aggregation. The availability of these flexibility units, in addition to how the flexibilities are to be operated, is then exchanged with the commercial aggregator. This information is then wrapped with a layer of trading in order to create the D-prognosis, an aggregation schedule of operation of the units based on 96 Program Time Units (PTUs) over a 24 hour period. This results in capacity trading, which uses capacity as the product. The D-prognosis is created only for the DSO's defined congestion points. The negotiation between the commercial aggregator and the DSO is conducted via the Flexibility Aggregator Platform (FAP). Once the D-prognosis, in addition to the internal DSO load forecast, is computed by the DSO using the GMS, and if there is a need for flexibility in any of the congestion points, the DSO and the commercial aggregation begin the flexibility trading negotiation process. These processes follow a market timetable as shown in Figure 2.

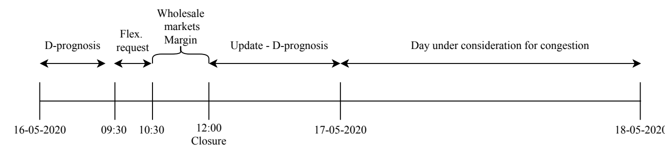


Fig. 2. Market structure [10].

The second step of the methodology consists of the identification of the network locations where the system will be tested. The network, provided by the local DSO Enexis, consists of two radial networks located in Strijp S, The Netherlands. The first is comprised of a total of eight feeders, whereas the second consists of 7 feeders. In the network there are four congestion points established by the DSO. These congestion points are distributed with one at each secondary substation and two at the point of connection of the flexibilities. A representative network diagram is shown in Figure 3, where the congestion points are marked in red. These two low voltage networks define the local flexibility market scope in this paper.

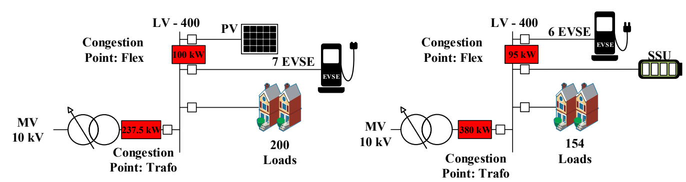


Fig. 3. Simplified Strijp S distribution topology.

The third step is to replicate the logic of the system. This is done through Python modules, further explained in section III. This replication however, is not a one-to-one replication due to the complexity of the internal GMS, FAP and LIMS/CPMS modules. Privacy and availability of data exchange or system logic is a barrier to the replication process as they are commercial products. Hence, the approach followed consists of a core framework with two modules. The GMS is replicated with the focus on day-ahead operation, considering offers made until the 10:30 "gate closure". It includes a load forecasting module and an evaluation tool for the D-prognosis. The second module is the commercial aggregation module, mimicking the FAP system. The D-prognoses are created based on the flexibilities available and shared with the DSO. The data provided to the commercial aggregator is generated through several forecasting modules and is explained in section III.

The fourth step, is to create relevant scenarios in collaboration with the DSO. In this step, it is necessary to define the scope, assumptions and intentions for the scalability and replicability. The scope defines the aim of the analysis which is to assess the impact of flexibility used in local markets on the network. The assumptions made allow for the downsizing of the system in order to bring the focus toward the main components, the GMS and the FAP. For the purpose of this study, the scalability is defined as the increase in the magnitude of the DER technologies using different scaling factors. The replication is defined based on two dimensions. A *time dimension*, where seasonal analyses are considered, simulating one week every season and a *location dimension*, where flexibilities are placed in various locations. To achieve the former, a third theoretical substation is created. It takes as a foundation the first substation information and data, with the inclusion of the SSU from the second substation. The scenarios are simulated for an entire week using 96 PUTs or time steps per day, thus 672 for a week following the USEF specifications [9].

Finally, the last step of the methodology is dedicated to simulations and analysis of the future scenarios developed.

III. Modules and Scenarios

The environment for the simulations is based on several modules. The GSM module is separated into two internal modules: firstly the substation module, which is used for congestion management calculations and secondly the load forecasting module, which is used to define load demand. The commercial aggregator module is likewise separated, however in this case three independent modules are constructed. These modules are responsible for the forecasting calculations of the PV, EV and the SSU, which can later be used as flexibility sources. The PV module is, however, only developed for the aggregator as for the DSO it is out of the scope in this analysis.

A. Households - load module

The load module has the objective of generating unique profiles for each of the loads considered in each substation. This results in 200 unique and realistic profiles for substation-1 and 194 for substation-2. Substation-3 uses the same profiles as substation-1. The load module constructs load profiles based on the available information from the USEF foundation repository [11] and the information provided by the DSO. This results in a load-profile example as shown in Figure 4.

Once the baseline generation profile is created, the result is validated for network data coherence with the available measurements at the beginning of the load feeder. For the simulations, a scaling factor of $k = 1.3$ is used and is based on the potential increase of load electrification as shown in [12].

B. Photovoltaic - PV module

The PV generation module provides a generation forecast. This is carried out in two steps. The first step is to calculate the maximum PV peak power to which the current installation

Fig. 4. USEF load profile adjusted to DSO data.

can be scaled. Due to the location of the demo there is no possibility to include distributed PV at any other locations. This step uses the existing PV plant information, its peak power and the area location, which is based on the Graphical Information System (GIS) of the rooftop of a parking garage. The current PV plant consists of two strings of 134 kW_p, whereas the scaled version reaches up to 303.8 kW_p.

Once the maximum amount of PV is determined, the forecast tool calculates the annual power production of each of the PV farms. The data for the forecast is based on the historical available data from the location (between 2007 and 2016) using the Joint Research Center tool [13] with 14% losses and PV crystalline silicon as input parameters.

C. Electric vehicles - EV public module

The forecasting of EV charging uses historical data provided by the CPMS, Elaad [14]. The data consists of a sets of real measurements for various public charging points around The Netherlands which were collected in 2016 in addition to specific data from the demo site collected in 2019. In order to conduct the quantification of the potential scaling in The Netherlands and thereafter extrapolate it to the demo site, an extensive analysis is conducted based on the available documentation as in [15]–[17]. Using this potential scaling information, the forecasting system provides a weekly forecast detailing the *total charging time* [h], the *total energy use* [kWh], the *max peak power* [kW] and the *weekly occurrence* [%]. This *weekly occurrence* represents the likelihood of charging. An example of a charging forecast for 1 day is given in Figure 5. The orange forecast represents the charging periods where only *selected periods* of the charging stations are under operation. The blue forecasts represent the worst case scenario, using all periods with higher than "1%" *weekly occurrence*. It should be noted that it has been assumed that all charging stations operate at the same time creating a worst case scenario, although the forecast tool can create individual schedules for each public charging station.

The impact of EV seasonality is explored primarily during the winter months due to there being a higher overall energy demand in comparison with other seasons of the year. The forecast provided however is not weighted with the EV sea-

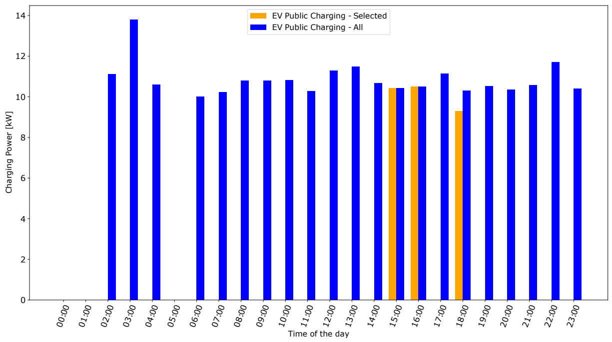


Fig. 5. EV forecast for 1 day.

sons. This is due to a low fluctuation, less than 7.54% between the maximum and minimum peak power.

D. Battery - SSU module

The SSU module uses a simple maximization strategy based on price. This replicates the current aggregators' strategies, where it seeks to charge the battery at the lowest prices and discharge at the highest price. The price signals, since there is no real market connection in the testing, are taken from the available data history of EPEX (day-ahead) prices [18]. The battery model considers charging and discharging efficiencies. The scaling of the battery can be done via two dimensions, either by scaling the power rating at the Point of Coupling (PoC) and/or scaling the size of the battery packs. The latter one is chosen in order to create a longer impact scenario due to its larger storage capacity, as suggested by the DSO since the power specification is considered adequate. For simulation purposes, it is considered, for simplicity, to consider a minimum of one complete cycle (charging and discharging) per day. Figure 6, represents an example of the battery operation for a one day period.

E. Substations module

The substation module consists of an aggregator and data parser module. It mimics the GMS operation, which is to receive, process and compute data for the DSO. However, for the simulations presented in this paper, it was not necessary to calculate the computation time for parsing and decision making, as was shown in the information and communication technology SRA [19]. The output of this module provides the time and volume schedule of flexibility required in each of the congestion points, replicating the real process. Nonetheless, this module is severely downsized from the real GMS, since it can only operate in day-ahead (as per the objective) and eliminated all other complex communication services which is present in USEF.

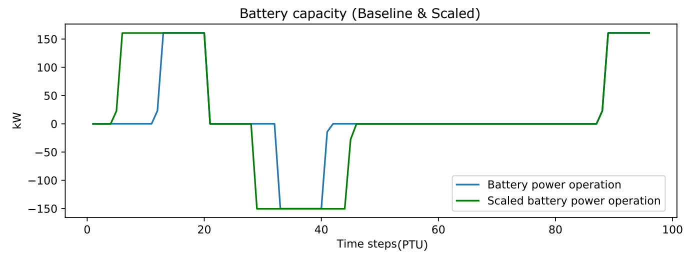


Fig. 6. Battery operation example for 1 entire day or 96 PTUs used.

F. Scenarios

A total of five main scenarios are created and tested for each of the substations. The first scenario is always the baseline scenario , based on the existing demonstration assets and their properties, to which future comparisons can be made. The scenarios are based on a combination of different scaled versions of EVs, PV and SSU, with the focus on EV penetration. For each of the scenarios, the load profiles are scaled based on the original profiles calculated and applied throughout each scenario.

In case of the EV variation, for the *baseline* and *x.1* scenarios, only partial use of the charging points are implemented as opposed to using all those that are available and thereby representing the current operation status. The remainder of EV scenarios consider the case where all charging points in the network are in use and are operating at their maximum power. A summary of the scenarios is shown in Table I.

The scenarios previously exposed are used as the basis for the scalability analysis scenarios, using specific data sets for the flexibility sources (PV, EV and SSU). However, they are also used for the replicability analysis. *Time replicability*, is evaluated through the same scenarios but using different data sets for the flexibility sources. *Location replicability*, also

TABLE I

LIST OF SCENARIOS BASED ON SUBSTATIONS AND SOURCES INCLUDED FOR THE SIMULATIONS.

Substation	Source	Baseline	Scenario x.1	Scenario x.2	Scenario x.3	Scenario x.4
1	Load	200 unique profiles				
1	EV	7 to 15 kW	22 kW	7 to 15 kW (all chargers)	22 kW (all chargers)	50 kW (all chargers)
1	PV	2 strings of 134 kW_p	1 string of 303.8 kW_p			
2	Load	156 unique profiles =! 200 unique profiles				
2	EV	7 to 15 kW	22 kW	7 to 15 kW (all chargers)	22 kW (all chargers)	50 kW (all chargers)
2	SSU	315kWh-255 kVA inverter/PoC 173 kVA				
3	Load	200 unique profiles == substation 1				
3	EV	7 to 15 kW	22 kW	7 to 15 kW (all chargers)	22 kW (all chargers)	50 kW (all chargers)
3	PV	2 strings of 134 kW_p	1 string of 303.8 kW_p			
3	SSU	315kWh-255 kVA inverter/PoC 173 kVA				

considers scalability scenarios and *time replicability* simultaneously within it simulations. Furthermore, the specific data sets for the scalability analysis considers the week in which PV injection was the highest, while for the replicability, one representative week from each season is selected as data input.

IV. Results

The results presented within this section are obtained from the 75 simulations executed.

Only the results for *baseline* and *scenario x.3* are presented here as they represent the most likely future scenario to be faced. While, on the one hand, the baseline represents the current operation without a high penetration or use of DER, on the other hand, the specific scenario *x.3* presents a moderate-high penetration of DER, increased SSU capacity and higher penetration of EV. The results are divided into two sections. The scalability section focuses on the impact of increase flexibility source and load demand whereas the replicability section explores the impact of seasonal behaviour, specially for PV due to its large power variation throughout the year. For both sections, three substations are included, two being actual demo substations and the third as a fictitious representation.

The results focus on the output from the replicated GMS which identifies and quantifies the potential issues when the D-prognosis from the commercial aggregator goes beyond the established threshold of the network. This paper presents only the identification of congestion points when the thresholds are exceeded, which results in the number of points which requires flexibility procurement between the DSO and aggregators. Total volume of flexibility needed for solving the potential congestion is addressed in [19]. Other specific aspects such as traditional reinforcement costs or flexibility costs fall out of the scope of this paper. The results are collected and later exposed in tables using the USEF communication exchange specific protocol notation, are as follows,

- *Available - PTUs* represents the number of PTUs [1] facing no constraints. This means that the commercial aggregation, and thereby the local aggregators, can change their operational schedule to more aggressive ones.
- *Reduce - PTUs* represent the number of PTUs facing constraints. Thus, the DSO needs to activate flexibility within those PTUs and therefore, needs participate in negotiation with the commercial aggregator through the FAP, for flexibility procurement. Within our simulations, this procurement it is not explored, as the strategies from the commercial and local aggregator are private and cannot be disclosed and therefore is out of the scope of this paper.
- *Congestion Points* represent those points where the calculations take place. As previously defined, there are a total of 2 congestion points per substations.

A. Scalability

The scalability results are collected and exposed in Table II. These results are obtained from the testing conducted over the week where there is maximum PV injection (July) from the PV forecast created. It uses the nominal conditions for the SSU. With regard to the EVs, normal operation and scaled versions are considered. Lastly, a scaled version of the consumer loads is also considered.

[1]PTU: Program Time Unit, 15 min

TABLE II
Scalability results collection for substations (sb) 1, 2 and 3.

	Trafo_baseline	Flex_baseline	Trafo_1.3	Flex_1.3
Available PTUs Sb1	100%	72%	83,5%	64,7%
Reduce PTUs Sb1	0%	28%	16,5%	35,3%
Available PTUs Sb2	100%	83,3%	100%	20,2%
Reduce PTUs Sb2	0%	16,7%	0%	79,8%
Available PTUs Sb3	100%	60,6%	81,1%	59,2%
Reduce PTUs Sb3	0%	39,4%	18,9%	40,8%

B. Replicability (time)

The replicability (seasonal) results are collected and exposed in Tables III, IV and V. Each season is evaluated with a representative week of a representative month.

TABLE III
Replicability results for substation 1 comparison.

		Trafo_Baseline	Trafo_Flex	Trafo_1.3	Flex_1.3
Jan	Available PTUs	100%	100%	16,7%	16,7%
	Reduce PTUS	0%	0%	83,3%	83,3%
May	Available PTUs	100%	74,1%	60,7%	17,7%
	Reduce PTUS	0%	25,9%	39,3&	82,3%
Jul	Available PTUs	100%	74,6%	17%	15,5%
	Reduce PTUS	0%	25,4%	83%	84,5%
Oct	Available PTUs	100%	79,3%	16,8%	15,2%
	Reduce PTUS	0%	20,7%	83,2%	84,8%

TABLE IV
Replicability results for substation 2 comparison.

		Trafo_Baseline	Trafo_Flex	Trafo_1.3	Flex_1.3
Jan	Available PTUs	99,7%	82,1%	23,8%	11,9%
	Reduce PTUS	0,3%	17,9%	76,2%	88,1%
May	Available PTUs	98,8%	82,1%	23,2%	13,1%
	Reduce PTUS	1,2%	17,9%	76,8%	86,9%
Jul	Available PTUs	99,6%	83,3%	22,6%	12,5%
	Reduce PTUS	0,4%	16,7%	77,4%	87,5%
Sep	Available PTUs	98,5%	82,1%	23,1%	13,1%
	Reduce PTUS	1,5%	17,9%	76,9%	86,9%

TABLE V
Replicability results for substation 3 comparison.

		Trafo_Baseline	Trafo_Flex	Trafo_1.3	Flex_1.3
Jan	Available PTUs	98,75%	82,1%	18%	11,9%
	Reduce PTUS	1,3%	17,9%	82%	88,1%
May	Available PTUs	99,9%	62,6%	22,2%	16,2%
	Reduce PTUS	0,1%	37,4%	77,8%	83,8%
Jul	Available PTUs	100%	60,1%	18,5%	8,8%
	Reduce PTUS	0%	39,9%	81,5%	91,2%
Oct	Available PTUs	100%	64,9%	18,3%	12,6%
	Reduce PTUS	0%	35,1%	81,7%	87,4%

C. Analysis

Based on the results, it is interesting to derive that even in some cases, such as the baseline scenarios, that by the potential increase of load, congestion issues are already present with the current state of penetration of DER. This is specially clear in the results shown in substation-2, where there is a lack of pure injection to compensate this demand increase in addition to a potential battery operation, which depending on the operation, can act as load.

However, the most interesting results are observed when analysing substation-3, as there is a combination of assets. Most of the evaluated scenarios shows that it performs worse when compared to the other two substations. This is due to the mismatch of upwards and downwards flexibilities. It is clear that the seasonal behaviour has a significant impact on the network. The load demand is also impacted by seasonal changes, however when using average consumption profiles the impact of these fluctuations is reduced. Furthermore, this can be seen in Figure 7. The limited injection from the PV leads to high peaks of demand and injection from the battery.

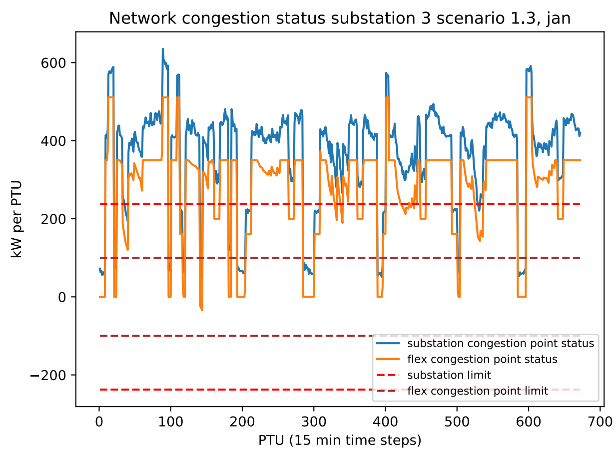


Fig. 7. Network congestion results of substation-3 over a week in January.

Withal, the results obtained follow the same principle, although there is a strategy from the aggregation for profit maximization, this goes against the network optimization creating, in some cases, congestion with even more than 87% of the time in a one week period. Either the commercial aggregator tries to compensate the upwards and downward flexibilities or follows a less aggressive strategy.

V. Conclusions & Lessons learnt

Although the replication process is a simple model and there is room for improvement especially with the forecast systems, the approach is still able to capture the essence of the system behaviour. Flexibility procurement between a DSO and aggregators is possible when there is a need. Until there is no need, although with small DER penetration, there is almost no congestion, as the network is majorly over-dimensioned. Hence aggregators' operation in today's networks, despite the accuracy of the system obtained from the different forecasting systems, has almost no major impact. Contrariwise, the moment there is a high penetration, due to a larger pool of DER, there is a complete necessity of a GMS tool in order to keep the safe and secure operation of the network as shown in section IV. Aggregator's strategies have by far the highest impact as their operation will rule how the network will be operated. Hence flexibility procurement is needed. The lessons learnt extracted through this entire process are several. There is a current over-dimension of the central storage unit when it is only used for congestion management purposes. This leads to a high impact into the network where it can either hurdle the rest of the flexibilities or remarkably compensate them. Forecasting systems from aggregators or DSOs, since they are not 100% accurate, are definitely recommended to establish a DSO-Aggregator communication system. However, the clear step forward lies with the DSO, who has the option to deal with identified congestion points by the creation of schemes where grid-supporting flexibilities can be aggregated. This approach would ease aggregator investments but also provides the DSO with alternatives to network reinforcement for grid operation.

References

[1] European Comission, "Eurostat: Your key to european statistics." https://ec.europa.eu/eurostat/web/main/home. [Online; accessed 11 September 2020].

[2] D. Gielen, L. Janeiro, L. Gutierrez, G. Prakash, and D. Saygin, *Renewable Energy for the European Union, Based on REmap analysis*. European Union and IRENA, 2018. ISBN: 978-92-9260-007-5.

[3] H. Ritchie, "Renewable energy," *Our World in Data*, 2017. https://ourworldindata.org/renewable-energy.

[4] K. O. Adu-Kankam and L. M. Camarinha-Matos, "Towards collaborative virtual power plants: Trends and convergence," *Sustainable Energy, Grids and Networks*, vol. 16, pp. 217 – 230, 2018.

[5] "H2020 Project InteGrid." https://cordis.europa.eu/project/id/731218. [Online; accessed 11 September 2020].

[6] "H2020 Project InterFlex." https://cordis.europa.eu/project/id/731289. [Online; accessed 11 September 2020].

[7] "InterFlex Dutch Demonstrator." https://interflex-h2020.com/interflex/project-demonstrators/netherlands-demonstration/. [Online; accessed 11 September 2020].

[8] R. Fonteijn, T. Van Cuijk, P. H. Nguyen, J. Morren, and J. G. Slootweg, "Flexibility for congestion management: A demonstration of a multi-mechanism approach," in *2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, pp. 1–6, 2018.

[9] "Universal Smart Energy Framework." https://www.usef.energy/. [Online; accessed 11 September 2020].

[10] M. Willems, "Grid Management System (GMS)." https://futureofcharging.com/wp-content/uploads/2019/03/Site-visit-Interflex-NKL-bezoek-20-1-small.pdf. [Online; accessed 10 April 2021].

[11] "Universal Smart Energy Framework Data." https://github.com/USEF-Foundation/usef-implementation.ri.usef.energy. [Online; accessed 11 September 2020].

[12] S. Jos, G. Pieter, d. J. Jeroen, v. W. Werner, and M. Michiel, "The demand for flexibility of the power system in the netherlands, 2015-2050," resreport ECN-E-17-037, FLEXNET Project, Nov. 2017.

[13] "JRC Photovoltaic Geographical Information System (PVGIS) - European Commission ." https://re.jrc.ec.europa.eu/pvg_tools/en/#PVP. [Online; accessed 11 September 2020].

[14] "Elaad data analytics." https://www.elaad.nl/research/data-analytics/. [Online; accessed 11 September 2020].

[15] Netherlands Enterprise Agency, "Statistics electric vehicles in the netherlands (up to and including February 2019)," resreport, Ministry of Infrastructure and Water Management, Mar. 2019. [Online; accessed 11 September 2020].

[16] K. N. I. for Transport Policy Analysis, "Key transport figures 2018," resreport, Ministry of Infrastructure and Water Management, Oct. 2018.

[17] "Electric vehicle Database." https://ev-database.org/. [Online; accessed 11 September 2020].

[18] "EPEX SPOT." https://www.epexspot.com/en. [Online; accessed 11 September 2020].

[19] S. Potenciano Menci, B. Herndler, F. Mesureur, A. Ahmadifar, and A. Izimova, "D3.8 scalability and replicability analysis (sra) for all use cases," resreport, InterFlex Project, Dec. 2019.

A.3.4 Research Paper 4 – *Functional scalability and replicability analysis for smart grid functions: the InteGrid project approach*

energies

Article

Functional Scalability and Replicability Analysis for Smart Grid Functions: The InteGrid Project Approach

Sergio Potenciano Menci [1,2,*,†], Ricardo J. Bessa [3,*,†], Barbara Herndler [1,†], Clemens Korner [1,†], Bharath-Varsh Rao [1], Fabian Leimgruber [1], André A. Madureira [3], David Rua [3], Fábio Coelho [3], João V. Silva [3,†], José R. Andrade [3,†], Gil Sampaio [3], Henrique Teixeira [3,†], Micael Simões [3,†], João Viana [3], Luiz Oliveira [3], Diogo Castro [3], Uršula Krisper [4] and Ricardo André [5]

1 Austrian Institute of Technology (AIT), Electrical Energy Systems, Giefinggasse 4, 1210 Wien, Austria; barbara.herndler@ait.ac.at (B.H.); Clemens.Korner@ait.ac.at (C.K.); bharath-varsh.rao@ait.ac.at (B.-V.R.); Fabian.Leimgruber@ait.ac.at (F.L.)
2 SnT—Interdisciplinary Center for Security, Reliability and Trust, University of Luxembourg, L-1855 Luxembourg, Luxembourg
3 INESC TEC—Institute for Systems and Computer Engineering, Technology and Science, 4200-465 Porto, Portugal; andre.g.madureira@inesctec.pt (A.A.M.); david.e.rua@inesctec.pt (D.R.); fabio.a.coelho@inesctec.pt (F.C.); joao.v.silva@inesctec.pt (J.V.S.); jose.r.andrade@inesctec.pt (J.R.A.); gil.s.sampaio@inesctec.pt (G.S.); henrique.s.teixeira@inesctec.pt (H.T.); micael.f.simoes@inesctec.pt (M.S.); joao.p.viana@inesctec.pt (J.V.); luiz.e.oliveira@inesctec.pt (L.O.); diogo.f.castro@inesctec.pt (D.C.)
4 Elektro Ljubljana d.d., SI-1000 Ljubljana, Slovenia; Ursula.Krisper@elektro-ljubljana.si
5 E-REDES, 1050-044 Lisboa, Portugal; Ricardo.Andre@e-redes.pt
* Correspondence: sergio.potenciano-menci@uni.lu (S.P.M.); ricardo.j.bessa@inesctec.pt (R.J.B.)
† These authors contributed equally to this work.

Citation: Potenciano Menci, S.; Bessa, R.J.; Herndler, B.; Korner, C.; Rao, B.-V.; Leimgruber, F.; Madureira, A.A.; Rua, D.; Coelho, F.; Silva, J.V.; et al. Functional Scalability and Replicability Analysis for Smart Grid Functions: The InteGrid Project Approach. *Energies* **2021**, *14*, 5685. https://doi.org/10.3390/en14185685

Academic Editor: Javier Contreras

Received: 19 June 2021
Accepted: 2 September 2021
Published: 9 September 2021

Abstract: The evolution of the electrical power sector due to the advances in digitalization, decarbonization and decentralization has led to the increase in challenges within the current distribution network. Therefore, there is an increased need to analyze the impact of the smart grid and its implemented solutions in order to address these challenges at the earliest stage, i.e., during the pilot phase and before large-scale deployment and mass adoption. Therefore, this paper presents the scalability and replicability analysis conducted within the European project InteGrid. Within the project, innovative solutions are proposed and tested in real demonstration sites (Portugal, Slovenia, and Sweden) to enable the DSO as a market facilitator and to assess the impact of the scalability and replicability of these solutions when integrated into the network. The analysis presents a total of three clusters where the impact of several integrated smart tools is analyzed alongside future large scale scenarios. These large scale scenarios envision significant penetration of distributed energy resources, increased network dimensions, large pools of flexibility, and prosumers. The replicability is analyzed through different types of networks, locations (country-wise), or time (daily). In addition, a simple replication path based on a step by step approach is proposed as a guideline to replicate the smart functions associated with each of the clusters.

Keywords: smart grid; scalabilty and replicabilty analysis; flexibility aggregation; flexibility impact; flexibility tools and SGAM

1. Introduction

The power sector is currently experiencing a revolution in the way electricity is generated, transmitted, and distributed. These changes are largely driven by enhancements of decarbonization policies, increased digitalization, and increased demand for the electrification of assets. As a result, the network has seen rapid growth in the integration of distributed energy resources (DERs), such as photovoltaic (PV), wind, and electric vehicles (EVs), within the distribution system. These ambitious goals, however, do not come without consequence to the distribution system operator (DSO), and their integration has resulted in several challenges, e.g., increased network congestion and voltage violations. The DSO, thus, plays a pivotal role when integrating these technologies while ensuring a safe, reliable, and continuous supply of electricity. Many technical solutions and business models have been developed in order to harvest the use of DERs within the flexibility market whilst supporting the DSO in ensuring the secure operation of their networks [1]. These smart grid functions range from forecasting services and energy management systems to optimization algorithms, thus composing an end-to-end chain of processes. A comprehensive overview of some smart grid functions and how smart grids are evolving over the last 20 years is detailed in [2]. In addition, these new solutions have allowed for the increase in new business models and actors such as virtual power plants (VPPs), who act as aggregators, to leverage flexibilities and offer their services to other network stakeholders, e.g., the DSO and the transmission system operator (TSO) [3].

To provide a platform for these smart grid technologies to be developed, tested, and implemented, various pilot projects around the world have been implemented [4,5]. Some of the many objectives of these projects aim to assess the feasibility of smart grid functions, new hardware, communication technologies, and business models. However, this novel approach considers these innovative solutions within the scope and boundary conditions set within the project. In this regard, several questions often arise, such as whether these solutions can perform adequately after large-scale deployments and within alternative network boundary conditions. It is, therefore, necessary to analyze and validate such solutions by conducting a scalability and replicability analysis (SRA).

The terms scalability and replicability analysis have become increasingly relevant in DSO network planning [6]. The need to conduct the SRA is, in current times, a vital component when considering future scenarios based on the increased connections of DERs and increased electricity demand. Therefore, the SRA allows the DSO to visualize and quantify the proposed scenarios to identify the impact of technical solutions on the network before their implementation. By doing so, the DSO can make informed decisions, particularly those relating to costly network refurbishment plans or their possible deferral. The DSO is, thus, able to realistically assess whether the technical solutions will allow for improved network performance and identify potential interoperability limitations when these solutions are applied to networks that extend beyond the demonstration grid's predefined boundary conditions. Therefore, the SRA can bridge the gap between pilot demonstration projects and large scale deployment of new technical solutions. For this study, scalability refers to the increase in a system in relation to its size, scope, or range while ensuring that its ability to adequately meet the grid's technical requirements is not compromised. The term replicability refers to the capability of the proposed technical solution to be implemented within another network, location or time.

1.1. European Context and Legacy for the Scalabilty and Replicability Analysis

Based on the aforementioned concepts, the InteGrid [7] project, formulated under the H2020 framework, is founded upon two key concepts. The first, to enable the DSO as a market facilitator for stakeholders to actively participate in the energy market using smart grid tools based on new business models, new data management, and consumer engagement. Although the second is to demonstrate that the integrated solutions proposed are scalable and replicable under a vast range of different circumstances, e.g., grids with a higher penetration of DERs.

The H2020 InteGrid project derives its concepts from a previous smart grid project, evolvDSO [8], which applied the IEC PAS 62559 use case methodology and defined eight new and evolving DSO roles for the efficient integration of distributed renewable energy sources in distribution networks. The possible establishment of these roles was supported by the development of methodologies and tools, where their respective technology readiness level was then enhanced in InteGrid. As was in the case of evolvDSO [9], InteGrid has extracted the lessons learnt from other EU projects such as Grid+ [10], where the SRA focus was primarily aimed at analyzing and understanding the prerequisites of smart grid projects, which are required in order to be scalable and replicable. Their contribution, condensed in [11] created the foundation for the SRA, as the paper addresses the influence of several factors to develop the requirements for scalability and replicability within smart grids. Grid4EU [12] proposed a step-wise methodology to combine technical analysis through load flow, dynamic, and reliability analysis with regulation and stakeholder analysis to provide a holistic view of drivers and barriers for potential up-scaling of the solutions. IGREENGrid [13] contributed to the development and importance of the SRA. Within it, two approaches were used to (1) filter the solutions with the most potential (qualitative) and (2) from a technical and economic point of view (quantitative) to understand the performance and benefits of the solutions within a potentially large-scale implementation. Additionally, these results served to help DSOs draft recommendations for deployment and investment prioritization while allowing the industry to develop products and policies. Within InterFlex [14], the project developed and implemented a targeted SRA to assess the response of the network to the implementation of design solutions when they are scaled up. These vary from network calculations, which compare the hosting capacity under different future scenarios, to voltage response of inverter functions (autonomous and centralized). A common approach to provide a holistic overview through a visual representation of these smart grid projects has been to use the smart grid architecture model (SGAM) [15]. This reference standard process helps depict the different aspects that define the smart grid through its five interoperability layers (business, functional, information, communication, and component) and provides a well-established source of information.

Each one of the aforementioned projects provided valuable and diverse contributions to the SRA state-of-the-art. This diversity, which is natural and should be encouraged, should also be condensed to become a recognizable process for any stakeholder. InteGrid focuses precisely on this aspect by proposing a standardized and multi-focus approach (functional, information and communication technology, economic, and regulatory) toward the way in which scalability and replicability can be analyzed within smart grids. This is approached can be achieved through the use of the SGAM which is used as a foundation upon which additional context and information can be sourced.

1.2. Research Questions, Key Contributions, and Paper Structure

This paper presents the functional scalability and replicability analysis of the smart grid functions implemented within InteGrid. Thence, the multi-focus approach is presented as a foundation upon which the context for the functional-oriented SRA and the various case studies are conducted. Furthermore, it is crucial to analyze the functions and assess their performance and impact within the distribution grid when future scenarios with high penetration of RES and their exploitation as flexibility sources become a reality. In this direction, this paper provides the following key questions:

- How can different scopes such as technical, economic, and regulatory be combined within a unified SRA approach?
- Does clustering of tools for a single SRA bring any benefits compared to conducting an individual SRA of each tool?
- What are the results of the set of tools when facing a scaling process (e.g., increase in RES penetration; network; flexibility offers and device controllability)?
- What are the results of the set of tools when they are exposed to other networks, characteristics, or resources?
- Would other stakeholders be able to replicate the set of tools in their own context?

Two contributions to the development of the SRA can be considered in this paper. On the one hand, to propose a standard and replicable quantitative analysis methodology for smart grids. This is achieved through a multi-focused SRA approach aligned with the SGAM. Considering the SGAM as a key foundation for the methodology, it enables a common reference representation of smart grids, which can also be replicated among various projects. The SGAM, although not considered a standard by definition, provides a simplification of the process for achieving a common reference model. The standardized consideration is a result of the SGAM becoming popular within the smart grid community. A clear example is its adoption in national, international smart grid projects or cross-domain as described in [16].

On the other hand, to show the functional-oriented scalability and replicability analysis of the set of functions proposed in InteGrid. The analyses presented in this paper provides a holistic approach to test a collection of tools in order to capture the various future challenges which will be faced when the are in real operation. The SRA is the natural step for developing tools in academic research and bridges the gap towards real implementation. The set of functions presented in this paper vary from newly developed forecast systems [17], state estimator for medium voltage (MV) or low voltage (LV), controllers for flexibility operation [18], a multi-period optimal power flow (MPOPF) [18], home energy management systems (HEMS) [19,20], aggregation through VPP [21], or even a traffic light system used for TSO–DSO indirect coordination [22]. To facilitate the integration of these tools, and noted as an additional contribution of the InteGrid project, the grid, and market hub (gm-hub) is presented in [23,24].

Although the backbone of this paper is founded upon the SRA implementation conducted within the InteGrid project, the novelties of each smart grid function are also highlighted throughout the paper.

The structure of this paper is as follows. Section 1 provides an introduction and motivation for conducting the SRA for the developed smart grid functions. Section 2 focuses on the proposed multi-focused methodology by using the SGAM as a basis for the conceptualization of the analysis. Moreover, the simplified functional methodology is presented in addition to the clustering approach, which enabled the holistic analysis of the tools. The analysis is split into two primary case studies. The first case study in Section 3 presents the SRA for the Portuguese demo through a two part analysis. The first part focuses on the set of tools for predictive operation in medium voltage networks. The second part focuses, likewise, on predictive operation but from the perspective of low voltage networks. The second case study, in Section 4, presents the SRA for the Slovenian demo which focused on the indirect TSO–DSO interaction. Within each case study and their SRA, the authors provide (1) a description of the cluster, (2) the objectives for the SRA, including an introduction to the scenarios which are to be considered, (3) the results of the scenarios presented, and (4) a discussion subsection driven by the results obtained from the analysis of each cluster. Section 5 presents the potential replication paths for the set of tools covered in this paper. Finally, Section 6 provides the overall conclusions of the SRA process and outlook for the SRA.

2. Methodology

2.1. Generic Smart Grid SRA Methodology

It is necessary to consider several system aspects to capture the impact of smart grid technologies. A smart grid, per-se, can be expressed as two-way communication, which enables different use cases [25]. Authors in [26] describe the smart grid as *"…an integrated array of grid technologies, devices, and control systems that provide and utilize digital information, communications, and controls to optimize the efficiency, reliability, and security of electric power delivery"*. This combination of assets, ideas, and tools cannot only be analyzed through one unique point of view. Instead, a multi-focused approach is necessary to provide a complete analysis of the smart grid technologies. Nonetheless, the multi-focused approach is not a simple and trivial task and can be associated with a wide scope of challenges, such as tool indecencies and context. Within these challenges, the SGAM aims to provide a multi-layer approach that can simultaneously capture the required points of view which are necessary to fully understand the smart grid. The use of the SGAM in InteGrid was motivated by (1) the implementation of a standard approach of describing the smart grid solutions which enables all stakeholders to have a common reference point and (2) the project's architecture, which consists of 12 defined high-level use cases (HLUC), which are a description of the use case from a business level (business interoperability layer of the SGAM). These HLUCs have their individual requirements and one or more objectives [27]. Hence, the SRA in InteGrid is developed based on 4 focus areas [28–30], mapped to the SGAM in Figure 1. The description of these focus areas is as follows:

- *Functional* : validates the technical integration of the smart functions through their impact when integrated within the distribution network while considering the network technical capabilities.
- *Information and communication technologies (ICT)*: provides a system architecture characterization based on the SGAM representation conducted via a qualitative analysis, which identifies the potential bottlenecks and a quantitative analysis which uses stress simulations to evaluate future performance;
- *Economic*: provides a cost benefit analysis based on the net present value and the initial rate of return of the implementation of the new functions and tools. The analysis gives an overview based on the economies of scale, macroeconomics, and key performance indicators (KPIs);
- *Regulatory*: investigates the regulatory drivers and barriers which may be imposed within various countries in order to highlight the compatibility of these regulations during the deployment of the smart grid functions.

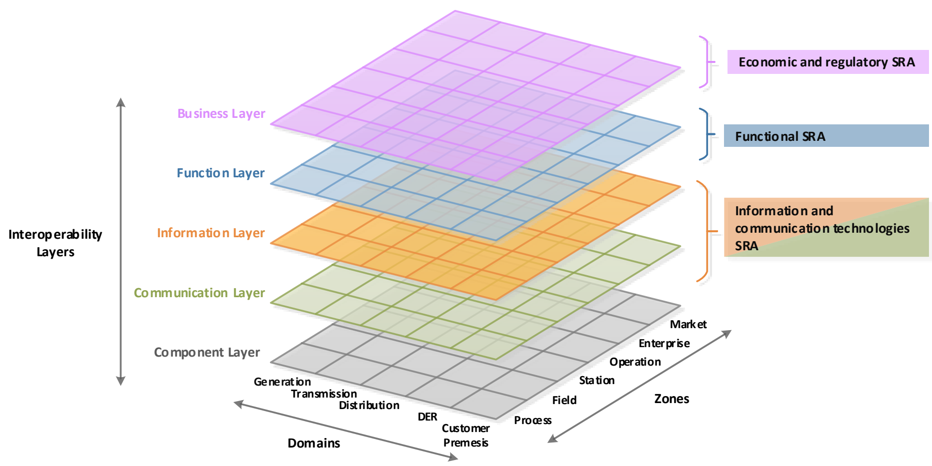


Figure 1. Mapping of focus areas to the SGAM.

The mapping proposed in Figure 1 shows the main information points for each of the focus areas. However, all the interoperability layers should be considered when assessing a specific focus area due to inter-relationships. The component layer provides the devices that compose the grid backbone, e.g., generation units. The communication layer details the technologies of communication used and their protocols, whereas the information layer provides the inputs contained in the data models. The functional layer is associated with the technical scope of the smart grid functions, while the business layer relates to the business and political (regulatory) frameworks.

2.2. Functional Clustering Process

Boundary conditions of the three considered demos serve as the foundation for the HLUCs. Although they might implement the same smart grid functions, their objectives for implementation may differ. The Portuguese demo focuses on the flexibility usage for the DSO purposes at both the MV and LV levels. The DSO uses flexibilities from several sources, such as wind, solar, batteries, and industrial consumers to ensure the reliable operation of the distribution networks. The Slovenian demo encompasses a TSO–DSO indirect interaction process. It implements a traffic light concept to assess the impact over the distribution network when flexibilities are used for purposes other than local DSO flexibility. These flexible units might be distributed storage systems, industrial customers or distributed generation aggregated under a commercial virtual power plant. The Swedish demo analyses the social impact of steering customers to solve grid constraints through active participation in demand-side management programs.

Given the diverse context of each demonstration, a pre-evaluation process [31] using a qualitative analysis is performed. This approach allows for the filtering of necessary HLUCs and identifies the potential benefits (if any) of a applying a combined HLUC approach in order to conduct a joint SRA. The pre-evaluation considers a wide variety of aspects, such as *the objectives of the HLUC, potential analysis, specific SRA methodology considered for analysis, potential scalable sources, pre-requirements for analyzing national and international replicability, tools to perform the SRA, KPIs* which can be measured and *potential baselines* for the analysis comparison. From this analysis, one outcome is clear: if there is an objective to truly capture the potential of the tools, a solution has to be found to incorporate the interdependency of the tools. The solution could be to identify many assumptions when analyzing each tool individually. Another solution is to group them into a cluster. By grouping them, assumptions are reduced, and specific data can be used. Such an approach is used in this paper, as the benefits of having real data, fewer assumptions and real mapping to a demonstration site enables a holistic analysis.

Subsequently, 5 clusters were identified as represented in Figure 2. Clusters 01, 02, and 04 are mapped to the *Portuguese* demo, Cluster 03 to the *Slovenian* and Cluster 05 to the *Swedish* demonstrator. The common denominator among most clusters is the gm-hub platform, which acts as a secure, interoperable platform oriented to facilitate market access and operate as an intermediate platform connecting the different energy agents and roles. Within the scope of this paper, only Cluster 01, Cluster 02, and Cluster 03 are presented as they (1) implement the main tools characterized in within the InteGrid project (programming languages and technology are listed in Appendix A) and (2) each cluster fully implements a set of tools within the demonstrations.

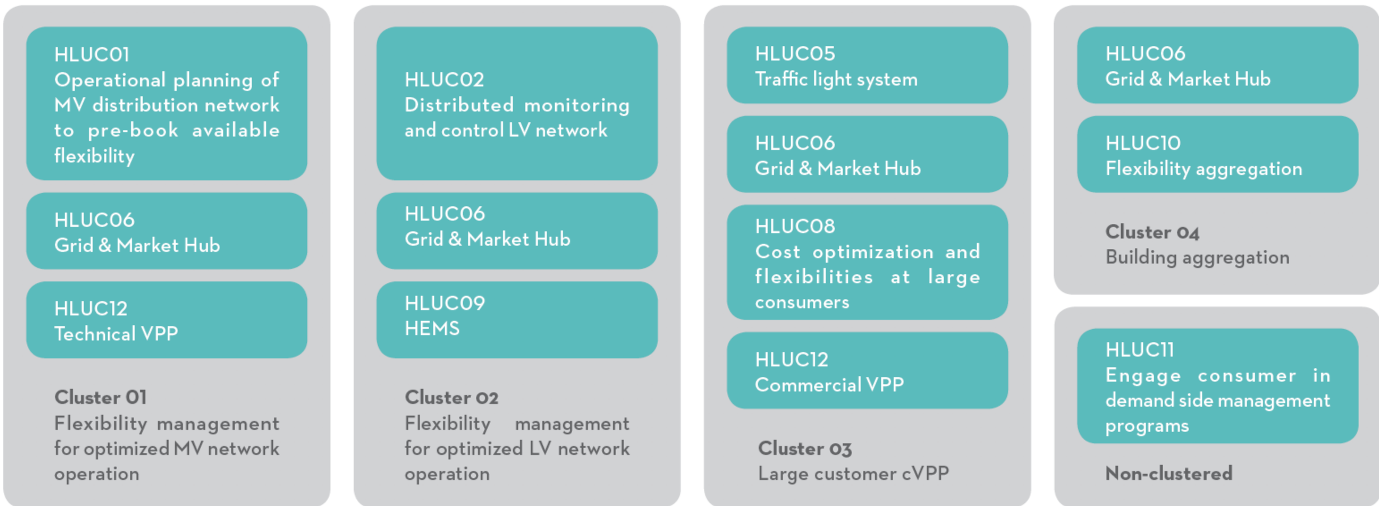


Figure 2. Clusters identified within InteGrid.

2.3. *Functional-Oriented Methodology*

As previously mentioned, the focus of this paper is on the functional-oriented SRA, meaning that the analysis focuses on the output of the different smart grid functions when they are implemented under various high impact conditions. Although 5 clusters are considered for the analysis, each having their own specific requirements for the analysis, a general process for the functional-oriented methodology is applied and is shown in Figure 3. This approach is based on the methodology presented in [32].

Figure 3. Functional-oriented methodology.

As shown in Figure 3, the first step to collect data (as realistically as possible). It includes network and profile data required to produce a representative system model. This step allows for the evaluation of data availability and accessibility and whether alternative generic sources are required. Thereafter, various scenarios and KPIs are defined in order to provide case studies and assessment criteria, respectively. Several communities of practices help with the creation of the scenario for each cluster. The functional SRA execution consists of implementing the developed scenarios in a simulation environment based on the real or representative network model. The results are then heavily discussed among the different stakeholders to include perspectives ranging from the system operator to the flexibility provider. Finally, the last step is to draw conclusions that can be applicable for a wide range of stakeholders.

3. Case Study: SRA for Portugal

3.1. Cluster 01: Flexibility Management for Optimized MV Network Operation

3.1.1. Description of the Cluster

Cluster 01 is based on a set of smart grid functions developed for the predictive operation of MV networks. The objective of Cluster 01 is the exploitation of flexibility-based actions to support the DSOs in their operational tasks. Examples of these operational tasks are solving grid constraint violations (voltage or congestion) or decreasing the active power losses. Flexibility resources are considered from two categories. The first category (asset level) are DERs, such as on-load tap changers (OLTC), capacitor banks, or storage systems (assuming that the regulatory framework allows DSOs to own and operate this asset). Storage systems may or may not be owned by the DSO depending on the regulatory framework of the country. The second category of flexibility resources is provided by virtual power plants (VPPs). In this specific case, the VPP is considered a technical VPP (tVPP) as its business model is to provide flexibility to the DSO.

Thence Cluster 01 is dependent on several smart grid functions being, a *load* [33] *and RES forecasting* [34] system, a *tVPP*, a *MV load allocation* system, and a multi-period optimal power flow (MPOPF) (algorithm). These smart grid functions are represented in Figure 4, including data sources and the flow of the process. Each of the smart grid functions are hereafter briefly explained.

The load and RES forecasting system is a centralized service developed and installed within the DSO infrastructure to support every tool envisioned for the operational planning of MV distribution networks. This service is of utmost importance as it enables access to active and reactive power forecasts—generated daily (i.e., twice a day)—for the different grid locations of each demonstrator. The forecasts are generated based on predicted weather information and past operating conditions.

The MV load allocation (MVLA) plays a fundamental role as it allows solving observability constraints that could prevent the execution of other tools [18], such as the MPOPF. In this sense, the MVLA tool requests the available forecasts (and measurements, in real-time) of the active and reactive power of the MV/LV substations and the feeders' heads. It either estimates the operating state of the MV/LV substations when measurements/forecasts are not available or performs corrections to the MV/LV substations' measurements/forecasts (when available) to make them coherent with the measurements/forecasts available for the corresponding upstream feeder. Meanwhile, the tVPP aggregates the flexibility of energy consumers or producers and offers the available flexibility margins to the DSO for the short-term management of the distribution networks.

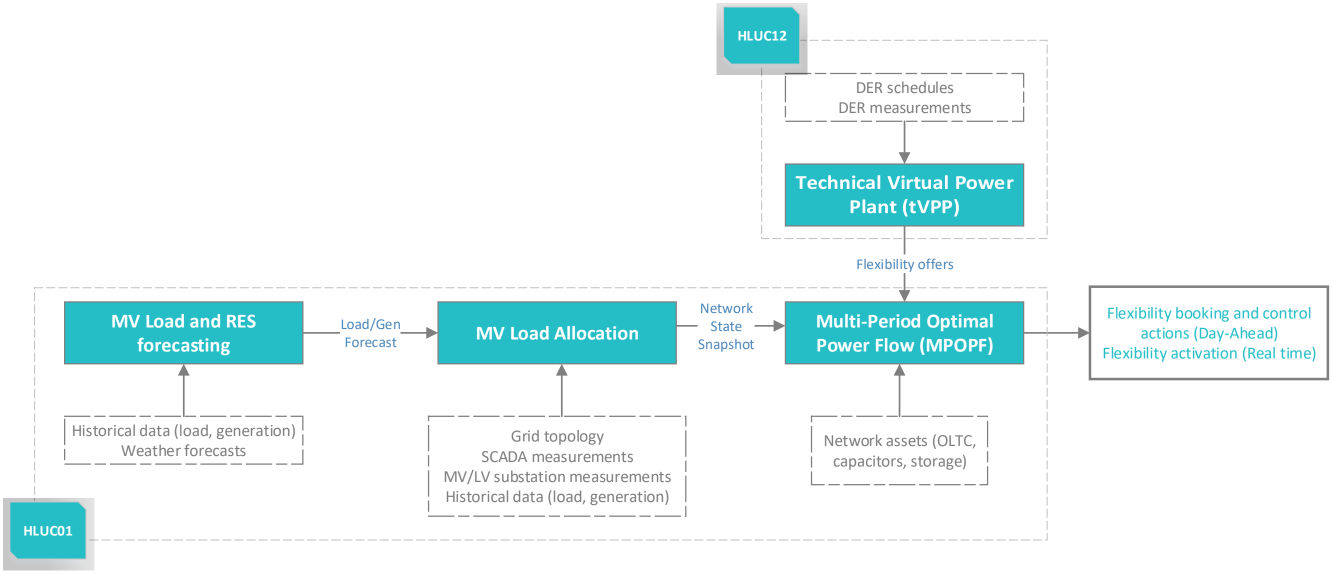


Figure 4. Cluster 01. Global architecture.

Finally, the MPOPF intends to be a decision support module capable of providing operational optimization actions to the DSO while keeping the grid power flows and voltage magnitudes within their corresponding technical limits [18]. The MOPF focuses on specific objectives (e.g., flexibility cost minimization, active power losses minimization), always solving a minimization problem. The result is an identification and a reservation of flexibility-based actions while the optimization meets *technical grid constraints*. The MPOPF objective function, is illustrated in Equation (1),

$$Objective function = \sum_{t \in T} \sum_{i \in F} a_i^t \cdot (P_i^t)^2 + b_i^t \cdot P_i^t + c_i^t \tag{1}$$

where a_i^t, b_i^t, and c_i^t are the cost factors of each flexibility resource i in period t. Since it enabled a simpler implementation and did not compromise the simulation goals, b_i^t was the only factor considered in the tests hereby presented thus leading to a linear relationship between the flexibility amount (P_i^t) and the objective function value. The OLTC and capacitor banks are assumed to have a zero cost value since they are usually owned by the network operators. The minimization of the active power losses can either be modeled by a dedicated objective function or by setting equal marginal costs to all flexibilities in Equation (1). The two inter-temporal constraints for the state of charge (SOC) control and the energy rebound effect are illustrated in Equations (2) and (3), respectively,

$$0 \le SOC_i^t \le SOC_{imax} \quad i \in N_{ESS}, \ \ t \in T \tag{2}$$

where SOC_i^t is the SOC of the energy storage system (ESS) i by the end of period t and SOC_{imax} represents its upward limit. For the energy rebound effect shown in Equation (3), P_i^t and P_i^{t+1} illustrate flexibilities offered by the same resource i in two consecutive time instants, but with opposite directions (i.e., one upward and one downward or vice-versa). By setting their ratio to 1, it is ensured that the flexibility activation in instant t is rebounded (i.e., same amount of flexibility in the opposite direction) in *timestamp* $t+1$.

$$\frac{P_i^t}{P_i^{t+1}} = 1 \quad i \in F, \ \ t \in T \tag{3}$$

The optimization works in two operational modes: predictive (typically one day ahead, with hourly intervals); and quasi-real-time (typically 45 minutes ahead). As the name indicates, in the first stage, the goal is to foresee potential technical problems and, based on such assessment, define the necessary control actions to avoid them. By doing so, the flexible DERs are warned in times in which activation of their bids are possible. Additionally, the network operators can analyze the defined predictive plan and provide their validation. The real-time assessment has a validation and, if necessary, a corrective character. It relies on the availability of real-time measurements to assess the reliability of the predictive analysis. Therefore, in cases where the forecasted conditions significantly differ from the current ones, the MPOPF updates the predefined control actions.

3.1.2. Objectives of the SRA and Scenarios

The functional-oriented SRA aims to evaluate the four smart grid functions developed to stress them under new conditions and challenging situations. It is possible to use all of the smart grid functions separately. However, the MPOPF is the primary function and, thus, can provide the *"aggregated"* outcome when implemented in the distribution network. Hence, the output of the MPOPF can indirectly enable the analysis of the other tools.

The following parameters are considered for the scalability analysis,

- *Penetration of RES in the network:* the amount of RES is increased to create constraint violations in the MV network and to evaluate the potential of the tools to allow higher levels of hosting capacity. The location and the size of the RES are carefully selected to create challenging situations. The goal is not to perform an exhaustive analysis of the hosting capacity but rather to assess how scaling-up the quantity of RES can be handled by the DSO when empowered with adequate operational tools to manage flexibility;
- *Available flexibility of the tVPP:* the amount of flexibility is increased compared to the current baseline (i.e., minimal amount of flexibility) to observe how flexibility can be used as an alternative to more traditional solutions such as OLTCs or capacitor banks;
- *Network size:* the number of nodes is increased as it has a direct influence on the computational effort of the tools (in particular the MPOPF). The network size is relevant for the real-time operation where time constraints are more important than in predictive mode.

Concerning the replicability, the following parameters were considered:

- *OLTC and capacitor banks control:* evaluation of the capability of OLTCs and capacitor banks—usually owned by DSOs—to solve voltage problems by enabling their control through the MPOPF;
- *ESS control:* integrate ESS to evaluate their impact;
- *Reactive power control:* as an alternative to local reactive power controls (droop control) used by generators;
- *Rural and urban network types:* assessment of the performance of the tools under different conditions through the Slovenian and Portuguese network;
- *Historical data availability:* evaluate the impact on the forecasting accuracy and the MOPF control actions when the length (time-period) of historical data changes;
- *Metering primary substation:* the grid points for which historical data are available are reduced to evaluate the impact on the MVLA accuracy and MPOPF control actions.

Although the impact of all these parameters was evaluated, not all of them were considered in both demonstrators. Inherent characteristics of the demo sites explain this fact, e.g., the higher RES penetration in the Portuguese demo resulted in suitable conditions to test the possibility of reactive power support provided by these resources. Due to the significant number of simulations performed, it is impossible to assess all the scenarios in the scope of this paper. Therefore, a selection of the most significant scenarios made in the Portuguese and Slovenian demo sites are presented in this paper and summarized in Table 1.

Table 1. Overview of the scenarios for Cluster 01.

Scenario Name	Network	Variation
Baseline Portugal	PT demo	Baseline—No variation considered
Overloading occurrence	PT demo	RES connected to create overloading. Different control actions are tested (ESS; tVPP)
Baseline Slovenia	SI demo	Baseline—No variation considered
Overloading/voltage occurrence	SI demo	RES connected to create overloading and overvoltage. OLTC and the tVPP are available
Network size increase	SI demo	Size of the network is increased
Limited measurements available	SI demo	Historical data for primary substation transformers only

3.1.3. SRA Results

- **Baseline—Portugal**

The simulation uses a 10 kV network located in Mafra, Portugal. It consists of 855 nodes and is connected to the transmission grid by a 60/10 kV primary substation composed of 4 OLTCs and 1 capacitor bank coupled to the MV side. Approximately 13,000 customers are supplied by this MV grid, 79 of them being MV customers. From the renewable generation side, 4 different RES are directly connected to the Mafra distribution network. An hourly load and RES profile for 24 h was extracted from the available historical data. It enabled a power flow study to observe the network status. This first analysis showed that neither voltage nor overloading problems occur in the baseline scenario. Thus, the MPOPF did not provide any flexibility-based suggestions.

Despite the absence of technical problems in the Portuguese demo, flexibility could still reduce the active power losses. Two options were considered: OLTC and local generation increase. From these two options, only the first was initially available on the demo site. The tVPP provides the local generation increase in the form of bids, and, therefore, it constitutes a new flexibility option for the Portuguese demonstrator. In the first hypothesis, the primary substation OLTCs increased the global voltage magnitude throughout the distribution grid. Such an increase subsequently led to decreased active power losses from 4.15 MW to 3.34 MW. The second possibility was to exploit the DERs by increasing their local production. The MPOPF entirely exploited this flexibility during the 24 h time horizon, reducing the active power losses from 4.15 MW to 3.48 MW.

This first assessment of the baseline helped to built the SRA scenarios, already illustrated in Table 1, to capture the expected changes of the power systems environment in the coming years. Such modifications lie in scalability (e.g., predictable increase in RES integration) and replicability (e.g., different flexible DER) scopes and intend to assess how the MPOPF would behave when facing other and more challenging conditions than those considered in 'business as usual'.

- **Overloading Scenario—Portugal**

The Portuguese demo site emphasises the use of an ESS as a future scenario. Meanwhile, in the Slovenian demonstrator, this scenario is not tested.

The ESS considered was a 0.5 MW battery storage system to solve branch overload occurrences observed in the Portuguese demo grid, particularly at the beginning and end of the day. These technical problems resulted from the connection of two new wind parks (5.82 MW and 3.1 MW) in one of the network feeders. Several transmission lines observed reverse power flows, which led to maximum overloading of 103%. Figure 5 depicts how the SOC of the ESS evolved during the day while following the MPOPF recommendations.

As expected, the ESS was charged in the extreme hours of the day, thus accommodating the excess of renewable energy injection available in the distribution grid. The partial SOC decrease after the two first charging actions is illustrative for the multi-temporal capabilities of the optimization algorithm. Without such discharge procedure, the ESS would not have enough capacity to relieve the distribution grid from the excess of RES production in the last periods of the day. Therefore, in this scenario, the MPOPF was challenged to control the SOC of the battery system to solve the existing branch overloads and while sustaining the battery's technical limits.

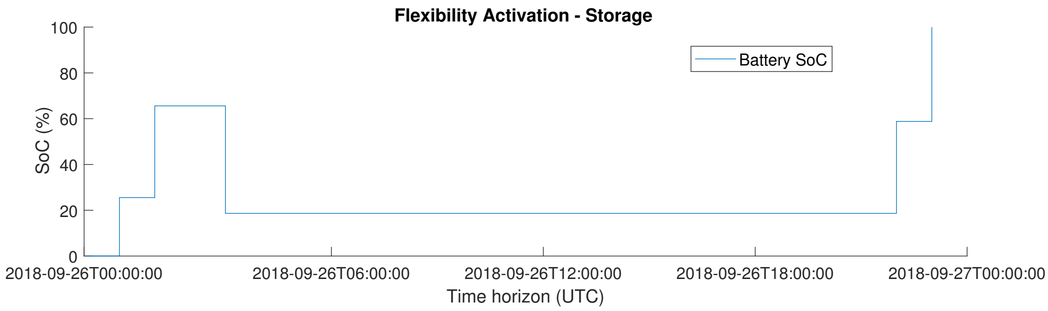


Figure 5. State of charge of the storage system.

This scenario also considered the flexibility provided by the tVPP. Two MV customers adjusted their consumption in the upward direction (i.e., consumption increase) and provided a solution to the overloading occurrences. The choice of these MV customers was based on their flexibility costs since the MPOPF provides a feasible technical operation plan and an optimal assessment of the activation costs.

In addition to illustrating the main KPIs for this specific scenario, Table 2 has a hidden and severe warning to the DSO, which does neither use the evaluated solutions evaluated in the Mafra grid. The lack of implementation of these solutions is an important conclusion. It indicates the need for a pro-active distribution network where flexibility exploitation is one of the primary keys to overcome potential grid constraint violations. This example perfectly highlights the ambition of the SRA methodology developed in InteGrid. By mixing scalability and replicability into a single scenario, it was possible to measure the impact to the grid of RES penetration growth and suggest potential assets that would be effective in handling the upcoming challenges when managed by a dedicated optimization algorithm. Neglecting the benefits of hybrid scenarios (i.e., mixing scalability and replicability) could lead to incomplete messages. In this scenario, the more traditional solutions, such as OLTCs or capacitor banks, would not fit to the type of problem, and, as such, it is of utmost importance to provide alternative pathways to the DSO. The complete roadmap to achieve such ways results from the joint analysis of these functional outputs with the economical, ICT, and regulatory SRAs.

Table 2. KPIs—Portuguese overloading scenario.

	Reduction of Overloading Occurrences (%)
Energy Storage System	100
tVPP (MV customers)	100

Although not all the future scenarios detailed in Table 1 are analyzed in this paper, it is essential to emphasize that feasible predictive plans were elaborated for each of them. Several different flexibility options were used—centralized Q(U) control, OLTC, tVPP—which highlights the versatility of the employed algorithms.

- **Baseline—Slovenia**

The simulation in the Slovenian case uses a 10 kV network located close to Ljubljana. It consists of 720 nodes and is connected to the transmission grid by two 110/20 kV primary substations composed of 4 OLTCs. The existent capacitor banks were out-of-service during the demonstration phase. This MV distribution network is responsible for feeding approximately 23,000 customers, many of whom are prosumers. The assumptions for the Slovenian baseline considered that neither OLTCs, capacitor banks, or the tVPP would provide flexibility. Such impositions were following the demo site characteristics.

Considering the available load and RES forecasts for a 24 h time horizon, the MPOPF detected an undervoltage occurrence on the LV side of an MV/LV transformer. There was no solution to overcome such technical problems since no flexibility options were available within the Slovenian network. The fact that no flexibility options were available was a severe warning to the DSO. It highlighted the impact that flexibility may have on the network operation procedures.

The analysis of more complex scenarios in the Slovenian grid required the availability of a feasible baseline. Therefore, the solution developed within InteGrid was to include a flexibility provider: the tVPP. A new flexibility resource was added to the tVPP portfolio, which initially only considered customers engaged in the project. The inclusion of an additional client allowing the partial curtailment of this consumption was sufficient to solve the undervoltage problem. Other options, such as the inclusion of a 10 Mvar capacitor bank group on the MV side of the primary substation, were also assessed and proved to be effective. Independently from the selected option, it resulted in a feasible baseline, thus, enabling the evaluation of the MPOPF effectiveness in diverse and scaled-up contexts, like the ones proposed in Table 1.

- **Slovenia—Overloading and Overvoltage Scenarios**

This scenario tested the capability of the grid to host an increase in the RES injection. First, two PV generation groups with 3.5 MW and 9 MW of installed power were connected in the demo grid. Although the former was responsible for several overvoltage occurrences, the latter was used to set a specific branch on the verge of congestion. The solution to the overvoltage problems was to use the flexibility provided by a consumer (consumption increase) via the tVPP.

After this first trial, the network was further stressed to capture the MPOPF's ability to manage flexibility in complex situations. The stress test consisted of increasing the amount of existing production in 10% steps until the flexibility resources were no longer capable of solving the technical problems. This study allowed for the conclusion that this specific grid can accommodate a maximum of 30% increase in the generation in case the tVPP and the OLTCs are available for flexibility purposes.

The KPIs presented in Table 3 highlights the conclusion mentioned above but also provides other valuable insights for the network operator. The DSO becomes aware of (1) the DER technologies that best fit each type of technical problem; (2) the network challenges that highly constrain the hosting capacity. Such conclusions were only possible due to a standardized SRA methodology that, during the scenario development phase (Step 2 in Figure 3), gathered technology providers and stakeholders to define the best pathway to assess future challenges. In the particular case of the Slovenian demo grid, the test and trial of several RES penetration levels was the best mechanism to characterize the predictable changes in this power system environment. Based on such procedure, the MPOPF enabled a 30% RES growth by using the flexibility available from the tVPP (generation curtailment) to manage the branch overloading occurrences while simultaneously sending set-points to the OLTCs to tackle observed overvoltages. In fact, and as depicted in Table 3, if the unique concerns were related to the overvoltages, the OLTC would enable even higher levels of RES penetration. The increased severity of the voltage problems and the reduced volume of flexibility available from the tVPP (consumption increase) explain why the solution to address these occurrences changed compared to the first trial. Figures 6 and 7 illustrate the technical problems, as well as the solutions to avoid them.

Table 3. KPIs—Slovenian overloading and overvoltage scenario.

	Reduction of Overloading Occurrences (%)		**Reduction of Overvoltage Occurrences (%)**	
	10–30% RES Growth	**=40.0% RES Growth**	**10–30% RES Growth**	**=40.0% RES Growth**
tVPP(generation curtailment)	100	70	-	-
OLTC	-	-	100	100

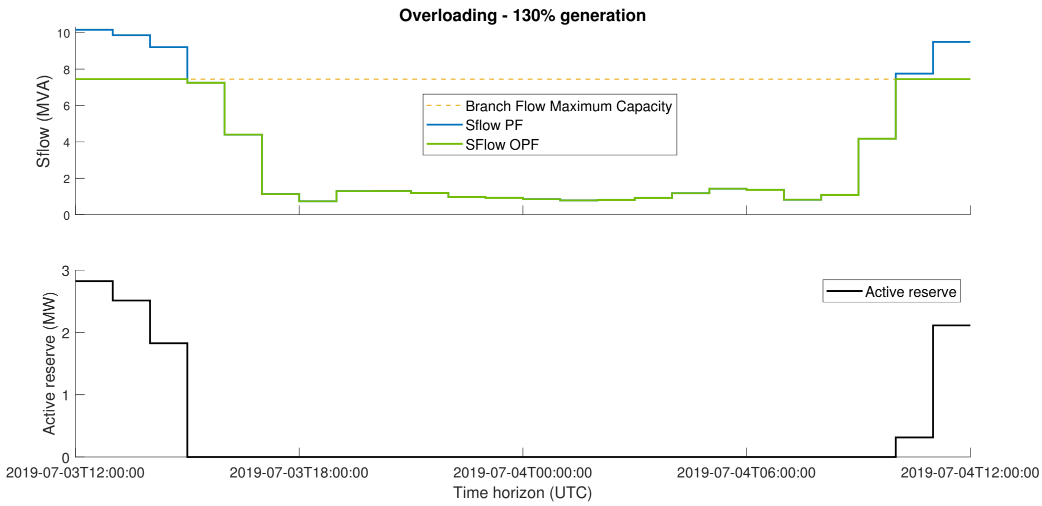


Figure 6. MPOPF impact on the congested transmission line and the corresponding control-actions (30% generation increase).

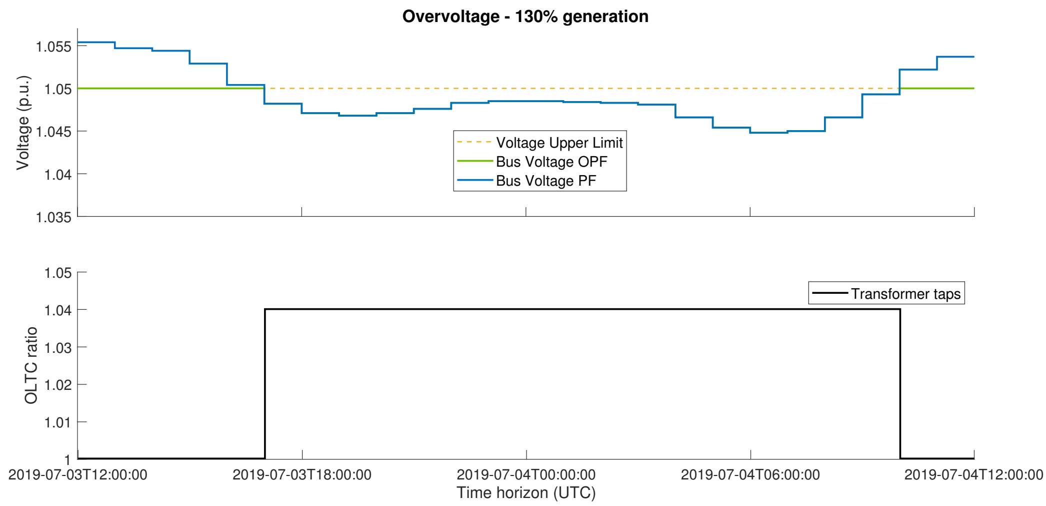


Figure 7. MPOPF impact on the voltage profile of a busbar and the corresponding control-actions (30% generation increase).

- **Network Size Increase—Slovenia**

The analysis of the grid size expansion impact is once again a consequence of the scenario development phase (Step 2 in Figure 3) employed by the proposed SRA methodology. Usually, for the tools with higher technology readiness level, their correct execution needs to be associated with high performance in non-functional requirements. However, answering which of these requirements should be fulfilled is not a trivial question and depends on how the stakeholders intend to explore the tool results. In Cluster 01, the smart-grid functions are envisioned to work on a short-term horizon, thus, demanding minimum requirements concerning their computational effort. Therefore, the baseline grid size was expanded (5 and 10 times), which led to positive linear growth of the computational time. By avoiding an exponential time increase, the tools of Cluster 01 proved to be compatible with the requirements of daily network operation. Furthermore, these results are comparable with state-of-the-art approaches. The MPOPF took 94 s to provide a 24 h predictive plan, while the forecasting and the MVLA algorithms computed their outputs in 8459 s and 5 s, respectively, for the larger network.

- **Limited Historical Data Available—Slovenia**

The availability of historical data is of utmost importance for any forecasting method. This scenario focuses on reducing the amount of available data to observe the impact on the

MPOPF output. *To properly analyze the results, it has been considered that it is possible to carry a perfect estimation when in possession of historical data for an entire year of operation (i.e., baseline).*

The results indicated that an increase in the predicted technical problems was observed for reduced sets of historical data. In the case of computed forecasts with one month of historical data, 1 additional overloading occurrence and 15 additional overvoltages were detected in the power flow execution. Therefore, if the MPOPF operated according to this network state, unnecessary flexibility activations would be recommended. Theoretically speaking, the opposite situation could also be observed (i.e., decrease in the predicted technical problems with the reduction in the historical data content), thus leading to a lack of control-actions. These observations highlight the crucial role of DSOs in ensuring the availability of proper historical datasets.

- **Limited Measurements Available—Slovenia**

This scenario considered the case where only historical data (active and reactive power) for the HV/MV primary substation transformers was available. The remaining variables, i.e., the active and reactive power of each MV/LV secondary substation, were estimated by the MVLA using other input information types (contracted/installed power, mean power factor, etc.).

The results showed two different situations. The first situation was the detection of 15 additional overvoltage occurrences. Meanwhile, in the second situation, the undervoltage problems decreased. Therefore, for this specific grid, the lower observability in the MV network led to a less reliable estimation of the grid condition (since the allocation procedure was only guided by the forecasts at the primary substation). Consequently, an erroneous optimization of the network state would be carried by the MPOPF.

3.1.4. Discussion

The design and analysis of Cluster 01 aimed to show the effectiveness of the developed tools independently of the characteristics of the environment where they are implemented. The analysis of Cluster 01 through the SRA helped to perform stress testing on the networks to understand the network limits, valuable to the DSOs. Additionally, the study through specific scenarios helps to evaluate the holistic output of the tools when working together, as they do in actual operation. Nonetheless, the analysis took the point-of-view of the MPOPF since this is the primary support decision tool for the DSO.

The MPOPF proved to be a robust tool, capable of adapting to different network characteristics, as seen during the testing of the Portuguese and Slovenian networks. On the one hand, the lack of available flexibility to solve the network's technical problems remarks the importance of flexibility even in current situations as the baseline for Slovenia exposed. In all other cases, the MPOPF computed N-hours ahead predictive plans to avoid the occurrence of grid constraint violations at a minimum cost. This predictive management ability, therefore, enabled an increase in the network hosting capacity. On the other hand, the presented computational performance remained within the time constraints required for adequate field operation.

A variety of different grid assets—which may or may not be owned by the DSO—can contribute to developing the MPOPF optimization plans. The combination of grid assets is of utmost importance for network operators, who usually have limited options which only consist of assets, such as OLTCs or capacitor banks. These types of resources are typically centralized at the primary substation level, which may lead to difficulties when searching for a solution to multiple problems simultaneously, e.g., under and overvoltage occurrences in feeders connected to the same HV/MV transformer(s). In addition, storage units are among the assets that the MPOPF can manage, and the simulations highlighted the importance of their contributions.

Furthermore, the MPOPF also relies on the availability of flexibility. Without resources that can adapt to their typical injection and consumption patterns, ensuring a safe and reliable network operation becomes increasingly challanging. Therefore, DSOs have an essential role in engaging customers who can participate in grid operational tasks, particularly in areas where problematic situations most commonly arise.

Although the results indicated the robustness of the MPOPF, it is necessary to remark that it is highly dependent on the input data. The availability of an accurate grid status, provided by the forecasting services and the MVLA (dependent on the SCADA), is crucial for the correct execution of the MPOPF. The lack of data affects the MPOPF, suggesting unnecessary set-points due to non-existent problems or not recommending any control-action even though issues exist within the network.

These conclusions derived from the holistic SRA of Cluster 01, are only possible through a standardized approach that focuses on the stakeholder's final objective while mixing scalability and replicability criteria. The functional-oriented SRA profoundly helped the DSOs in understanding their current and future problems while testing InteGrid's tools in current and future scenarios.

3.2. Cluster 02: Flexibility Management for Optimized LV Network Operation

3.2.1. Description of the Cluster

Cluster 02 combines advanced tools for the predictive operation of LV networks recurring to the flexibility provided by domestic consumers through their HEMS and DSO-owned resources, such as OLTCs and ESSs, taking Cluster 01's assumptions for these DSOs resources. In the context of InteGrid, it is assumed that DER available in the LV network can be exploited by the DSO for grid control and management purposes [35]. Similarly, Cluster 02 is dependent on several smart grid functions, review LV load and generation forecasting tool (solution), the low voltage state estimator (LVSE) (solution), the HEMS (solution), and the low voltage control (LVC) tool (algorithm).

These smart grid functions are represented in Figure 8, including data sources and the flow of the process. The LV load and RES forecasting is almost equal to the load and RES forecasting presented already in Cluster 01. The main difference is the target group. In case of Cluster 02, the forecasting targets LV load and RES in the network.

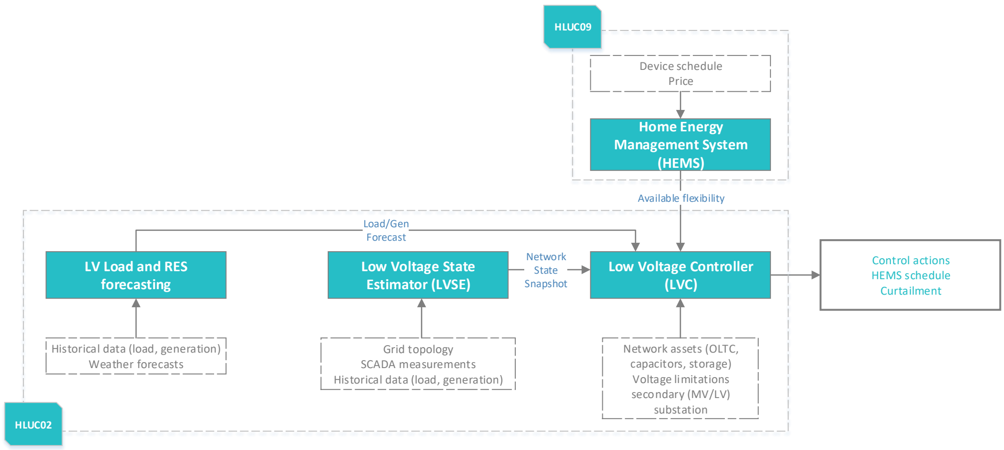


Figure 8. Cluster 02. Global architecture.

The LVC tool aims to be a decision support tool to assist the DSO in the active management of the LV grid. It seeks to identify a set of preventive control actions to avoid foreseeable technical problems in the LV network, such as voltage violations [36]. The LVC tool performs the active management of the LV network recurring to two main resource types: DSO-owned resources, such as OLTCs and ESSs, and privately-owned resources. The DSO needs a contractual agreement with the private customers willing to participate in grid operation using demand response schemes. The assumption is that those private customers who participate have installed a HEMS [37]. The HEMS is a local controller, installed locally at the private consumer household, that is simultaneously responsible for optimizing the consumption of the household itself and the computation of the flexibility available for the different periods of the day.

The HEMS acts as an interface between the LVC tool and the consumer's household appliances. It is responsible for communicating the flexibility available to the DSO and for receiving consumption set-points sent by the DSO. The interaction between the DSO and the private consumers willing to participate in grid operation is through the gm-hub, which collects flexibility offers from the private consumers. Furthermore, the gm-hub is also responsible for receiving the control actions from the DSO (flexibility activation requests) and communicating them to the HEMS [23]. The LVC tool operates in two main timescales: preventive scale (typically one day ahead, quarterly-hour intervals); and quasi-real-time scale (typically 15 min ahead).

In the preventive timescale, the algorithm requires forecasts of generation, load, and flexibility provided by private consumers to determine a preventive control action to apply to the LV network controllable resources [33,34]. The DSO receives these control actions produced by the preventive control module and validates them. The DSO can accept or change the control action.

In real-time timescale, the algorithm uses a state estimation algorithm, the LVSE, to obtain a snapshot of the network in real-time recurring to a subset of the measurements of the smart meter available in the LV network [38,39]. It is essential to highlight the requirement for the usage of an LVSE algorithm since current advanced metering infrastructure (AMI) solutions are unable to provide accurate synchronized real-time measurements in useful time [39]. The main objective of the real-time control module is to assess the actual network conditions registered in real-time and compare them to the forecasted conditions at the preventive stage. If these differ significantly, the control action is updated accordingly. Therefore, the real-time control module of the LVC tool has a corrective character, acting solely if the network conditions significantly differ from what was forecasted.

Given the unbalanced nature of LV networks, due to the existence of single-phase and unbalanced three-phase resources, the LVC algorithm recurs to an unbalanced three-phase power flow algorithm to obtain a detailed network snapshot for each instant of the control period. The unbalanced three-phase power flow routine was implemented according to the formulation presented in [40] and covered in a previous publication [36].

3.2.2. Objectives of the SRA and Scenarios

The objective of the SRA in Cluster 02 is to stress the networks and tools using different integration levels of DER, RES, networks with different sizes, and networks with other electrical characteristics. Similar to Cluster 01, it is possible to analyze all the smart grid functions of the cluster separately. However, anew if the SRA focuses on the LVC (main smart grid function), the analysis can provide a holistic analysis and indirect analysis of the other smart grid functions used in the cluster. Nonetheless, it was necessary to limit the number of scenarios to consider, as there are a large number of variables involved. Thence, the SRA considers worst-case scenarios, i.e., scenarios that could impact the grid's controllability, the tool's performance time, number of avoided violations, or the grid's RES hosting capacity.

With respect to scalability, the following parameters are considered:

- **Network size:** increase in the number of nodes since it directly influences the computational effort;
- **Penetration of RES in the network:** increase in the RES penetration in order to create constraints within the LV network and to evaluate the potential of the tool to host more renewable energy;
- **Flexibility from HEMS:** increase the number of consumers equipped with HEMS to observe whether HEMS can be used as an alternative to DSO's owned assets such as OLTCs or ESSs;

- **Number of controllable devices:** increase in the number of controllable devices in the households to evaluate the impact on the resulting load profile and their energy savings.

Concerning the replicability the following parameters are considered:

- **OLTC control:** evaluate the potential of the set of tools when the secondary substation transformer is controllable, as currently not many secondry substations are equipped with OLTCs;
- **Energy storage system control:** evaluate the possibility of using central or distributed ESS;
- **X/R ratio:** modify the the X/R ratio to evaluate the performance of the set of tools in more inductive networks;
- **Availability of historical data:** modify the amount (time horizon) and the quality of the historical data available for the forecasting and LVSE tools, to assess the impact on the overall forecasting accuracy.

Analogous to Cluster 01, due to the serious number of simulations performed, the scope of this paper is limited to several simulations. The selection is based on the most significant analysis for the Portuguese demo. Thus, Table 4 provides an overview of the simulations considered within the scope of this paper, although not all the internal iterations are exposed for each scenario due to the length of the paper. These internal iterations are based on the type of resources the LVC is able to control, being:

- **All controllable resources**: the DSO using the LVC considers for operation all available resources, the OLTC, ESS, HEMS, and curtailable microgenerators and loads;
- **HEMS**: the DSO using the LVC considers for operation the flexibility provided by the HEMS;
- **ESS and HEMS**: the DSO using the LVC considers for operation the combination of a central ESS (at the secondary of the MV/LV substation) and the flexibility provided by the HEMS;
- **Curtailable load and microgeneration**: the DSO using the LVC considers for operation the curtailment of the loads and microgenerators.

Table 4. Overview of the scenarios for Cluster 02.

Scenario Name	Network	Variation
Baseline Portugal	Typical PT LV network	Baseline—No variation considered
Large network	Typical PT LV network	Increase the number of nodes
Location of HEMS	Typical PT LV network	Change the location of the HEMS to primarily at the end of the feeders
Distributed ESS	Typical PT LV network	Introduce controllable distributed ESS in the network
Inductive network	Typical PT LV network	Modify the networks parameters to resemble an urban network
Forecast functions	Typical PT LV network	Variation of the data used to train the algorithms
State estimation functions	Typical PT LV network	Real data consideration and variation thereof the smart meter data available

3.2.3. SRA Results

- **Baseline—Portugal**

The baseline scenario is a small radial LV network with approximately 30 nodes. The network has the electrical characteristics of a typical Portuguese LV network, described in Appendix B. Moreover, Figure A1 from the Appendix, is a single-line representation of the network diagram with the electrical characteristics shown in Table A2. Additionally, Table A3 collects the microgenerators' installed capacity, the loads and the HEMS apparent power considered in the baseline. The radial network is composed of 33 buses and 32 lines. The assumption is that the network consists of 24 microgenerators and 43 consumers, 20 equipped with HEMS. It is also assumed that a DSO-owned 10 kW/30 kWh ESS, installed at the secondary side of the MV/LV transformer. The consumers were distributed between the three phases according to their contracted power to reduce unbalances between phases.

The network, when simulated, already presents over- and undervoltages. Not all the potential solutions considered tackled the voltage problems. The ideal solution of the LVC controlling all the available resources, although the LVC was only recurring to the OLTC, mitigates the voltage violations with an average execution time of 0.39 s. The results are depicted in Figures 9 and 10.

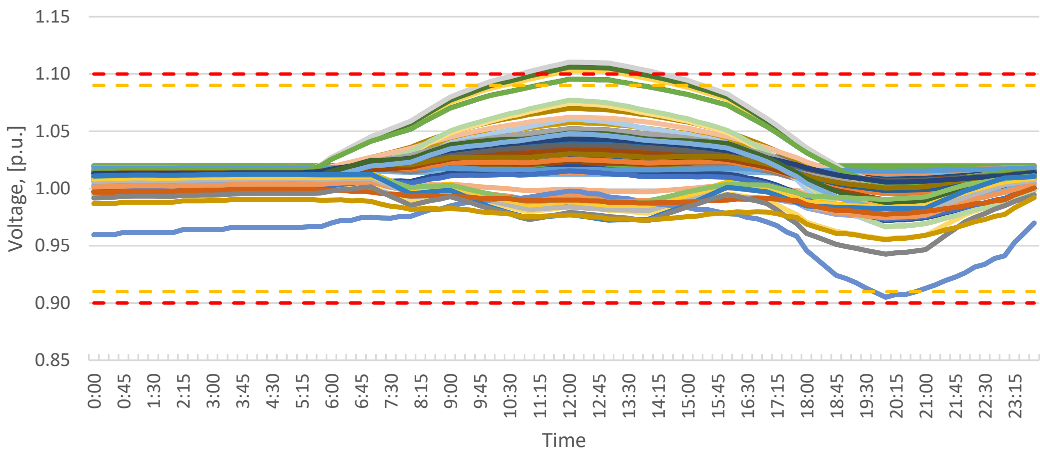


Figure 9. Baseline voltage profiles before the application of the LVC.

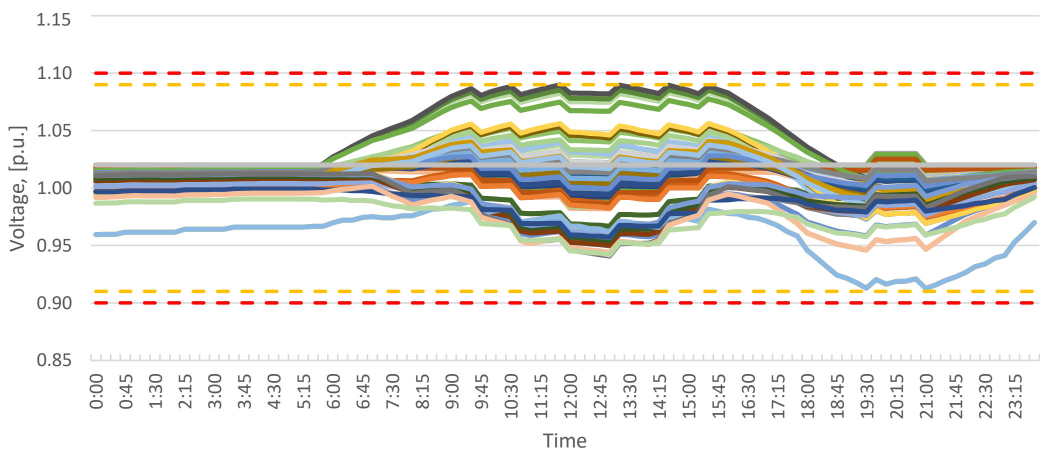


Figure 10. Baseline voltage profiles, after the application of the LVC controlling all resources.

Given the case of the LVC using only the flexibility from the 20 available HEMS, the LVC does not solve all voltage problems. Although all the undervoltage problems are mitigated, the overvoltages are only attenuated but not solved. The average execution time is 1.37 s. The use of the ESS and HEMS by the LVC also cannot mitigate all overvoltages registered. The result is that the storage system location is the most efficient in addition to HEMS flexibility not being enough. However, the LVC mitigates all undervoltages scoring an average of 1.63 s. Applying load and generation curtailment technique by LVC, the LVC solves the voltage problems within an average execution time of 1.58 s and curtailment of 19.07 kWh.

- **Large Network**

In this scenario, the network size increases to approximately 150 nodes to evaluate the LV performance when facing larger nodes and resources. The resulting network is represented in Figure A2 in Appendix B. The ratio of consumers with HEMS, the ratio of microgenerators-to-consumers were kept constant. The result is a network with 223 consumers, 82 of them equipped with HEMS (distributed homogeneously) and 114 microgenerators.

Similar to the baseline, the scaled network presents voltage problems when there is no LVC. However, the LVC in this scenario is to solve the voltage problems. When the LVC considers all available resources, it recurs to the OLTC to solve the overvoltages due to the solar injection. Then, the LVC to solve the undervoltages, it is necessary to activate the OLTC, ES, and HEMS. The LVC algorithm first uses the OLTC positions. Once the OLTC reaches its maximum tap position, the algorithm tries to use the ESS. As the ESS resource is exhausted, the LVC recurs to the activation of 2 HEMS devices. The LVC needs an average execution time of 9.15 s. When the HEMS is the only resource for the LVC, it is necessary to activate 28 HEMS to solve under- and overvoltages with an average execution time of 64.26 s. When the LVC controls the ESS and HEMS, the ESS reaches its max SOC to solve the overvoltage problems and drops to less than 30% to solve the undervoltage violation. Using this combination of assets, the total amount of HEMS activated reduces, but the average execution time increases to 74.27 s. Concerning the curtailment of load and microgeneration to solve all voltage associated problems, the LVC needs to curtail 3.41 kWh of energy generation and 6.85 kWh of consumption. In this last case, the LVC needs an average execution time of 11.94 s.

- **Location of HEMS**

The location of assets is key in distribution networks [41]. Hence, in this scenario, the aim is to investigate the actual HEMS impact in the network. The baseline scenario is used for comparison. The simulation results are collected in Table 5.

Table 5. Results the location of HEMS scenario considering only "HEMS" and "HEMS and ESS".

	Voltage Problem Solved?	HEMS Flexibility, [kWh]	E_{ESS}, [kWh]	P_{loss} Reduction, [%]
Homogeneous Distribution of HEMS (Baseline)				
HEMS	No	16.53	-	0.09%
HEMS and ESS	No	16.41	94.63	0.11%
HEMS located at the end of the feeders				
HEMS	Yes	4.42	-	0.14%
HEMS and ESS	Yes	4.32	44.13	0.01%

Based on the results above presented, the location of the HEMS has a significant impact, as expected. While in the baseline, the available flexibility is not sufficient to solve all of the voltage deviation problems registered, the LVC in this scenario is able to solve all of the forecasted voltage deviation. Furthermore, it can also be seen that the total amount of flexibility required from HEMS decreases due to the location and if there is an activation of the ESS. Concerning the computation type, the average execution time decreased 36% for the HEMS and 31% for the HEMS and ESS. Although the results are expected, the simulations are empirical data to assess the decision-making process of the DSO in order to encourage the appropriate engagement of those customers located ideally at the end of the feeder. The fact of engaging these customers has an impact in potential future resources as the ESS, as less flexibility is needed to solve the voltage problems and these problems tend to be very localized.

- **Distributed Energy Storage Systems**

The objective of the scenario is to evaluate the impact of distributed ESSs on the controllability of the LV network when there is a high integration of DER along with the LV feeders. The assumption for this scenario is the inclusion of 5 ESS being one centralized, in the secondary node of the MV/LV transformer, and 4 distributed along with the feeders. Additionally, this scenario considers 49 generators and 54 consumers, 33 of them equipped with HEMS. In Table 6 are listed the characteristics of the ESS devices considered.

The results of the simulation are collected in Table 7, which includes the total flexibility required from HEMS, from ESS (E_{ESS}), and the active power loss (P_{loss}) reduction.

Table 6. Characterization of ESS.

Node	ESS Characteristics	
	Power, [kW]	Capacity, [kWh]
1	50.00	100.00
18	10.00	20.00
23	10.00	20.00
24	10.00	20.00
26	10.00	20.00
27	10.00	20.00

Based on the results, and as previously stated in the baseline, the HEMS and ESS combination for the baseline when there is a centralized ESS cannot solve the voltage problems. In comparison, when considering distributed ESS, the problems are solved and require less flexibility from the ESS and the HEMS, which impact the costs of operation for the DSO. Hence, this remarks the importance of DER when dealing with voltage problems at the LV side, which tend to have a localized character. The LVC needs an average execution time of 0.81 s for distributed ESS while the centralized needs 1.63 s, reducing the computational burden.

Table 7. Baseline and distributed ESS comparison, considering the control of "HEMS and ESS".

	Voltage Problem Solved?	HEMS Flexibility, [kWh]	E_{ESS}, [kWh]	P_{loss} Reduction, [%]
Centralized ESS (Baseline)				
HEMS and ESS	No	16.41	94.63	0.11%
Distributed ESS				
HEMS and ESS	Yes	4.96	86.13	6.30%

- **Inductive Network**

This scenario aims to study the behavior of the LVC tool for an inductive character LV network (e.g., urban network). The X/R ratio of the lines was increased by a factor of 2 compared to the baseline scenario. The electrical characteristics are listed in Table A5 of Appendix B. The installed capacity of loads, generators, and HEMS is similar to the baseline scenario are listed in Table A3.

The voltage profiles before and after the use of the LVC are depicted in Figures 11 and 12 when considering all resources are controllable.

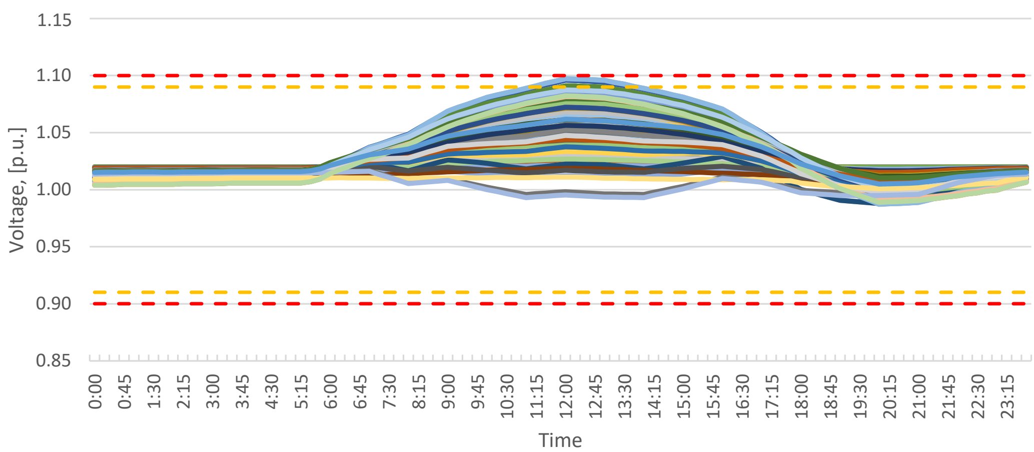


Figure 11. Inductive network voltage profiles, before the application of the LVC.

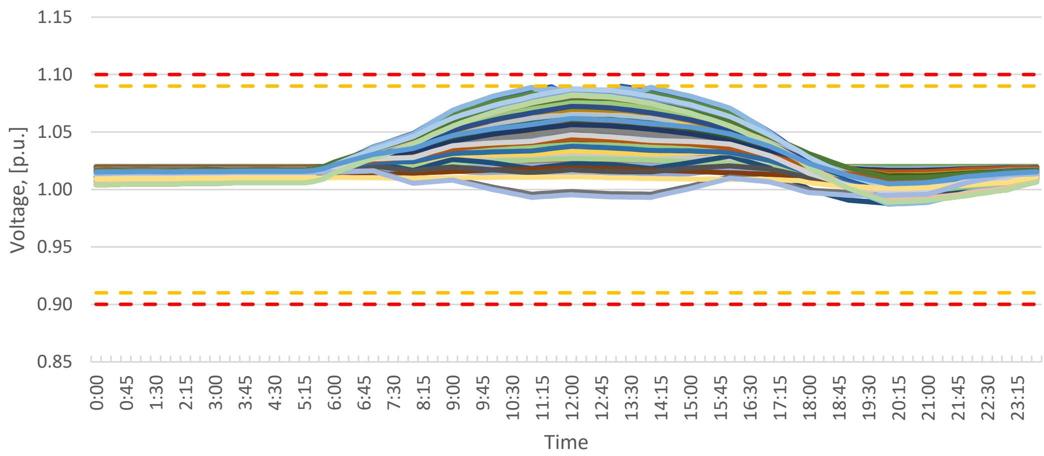


Figure 12. Inductive network voltage profiles, after the application of the LVC using all resources.

As expected, the LVC can solve the voltage problems regardless of the assets used (all resources, HEMS, ESS and HEMS, and curtailment of load and microgeneration). Nonetheless, the most exciting result is that the voltage fluctuates less than the baseline when using the LVC. Hence, the LVC is effective even in a more inductive network.

- **Forecast Functions**

In this scenario, the objective is to study the impact of forecast quality on the output of the preventive module of the LVC tool. This scenario uses the baseline network while the data input for the forecasting tools is changed as follows:

- Scenario A: 12 months of historical data;
- Scenario B: 3 months of historical data;
- Scenario C: 12 months of historical data, with missing values.

The results for the different simulations (A, B, and C) are summarized in Table 8 with positive results as all voltage problems are solved.

Table 8. Forecasting functions evaluation results.

Scenario	Voltage Problem Solved?	Flexibility Required, [kWh]	Average Execution Time, [s]	NRMSE, [%]
Scenario A	Yes	12.47	0.49	4.77%
Scenario B	Yes	12.22	0.50	4.86%
Scenario C	Yes	9.63	0.44	5.02%

From the comparison of the average normalized root mean square error (NRMSE) of scenario A and scenario B, the amount of data available has a positive impact on the error values—the error increases from 4.77% in scenario A to 4.86% in scenario B. Furthermore, it is also possible to see that missing data harms forecast quality. Comparing scenario A to scenario C, it is possible to see that the error increases from 4.77% to 5.02%. The control actions produced by scenarios A, B, and C are very similar. Nonetheless, Table 9 collects the amount of flexibility required from each HEMS when the LVC only considers the HEMS as an available resource.

Table 9. Impact of historical data in the flexibility required from HEMS for scenarios A, B, and C.

HEMS	Scenario #10	Scenario #11	Scenario #12
	12 Months, [kWh]	3 Months, [kWh]	12 Months Missing data, [kWh]
Node 12, phase T	1.32	1.51	0.89
Node 13, phase R	0.42	0.64	0.00
Node 20, phase R	3.92	3.29	2.49
Node 22, phase T	6.81	6.78	6.25

- **State Estimation Functions**

The LVC real-time module is dependant on the output from the estate estimation. Hence, three scenarios are used with different availability levels of real-time smart meter measurements to evaluate it. The network considered is similar to the one of the baseline scenario and the load, generators, and HEMS distribution.

- Scenario 1 (oracle): real data is considered (all smart meter measurements available);
- Scenario 2: 50% of real-time smart meter measurements available;
- Scenario 3: minimum real-time smart meter measurements available.

The mean absolute percentage errors (MAPE) obtained for the state estimations produced in scenarios 2 and 3 are collected in Table 10. Scenario 1 is not included as it is the oracle which uses perfect data.

Table 10. Scenario 2 and 3 mean absolute percentage errors results for the state estimations.

	Scenario 2	Scenario 3
	50% of Real-Time SM Measurements	Minimum Value of Real-Time SM Measurements
MAPE	0.33%	0.27%

The state estimation results considering different amounts of smart meter measurements are very similar. The MAPE is around 0.30% for both scenarios, resulting in a high level of accuracy of the LSVE even when limited data are available.

Table 11 shows a comparison example of the preventive and corrective set-point plans established by the LVC tool for the HEMS connected to node 22, phase T, for all the scenarios.

Table 11. Comparison between preventive and corrective set-point plans—12h30 time instant.

Scenario ID	Preventive Set-Point, [%]	Corrective Set-Point, [%]
Scenario 1	6	6
Scenario 2	6	6
Scenario 3	6	6

The snapshot produced by the LVSE tool was sufficiently similar to the voltage values obtained at the preventive control stage. Therefore, the previously established control actions did not require any update. It is worth noting that this result is an important validation step. The result compares the actual voltage values registered in the network with the values obtained through the LVC unbalanced power flow routine, based on forecasts for the load and generation.

3.2.4. Discussion

Similar to Cluster 01's approach, the SRA took the point of view of the LVC. However, the analysis is considered a holistic analysis as the tools impact the LVC and are modified.

Based on the several simulations performed, the OLTC can solve most of the voltage problems related to the increase in RES capacity or peak load, e.g., derived from simultaneous EV charging, in small and well-balanced networks. The ESS located at the secondary side of the transformer has a positive but limited effect on network operation. On the contrary, distributed storage is a more efficient solution to solve voltage violations in LV networks. This result is not surprising but helps the DSO to have data to support their potential inclusion into their operation based on location. In addition, it shows the capabilities of the LVC as a central tool for LV predictive maintenance in either case. However, if the network increases, neither the OLTC nor the central EES can mitigate the network violations. Contrariwise, distributed resources, such as HEMS enhance the controllability over LV networks since voltage violations are very localized. The adoption of distributed technologies enables an increase in the hosting capacity, enabling RES, and other DER, such as EV.

Therefore, DSOs responsible for large resistive networks will need to ensure adequate controllable devices within the grid to support active voltage control in future network scenarios. Distributed technologies solutions can provide a technical and cost-effective alternative to costly and time-consuming network reinforcement methods.

The flexibility of HEMS and distributed ESS showed adequate potential in achieving voltage control and reduced active power losses within the LV network. DSOs should, therefore, leverage the active engagement of customers to ensure the safe and reliable operation of their networks. In particular, the DSO should consider those customers close to the nodes that present the highest potential for voltage violations as key customers to participate in these types of flexibility schemes. These customers should be highly encouraged (possibly through incentives) to become active participants in network operation.

Concerning the forecasting and state estimation functions, the results show that the quality and amount of historical data available did not significantly affect the control actions produced by the LVC. The errors obtained were sufficiently small to not require any updates to the preventive control actions, therefore showing the accuracy and reliability of the proposed tools under Cluster 02.

4. Case Study: SRA for Slovenia

4.1. Cluster 03: Large Customer cVPP

4.1.1. Description of the Cluster

Cluster 03 is composed of tools that can assist the DSO in the safe operation of its network while customers provide their flexibilities to the manual frequency restoration reserve (mFRR) market. The TSO controls the mFRR market and, therefore, after the flexibilities of the flexibility operators (FOs) have been pre-qualified, the TSO can activate offered flexibilities. Thus, the DSO is currently not involved in the offering and activation process of flexibility bids. Depending on the volume of flexibilities and the dimensioning of the network, the activation of flexibility bids can lead to an increase in the number of constraints in the DSO's network. Such constraints can be, for instance, the overloading of transformers and cables or over- and undervoltage.

Within the InteGrid project, a traffic light system (TLS) has been developed (algorithm), which is involved in the flexibility bid offering and activation process. Thereby, it can curtail flexibility offers if network constraints are foreseen or suggest alternative flexibilities to be activated if an activation would cause problems in the network.

The TLS has two operation modes:

- *Day-ahead:* In the day-ahead mode, the flexibility operator (FO) periodically sends its flexibility bid offers to the TLS before the gate closure of the market. The TLS analyses these offers and flexibilities, which could lead to network constraints. With this information, the FO can adapt its bids to not interfere with the safe operation of the DSO's network. Before gate closure, the FO sends its final bids to the TSO, which the TLS has validated. If the TSO accepts the offers, the bids can be activated on the next day for the mFRR market;

- *Intraday:* In intraday, the TSO can activate the bids accepted on the day before. Thereby, the TSO forwards a bid activation to the TLS. It evaluates the bids to be activated and suggests an alternative bid activation to the FO if the activation would lead to network constraints.

Hence, Cluster 03 operates with various smart functions as depicted in Figure 13. The TLS is located within the DSO's premises. Thence, it has full access to the MV network model of the DSO. Furthermore, it periodically gets informed about the current state of the network including, for instance, the position of the breakers. In order to predict constraints in the network, the TLS uses load and RES forecasts for the next day. These forecasts are based on historical data like load and generation measurements and on external data like weather forecasts.

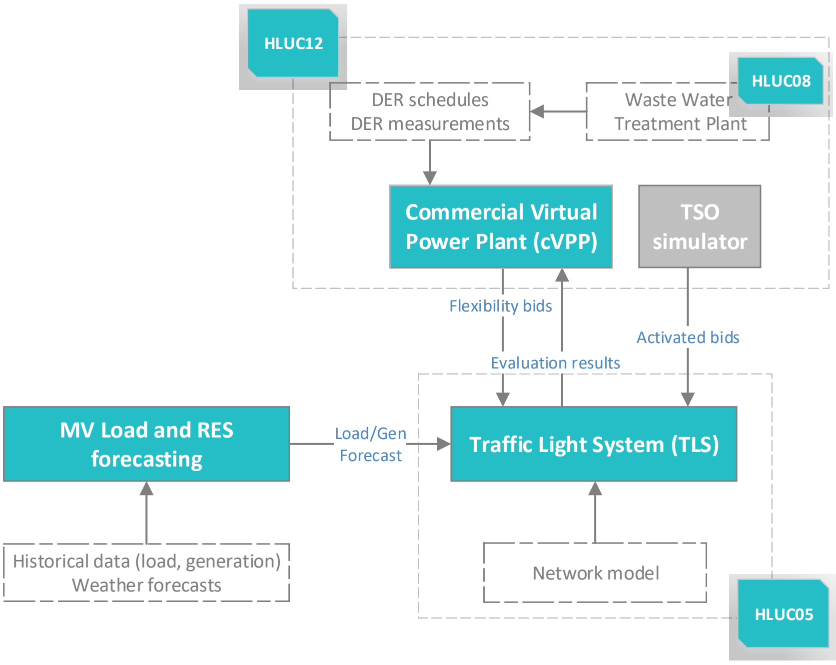


Figure 13. Cluster 03. Global architecture.

In InteGrid, a commercial virtual power plant (cVPP) acts as a FO. The cVPP's portfolio has various flexibilities, including, among others, a wind park, batteries, industrial customers, such as a wastewater treatment plant, and PV. The cVPP has its forecasting algorithms to predict the available flexibility volume on the next day. The TSO and the mFRR market are simulated with a TSO simulator. As previously stated, the TSO simulator is responsible for accepting the flexibility bid offers at gate closure and for activating bids for the mFRR market.

The TLS combines the previously mentioned data sources: forecasts, the network model, and the flexibility bids and their activation to predict and solve network problems caused by the flexibility bids. For these evaluations, the TLS leverages an instance of the same MPOPF used in Cluster 01. Using the MPOPF enables considering technical aspects—the safe operation of the distribution network (DSO)—and economic interests—a large flexibility volume with favorable prices (TSO).

In both cases, the TLS uses the data for the forecasts and the network model with the current switching state provided by the DSO. In this process, there is no sensitive data shared with third parties.

However, the flexibility bids from the cVPP and the TSO's activation signals come from sources outside the DSO's premises. These data are sensitive and should be transmitted with secured and encrypted connections. Otherwise, competing cVPPs, for example, could adapt their bidding strategy to the current leaked bid offers, which results in unfair competition. Therefore, the gm-hub is the interface between the TLS and the cVPP and TSO simulator for secure (encrypted) data transmission.

The MPOPF which is a key part of the TLS, has a quadratic cost function which is shown in Equation (1) on page 8. This type of cost function is usually used to reduce the cost of generation. The factors a_i^t and c_i^t are set to 0 in order to increase the amount of flexibilities that can be activated while considering the costs of the flexibilities. The linear term in the cost function uses different factors b_i^t for the upward and downward direction. Equations (4) and (5) show the calculation of the factors b_i^t for the upward and downward direction where p_i^t is the energy costs for flexibility i at the timestamp t and s is a small positive parameter in comparison to $\max_{j\in F}(p_j^t)$.

$$b_{i,up}^t = p_i^t - \max_{j\in F}(p_j^t) - s \tag{4}$$

$$b_{i,down}^t := p_i^t - \min_{j\in F}(p_j^t) + s \tag{5}$$

Prices for generation are assumed to be positive, when neglecting the parameter s. Equation (4) shifts all prices to non-positive numbers, such that the most expensive flexibility with the price $\max_{j\in F}(p_j^t)$ is $0\,€\,\text{MWh}^{-1}$. The optimiser activates as many flexibilities as possible because the injected powers are positive (producer frame) and if the prices are negative. Therefore, when minimizing the cost function, the optimizer gets rewarded for activating flexibilities. With the calculation of the factors $b_{i,up}$, the cheapest flexibility has the most considerable absolute value and has, therefore, the most substantial weight in the cost function, while the most expensive flexibility has the smallest weight. The constant s is used to shift the most expensive flexibility from $0\,€\,\text{MWh}^{-1}$ to $-s$ such that the optimiser is also slightly rewarded for activating it. In the downward case, negative prices are shifted to non-negative values because the active power injection of loads is negative. The product of $b_{i,down}$ and p_i results again in a negative number and the optimizer is rewarded for activating flexibilities.

4.1.2. Objectives of the SRA and Scenarios

The objective of the functional SRA for Cluster 03 is to help answer the following questions:

- What is the maximum flexibility volume in the network which can be activated without violating any network constraints?
- Does the TLS limit the provision of flexibilities in the DSO's network, and does it curtail the flexibilities fairly?
- Which prerequisites and conditions are needed such that an operation of the TLS is needed?

Following the same logic as in Cluster 01 and Cluster 02, the SRA for Cluster 03 focuses on the results of the TLS to directly analyze this tool and indirectly the other tools. The SRA, nonetheless, is performed from the DSO's perspective and modifies different parameters. From the viewpoint of the TLS, the flexibilities are treated as technology-neutral. The TLS only considers their location and offer prices. Furthermore, if multiple FOs offer bids for evaluation, the bids are aggregated such that the TLS cannot link flexibilities to their operators.

Concerning the scalability, the following parameters are modified:

- **Flexibility from the cVPP:** increase in the flexibility offered by the cVPP to evaluate the maximum amount of flexibility that each feeder can sustain;
- **Network size:** the size of the network has a direct influence on the computation time of the TLS. Hence the number of nodes is changed.

With respect to the replicability, the following parameters are modified:

- **Bid prices:** use different bid prices from homogeneous price to increasing and decreasing linear prices;
- **Distributed generation:** increase in distributed generation in a selection of feeders to evaluate the impact in the amount of upward reserve which could be provided;
- **Electric vehicles:** addition of electric vehicles in a selection of feeders to evaluate impact in the the amount of upward reserve which could be provided;
- **Urban/rural networks:** the analysis is carried-out on different grids to be as representative as possible;
- **Forecasting accuracy:** the impact of the forecasting accuracy on the post-activation evaluation is considered.

In comparison to Cluster 01 and Cluster 02, the simulations are performed on a feeder-level. In order to make the results comparable, the tapping position of the OLTC of the primary substation is fixed and the voltage on its HV-side is assumed to be 1.0 p.u. Each node in the network has an lower voltage limit of 0.9 p.u. and an upper limit of 1.1 p.u.

Cluster 03 uses the same Slovenian (SI) and Portuguese (PT) networks for the analysis as in Cluster 01. However, due to the large number of scenarios that can also have sub-scenarios, selected scenarios that yield the most relevant results are presented within this paper. These scenarios are collected in Table 12.

Table 12. Overview of the scenarios for Cluster 03.

Scenario Name	Network	Variation
Baseline Slovenia	SI demo	Baseline—No variation considered
Large homogeneous flexibility	SI demo	Large flexibility bids (power) at each node—Same price
Reduced homogeneous flexibility	SI demo	Reduced flexibility bids (power) at each node—Same price
Linear prices	SI demo	Introduce controllable distributed ESS in the network
RES and EV integration	SI demo	Future scenario with RES and EV integration in specific feeders

4.1.3. SRA Results

- **Baseline—Slovenia**

For the baseline scenario for scenario, the demonstration network in which Cluster 01 and Cluster 03 have been demonstrated is used. Details of the topology and properties of this network have already been described in Section 3.1. It consists of four networks (islands) which are denoted as “Domžale TF1”, “Domžale TF2”, “Mengeš TF1” and “Mengeš TF2”. Similarly to Cluster 01, no constraints are created with the currently available flexibility volume. These simulations have been performed with flexibilities with a total active power volume of 1.9 MW. Due to the over-dimensioning of many distribution networks in central Europe [6], the currently available flexibilities have a minor impact on the network condition. Therefore, they provide potential for additional flexibility. In the next sections the analysis of additional flexibility which can be added to the network without exceeding the network limits is discussed.

- **Large Homogeneous Flexibility**

In this scenario, the analysis focuses on the maximum flexibility that can be activated without causing network constraints. This is achieved by adding large flexibilities with 50 MW to each node in the network. The addition is done for downward and upward flexibilities separately, where downward means flexibilities which can increase their load or can decrease their generation. In contrast, upward flexibilities refer to a decrease in load or increase in generation. With 50 MW it is guaranteed that not a single flexibility can be fully activated without creating constraints in the network. Thus, the solution of the evaluation of the TLS provides the maximum potential in terms of flexibility volume.

Table 13 shows results for the flexibility potential. Thereby, the results for *one feeder per network* which has been selected is shown for both directions. Furthermore, it gives information about the number of critical lines, the number of critical nodes, and the number of critical transformers. Lines and transformers are referred to as “critical” when they are limiting the activation of additional flexibility into the feeder and, thus, reach their thermal loading limit. Critical nodes also reduce the flexibility that can be activated because they reach their voltage limit in the simulations. The column minimum and maximum flexibility quantify the number of flexibilities that can be activated for the hour with the smallest or largest volume within the 24 h.

Table 13. Maximum activate-able flexibility in the Slovenian demo network for selected feeder.

Grid Name	Direction	Critical Lines #	Critical Nodes #	Critical Transf. #	Min. Flex. MW	Max. Flex. MW
Domžale TF1	Upward	14	2	-	11.68 MW	12.69 MW
Domžale TF2	Upward	2	-	-	13.24 MW	13.95 MW
Mengeš TF1	Upward	1	-	-	25.18 MW	26.40 MW
Mengeš TF2	Upward	7	-	-	11.13 MW	12.14 MW
Domžale TF1	Downward	1	-	-	6.75 MW	7.94 MW
Domžale TF2	Downward	1	-	-	10.92 MW	11.63 MW
Mengeš TF1	Downward	-	-	1	8.60 MW	9.59 MW
Mengeš TF2	Downward	1	-	-	7.43 MW	8.46 MW

The results show the networks are load dominated. When comparing the upward with the downward results, more flexibility can be activated in the upward direction. When considering all feeders and not only those selected, as shown in the Table 13, 20 out of 21 analyzed feeders are constrained. The constraints are mainly by the overloading of lines for the upward direction. Only one feeder—which is also presented in the table—is also limited by overvoltage. For the downward case, in one network, in three out of four feeders, the flexibility potential is limited by the thermal limit of the primary substation. For the other feeders, the limiting element is, in all cases, one line. Lines that are close to the primary substations are, in most cases, the limiting factors (thermal limit) for those feeders.

- **Reduced Homogeneous Flexibility**

For the large flexible resources, only a few flexibilities are activated by the MPOPF. To get a better distribution of enabled flexibilities, the maximum activate-able volume of flexibility is distributed evenly across all network nodes. Equation (6) shows the formula for calculating the quantity of the flexibilities P_{flex}, where F is a set of all flexibilities, P_i is the active power activated from the MPOPF for flexibility i and α is a factor more significant than one to ensure constraints in the network ($\alpha = 1.05$ in the simulations). This approach is applied individually for upward and downward flexibilities and all feeders.

$$P_{\text{flex}} = \alpha \frac{\sum_{i \in F} P_i}{\dim(F)} \tag{6}$$

Figure 14 shows the available flexibility for all feeders of the Slovenian demonstration network for the downward direction. The results show that the location of the flexibilities plays a crucial role. In this scenario, it would be, in theory, possible to obtain the same flexibility volume to be activated as in the previous scenario. However, in some feeders up to 40 % less flexibility can be activated without causing problems in the network. Long feeders, such as "22051062" or "22051064" show a volume reduction, whereas short feeders, such as "22050999" or "22051034" are not considerably effected.

For the upward flexibilities, the results are comparable to the results in Figure 14, the maximum relative change is again at approximately −40 %, and long feeders get curtailed to a greater degree.

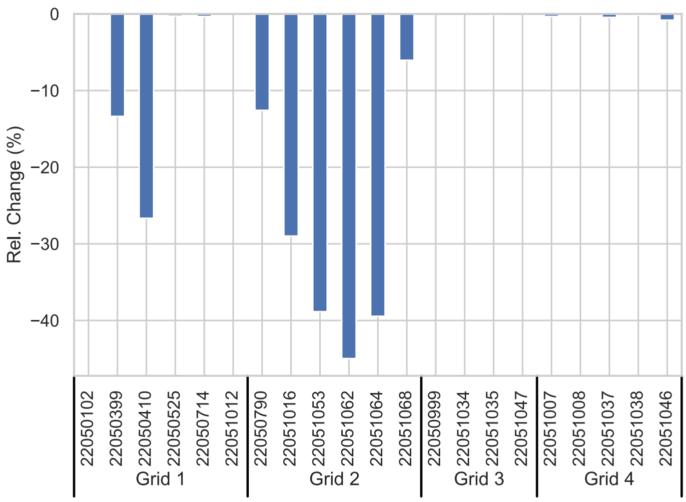


Figure 14. Comparison of activate-able flexibility between the scenario with flexibilities with a reduced and with a large volume (baseline).

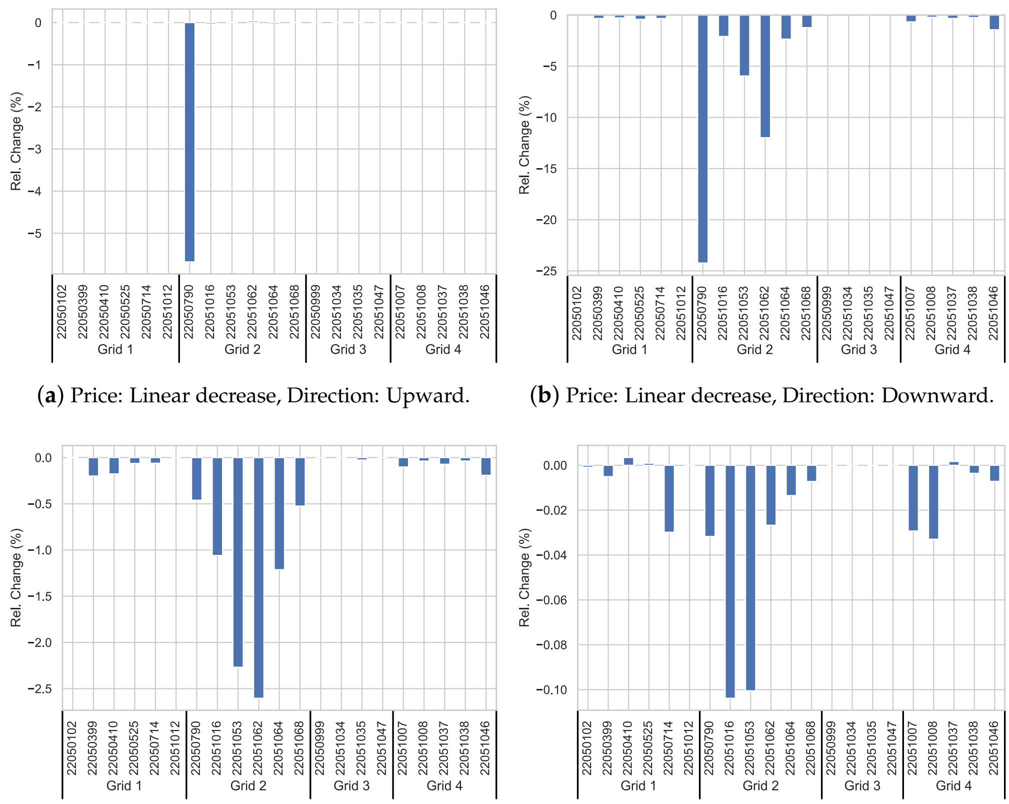
- **Linear Prices**

The last two scenarios show that each flexibility has been treated the same from a technical perspective: all flexibilities have the same active power volume and price. Therefore, the solver of the optimization problem activated or curtailed the flexibilities depending on their location in the network. However, in energy markets, the price of the flexibilities becomes substantial when selecting the flexibilities to be used. In addition to the *technical* constraints of the network, *economic* interests have to be considered as they are an essential factor.

Thence, this scenario analyzes the influence of the price on the flexibility volume that can be activated. As a baseline for comparison, the results of the previous scenario are used. A linear price change is assumed from the flexibilities at the beginning of the feeder to the feeders located at the end. The scenario is split into two sub scenarios. In the *linear price decrease* scenario expensive flexibilities with 300 €/MWh are at the beginning of feeders and the prices decrease linearly to 0 €/MWh for flexibilities at the end of the feeder. For the *linear price increase* scenario, it is the opposite; cheap flexibilities are at the beginning of the feeder and expensive flexibilities at the end of the feeder. Figure 15a,b show the results for the linearly *decreasing* prices.

In the case of upward flexibilities Figure 15a only minor differences between the baseline and the price scenarios are expected because the MPOPF preferably activated flexibilities at the end of the feeder when the same prices are assumed. The same is for all feeders; the results are close to the baseline results except for feeder "22050790". Feeder "22050790" was the only feeder for which the upper voltage limits have been reached in the baseline scenario. Therefore, activated flexibilities at the end of the feeder lead to a non-ideal solution because less flexibility volume is needed to reach the voltage limit. In comparison for downward flexibilities and decreasing prices (Figure 15b), the MPOPF preferably activates flexibilities at the end of the feeder, which results in additional losses and violations of the lower voltage limits. Therefore, if flexibilities get activated in a technical non-optimal way, it reduces activate-able flexibilities.

In Figure 15c,d and plots show the results for flexibilities which prices *increase* linearly from the beginning to the end of the feeder. As previously mentioned, the optimizer preferred to activate flexibilities at the end of the feeder for the upward direction. When assuming increasing prices and upward flexibilities (Figure 15c), the prices mislead—from a technical perspective—the MPOPF to activate flexibilities at the beginning of the feeder. Therefore, the results show a reduced volume of activate-able flexibility. However, when analysing increasing prices for downward flexibilities, the technical results align with the economic results. The relative changes are small with less than −0.12 %, due to that the deviations between these scenarios.



(**a**) Price: Linear decrease, Direction: Upward. (**b**) Price: Linear decrease, Direction: Downward.

(**c**) Price: Linear increase, Direction: Upward. (**d**) Price: Linear increase, Direction: Downward.

Figure 15. Comparison of the baseline results (all flexibilities have the same price) to the scenarios "linear price decrease" and "increase in the flexibilities".

- **RES Integration**

The previous scenarios showed that many additional flexibilities have to activate with the current network conditions to reach the network limits. In the scenario, additional volatile renewable energy sources are added to the network to test if the TLS can handle networks at their limits. In feeder, "22050790", four additional wind turbines are added which have in total nominal power of 11.5 MW.

Figure 16 shows in blue the upward flexibility, which can be activated without creating any network constraints with the currently installed loads and generation. The flexibility volume varies only marginally between 11.06 MW and 12.15 MW.

When adding the wind turbines (a historic wind profile has been used for this area), additional generation is in the network, and less flexibility can be activated in the upward direction.

Within Figure 16, in red is depicted the activate-able flexibility which varies between 0.62 MW and 8.76 MW.

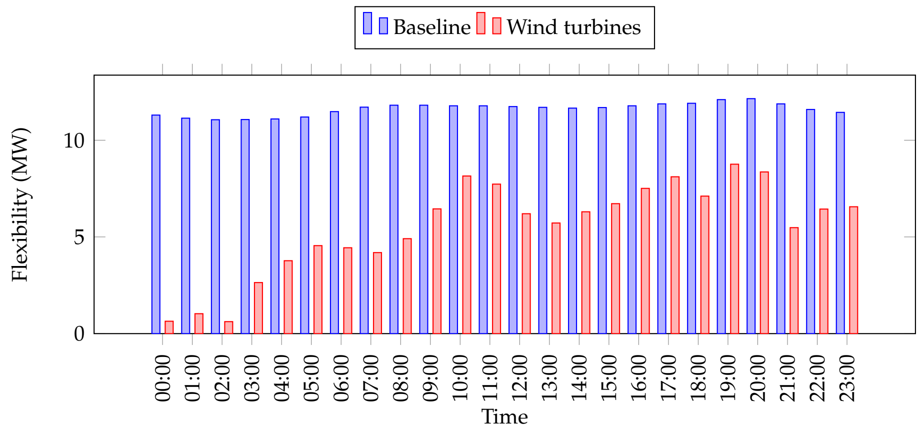


Figure 16. Activate-able flexibility volume with and without additional wind turbines.

4.1.4. Discussion

The TLS is designed to solve problems in the network caused by flexibilities by using an MPOPF to consider the network constraints (technical) and the economic interests in the energy markets. The SRA conducted for Cluster 03 assisted in evaluating the TLS and MPOPF against future scenarios and challenging situations. The analysis could answer the questions stated for the SRA.

The maximum flexibility volume was computed using two approaches, (1) increasing the number of flexibilities (2) adding additional non-flexible loads and generation, which drives the networks close to their limits. These simulations considered the same price for all flexibilities. These simulations showed that the MPOPF, if not faced with an even distribution of flexibility, has a bias towards large flexibility. The consequence of this operation could potentially result in unfair treatment by the TLS where only flexibilities located at the right place are always activated and can limit the amount of flexibility that can be activated. Hence, the TLS does limit the provision of flexibility. By its design, it can be considered in some instances unfair when curtailing flexibilities.

From an economic point of view, the use of linear prices decreases the activate-able flexibility volume. In the worst case, the decrease is approximately −24 % in comparison to the scenarios where all the flexibilities have the same prices, as the price can mislead to activate cheaper flexibilities which are not the best technical solution. However, a trade-off between the focus on technical and economic feasibility has to be made due to their contradiction.

When considering a future scenario with higher RES penetration (wind) to stress the TLS, the TLS performs correctly, decreasing activate-able flexibility volume. In the worst case, the activate-able flexibility decreases from 11.30 MW to 0.64 MW, whereas in other hours more than 8 MW. The result is interesting as with the increase in RES, the TSO might need more flexibility, but the volume from the distribution grid side might be limited.

The presented scenarios show that the TLS, combined with the cVPP, MV load, and RES forecasting and the MPOPF, can solve problems in the MV network caused by flexibility participating in energy markets. When problems are foreseen in the DSO's market caused by flexibilities and their simultaneity factor, the network operator has three possibilities to deal with this problem (1) restrict the number of flexibilities in the pre-qualification process (2) make grid reinforcements (3) curtail the flexibilities when needed by using approaches, such as the TLS. The first approach hampers the penetration of renewables in the network, while the second option might be expensive depending on the current status of the network.

When the problems caused by flexibilities are only expected to occur occasionally, the set of tools of Cluster 03 with additional measurement equipment can be used to solve these issues. The prerequisite is then to face problems caused by flexibilities.

5. Potential Replication Paths

The presented set of tools are implemented in real demonstration and developed within the context of an European project. Hence, this section tries to address and facilitate the potential replication of the tools presented. Current and future smart grid projects can capitalize on the experience gained. Thence, a simple replication path is developed to show a step oriented process which can guide future stakeholders in their endeavor towards implementing real smart grid functions in their projects. The replication path is depicted in Figure 17.

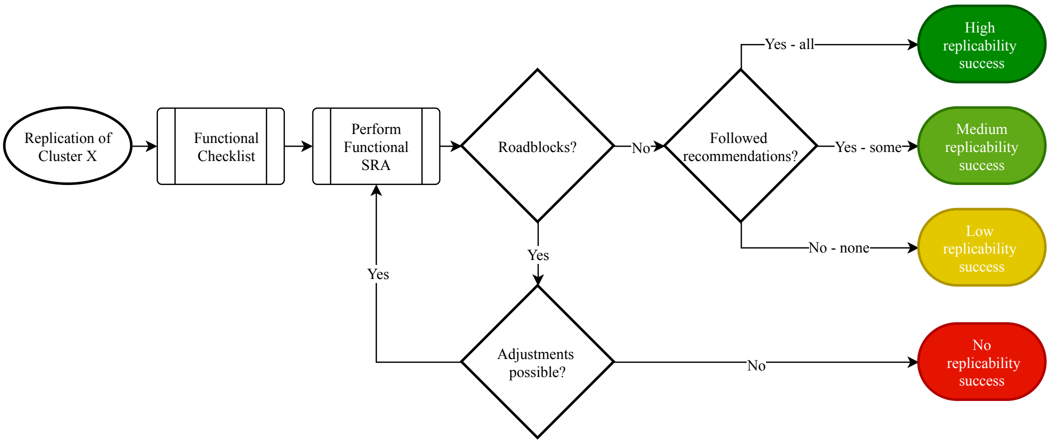


Figure 17. Functional-oriented replication paths identified.

Furthermore, this is complemented by a checklist offered in Table 14. The checklist approach ensures that the significant aspects are considered and allows the stakeholder to assess the smart grid implementation success rate in any network under consideration. More specifically, this will enable stakeholders to adequately evaluate whether the feasibility of smart grid function implementation (from the technical perspective) is comparable to traditional network reinforcement methods. The SRA plays a vital role in this decision-making process, particularly for stakeholders who wish to enhance their networks in the direction of flexibility markets and increase TSO–DSO interaction.

Table 14. Functional-oriented compressed checklist.

Cluster	To Be Checked
All	Are the relevant network characteristics known and available? Is there an OLTC (with control active) to provide support? Is there sufficient data available and accessible (devices, weather, future estimations)? Is the dataset complete and accurate to obtain?
01	Check the necessary tools information (MV Load/REs forecasting, MV Load Allocation, MOPF) Check the necessary actors: tVPP (VPP) and DSO Check the network: is it already experiencing any voltage/congestion violations. If so, how much, how long and at which nodes?
02	Check the necessary tools information (Load and RES forecasting, LVC, LVSE, OLTC, HEMS) Check necessary actors: DSO (also their assets) and customer/flexibility owners Check the network: is it already experiencing any voltage/congestion violations and size Check HEMS: location and number of customers
03	Check the necessary tools information (Load and RES forecasting, TLS) Check the necessary actors: cVPP (VPP), DSO and TSO Check current flexibility in the network: quantification, location, and feasibility

6. Conclusions and Outlook

This paper presented the SRA of advanced smart grid functions for MV and LV grid monitoring and control, as well as for TSO-DSO coordination, conducted in the framework of real-world demonstration pilots. The SRA provides the DSO with valuable information regarding the potential impact of DER flexibility on the future network and captures overlooked functional and non-functional requirements for new functions in the distribution management system.

The results obtained in the demonstration activities showed that the developed tools are: (1) scalable as they perform correctly (e.g., meet expected computational performance, numerical results accurately capture grid operating conditions) in real conditions (e.g., large MV distribution grids) and (2) replicable since they can be implemented under different regulatory frameworks, electrical network characteristics (e.g., R/X ratio, number and type of DER and other assets) and data availability scenarios. The use of clustering in the SRA enabled an evaluation of the interdependence (and dependability) between tools and functions and their impact in the overall system performance, in particular, the impact of observability in MV and LV grid operation, which represents a more realistic scenario. Moreover, this methodology also provides a relevant dataset to study other domains of SRA (i.e., ICT, economic, and regulatory), enabling a more detailed analysis of the requirements and main barriers (see [30] for the ICT domain). Regarding the potential replicability of the different tools by other stakeholders, this work provided a simple step-process for the possible success or failure when replicating the tools.

In the literature it is possible to find similar algorithms and functions for distribution grid and VPP management and control. However, the SRA (especially the methodology) remains a not fully established research topic and this analysis should be considered before deploying large-scale systems to guarantee the performance of the different tools used in the future. The topic of SRA will gain more importance as the decentralization, decarbonization, and digitalization in the energy sector continues to grow. The SRA is a natural step for tools that envision real deployment. The SRA allows the DSO to become empowered by increasing his knowledge of the status and requirements of their network by evaluating the impact of smart grid solutions through the implementation of a wide variety of scenarios and network conditions for which DSOs will be challenged in the future. This work, therefore, offers various network stakeholders an overview of the SRA and its approach based on the outcomes of the implementation of the InteGrid advanced smart grid tools within each of the demonstration sites and bridges the gap between proof-of-concept and large scale deployment.

Author Contributions: Conceptualization, S.P.M., R.J.B., B.H., C.K., B.-V.R., F.L., F.C., J.V.S., H.T., M.S., A.A.M., D.R., G.S., J.V., R.A.; methodology, S.P.M., F.C., M.S., H.T., J.V.S., M.S., L.O.; writing original draft preparation, S.P.M., J.V.S., M.S., J.R.A., D.C.; writing—review and editing, S.P.M., B.H., C.K., M.S., R.J.B.; visualization, S.P.M.; funding acquisition, R.J.B., U.K., R.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by European Union's Horizon 2020 research and innovation programme under grant agreement number 731218.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This work was developed within the framework of the InteGrid Project. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 731218. The sole responsibility for the content lies with the authors. It does not necessarily reflect the opinion of the Innovation and Networks Executive Agency (INEA) or the European Commission (EC). INEA or the EC are not responsible for any use that may be made of the information it contains.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AMI	Advanced Metering Infrastructure
BMS	Building Management System
cVPP	Commercial Virtual Power Plant
DER	Distributed Energy Resources
DSM	Demand Side Management
DSO	Distribution System Operator
ESS	Electric Storage System
EV	Electric Vehicles
FO	Flexibility Operator
GLPK	GNU Linear Programming Kit
gm-hub	Grid and Market Hub
HEMS	Home Energy Management System
HLUC	High Level Use Case
HVAC	Heating and Ventilation Air Conditioning
ICT	Information and Communication Technology
KPI	Key Performance Indicator
LVC	Low Voltage Controller
LVSE	Low Voltage State Estimator
MOPF	Multi Period Optimal Power Flow
MVLA	Medium Voltage Load Allocator
MW	Mega Watt
OLTC	On Load Tap Changer
P.U.	Per Unit
PV	Photovoltaic
RES	Renewable Energy Source
REST	Representational State Transfer
SCADA	Supervisory Control And Data Acquisition
SGAM	Smart Grid Architecture Model
SI	Slovenia
SRA	Scalability and Replicability Analysis
TLS	Traffic Light System
tVPP	Technical Virtual Power Pant
VPP	Virtual Power Plant

Appendix A. Developing Environments of InteGrid Tools

Table A1 presents the programming languages and technologies of tools presented in this paper and demonstrated in the InteGrid project.

Table A1. Programming languages and technologies of InteGrid tools

Tool	Prog. lang.	Technologies
MVLA	C++	RabbitMQ, Cassandra
Load/RES forecasting	Python	RabbitMQ, Cassandra, netCDF4, siphon, scikit-learn, tensorflow, statsmodels, Cron
MOPF	C++	RabbitMQ, Cassandra, Flask, pugixml, ATL
LVC	C++	Cassandra, libcurl, RapidJSON
LVSE	C++	Cassandra, libcurl, RapidJSON
TLS	Python	PostgreSQL
tVPP/cVPP	Java	RabbitMQ, MongoDB, Kubernetes, MySQL, KumuluzEE, React

Appendix B. LV Networks Characterization for Cluster 02

In this section are provided details regarding the characterization of the simulation scenarios of Cluster 02.

Appendix B.1. Baseline

The single-line diagram of the simulation network for scenario #1 (baseline) can be seen in Figure A1. In Table A2, are listed the electrical characteristics of the baseline scenario and, in Table A3, is listed the installed capacity of loads, generators, and HEMS.

Table A2. Cluster 02. Baseline LV network characterization and electrical characteristics.

Line	From	To	Electrical Characteristics	
Number	Node	Node	R, [Ω]	X, [Ω]
1	1	2	0.05666667	0.00850000
2	1	3	0.01904762	0.00400000
3	1	4	0.03666667	0.00550000
4	2	5	0.03095238	0.00650000
5	3	6	0.07692000	0.01800000
6	3	7	0.07000001	0.01050000
7	4	8	0.06666667	0.01000000
8	5	9	0.04666667	0.00700000
9	5	10	0.10395000	0.00525000
10	5	11	0.21874994	0.01050000
11	6	12	0.29166659	0.01400000
12	7	13	0.02333334	0.00350000
13	8	14	0.19890000	0.00975000
14	8	15	0.12415000	0.00975000
15	9	16	0.02333334	0.00350000
16	11	17	0.24955000	0.00525000
17	11	18	0.09550000	0.00750000
18	12	19	0.03809523	0.00800000
19	13	20	0.15280000	0.01200000
20	13	21	0.48405000	0.01575000
21	14	22	1.21210000	0.02550000
22	15	23	0.26740000	0.02100000
23	16	24	0.04666667	0.00350000
24	18	25	0.16135000	0.00525000
25	19	26	0.02380952	0.00500000
26	20	27	0.18749995	0.00900000
27	23	28	0.93450000	0.02100000
28	24	29	0.18440000	0.00600000
29	26	30	0.05333334	0.00400000
30	27	31	0.21420000	0.01050000
31	28	32	0.32270000	0.01050000
32	31	33	0.16135000	0.00525000

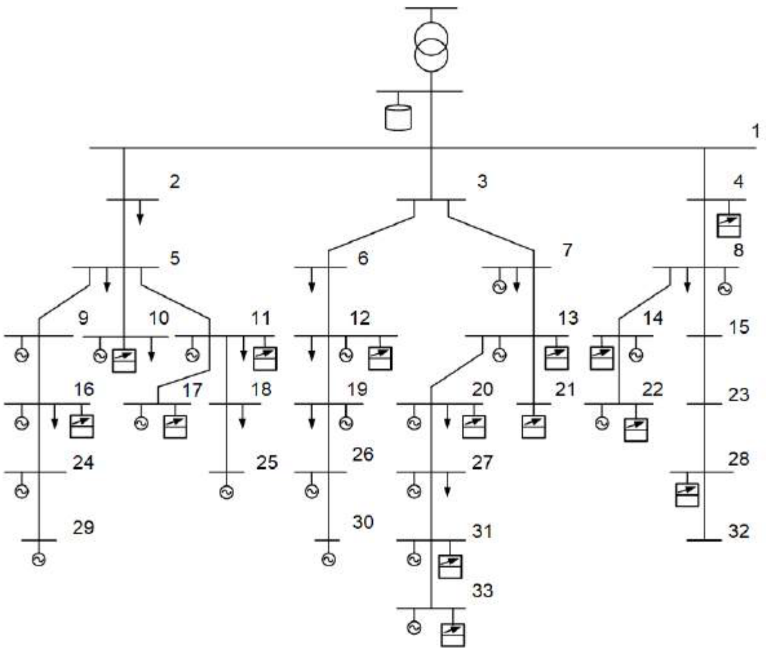


Figure A1. Cluster 02. Single-line diagram for the baseline.

Table A3. Cluster 02. LV network characterization, installed capacity of loads, generators, and HEMS for the baseline.

Node	Installed Capacity								
	Loads, [kVA]			Generators, [kVA]			HEMS, [kVA]		
	Phase R	Phase S	Phase T	Phase R	Phase S	Phase T	Phase R	Phase S	Phase T
2	3.45	3.45	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	5.75	-
5	-	-	3.45	-	-	-	-	-	-
6	1.15	-	-	-	-	-	-	-	-
7	6.90	-	-	5.75	-	-	-	-	-
8	3.45	3.45	3.45	5.75	-	-	-	-	-
9	-	-	-	3.45	-	-	-	-	-
10	3.45	6.90	-	-	5.75	-	-	5.75	-
11	3.45	-	-	-	-	3.45	-	-	5.75
12	3.45	3.45	-	-	-	3.45	5.75	-	5.75
13	-	-	-	3.45	-	-	5.75	-	-
14	-	-	-	5.75	-	-	5.75	-	-
16	-	6.90	-	-	3.45	-	5.75	5.75	5.75
17	-	-	-	-	-	-	5.75	-	-
18	-	3.45	3.45	-	-	-	-	-	-
19	3.45	3.45	-	-	-	5.75	-	-	-
20	-	3.45	3.45	5.75	-	-	6.90	5.75	-
21	-	-	-	-	-	-	-	5.75	5.75
22	-	-	-	1.15	-	-	-	3.45	3.45
24	-	-	-	5.75	5.75	5.75	-	-	-
25	-	-	-	-	-	5.75	-	-	-
26	-	-	-	-	5.75	3.45	-	-	-
27	6.90	3.45	3.45	3.45	-	-	-	-	-
28	-	-	-	-	-	-	-	3.45	-
29	-	-	-	-	-	5.75	-	-	-
30	-	-	-	-	-	5.75	-	-	-
31	-	-	-	3.45	3.45	-	-	6.90	-
33	-	-	-	1.15	-	-	-	-	5.75

Appendix B.2. Large Network

In Figure A2 is shown the single-line diagram of the simulation network used in the *Large network* scenario. For the sake of clarity, we refer the reader to [28] for more details regarding the characterization of the simulation network.

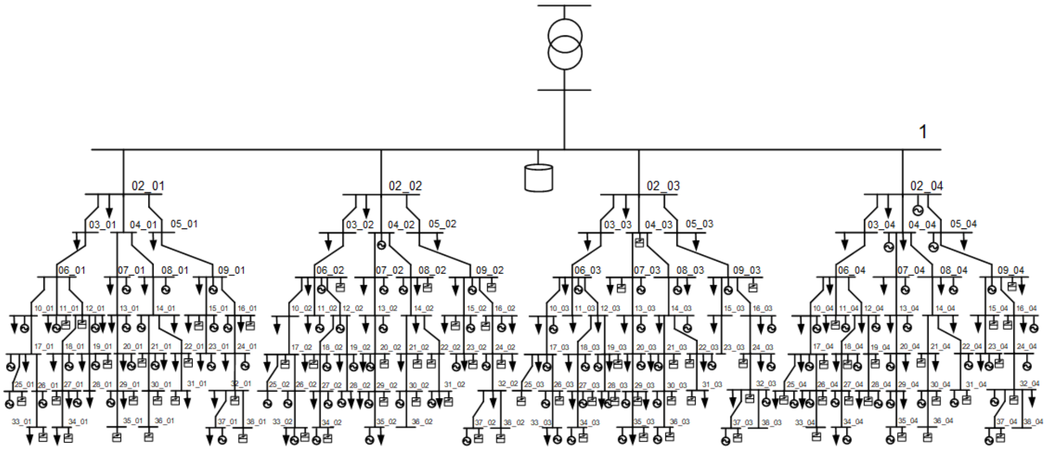


Figure A2. Cluster 02. Single-line diagram for the *large network* scenario.

Appendix B.3. HEMS Location

In Table A4 is listed the installed capacity of loads, generators, and HEMS of the *HEMS Location* scenario.

Table A4. Installed capacity of loads, generators, and HEMS.

	Installed Capacity								
	Loads, [kVA]			Generators, [kVA]			HEMS, [kVA]		
Node	**Phase R**	**Phase S**	**Phase T**	**Phase R**	**Phase S**	**Phase T**	**Phase R**	**Phase S**	**Phase T**
2	3.45	-	-	-	-	-	-	-	-
5	-	3.45	-	-	-	-	-	-	-
6	-	-	3.45	-	-	-	-	-	-
7	6.90	-	-	5.75	-	-	-	-	-
8	3.45	3.45	3.45	5.75	-	-	-	-	-
9	6.90	3.45	3.45	3.45	-	-	-	-	-
10	3.45	6.90	-	-	5.75	-	-	-	-
11	3.45	-	-	-	-	3.45	-	-	-
12	3.45	3.45	-	-	-	3.45	-	-	-
13	6.90	3.45	3.45	3.45	-	-	-	-	-
14	-	-	-	5.75	-	-	-	-	-
16	-	6.90	-	-	3.45	-	-	-	-
17	-	-	-	5.75	-	-	5.75	-	-
18	-	3.45	3.45	-	-	-	-	-	-
19	3.45	3.45	-	-	-	5.75	-	-	-
20	-	3.45	3.45	5.75	-	-	-	-	-
22	-	-	-	1.15	-	-	6.90	3.45	3.45
23	3.45	-	-	-	-	-	-	-	-
24	-	-	-	5.75	5.75	5.75	5.75	5.75	5.75
25	-	-	-	-	-	5.75	-	5.75	5.75
26	-	-	-	-	5.75	3.45	-	5.75	-
27	6.90	3.45	3.45	3.45	-	-	-	-	-
29	-	-	-	-	-	5.75	5.75	5.75	5.75
30	-	-	-	-	-	5.75	-	-	6.90
31	-	-	-	3.45	3.45	-	-	6.90	-
32	-	-	-	-	-	-	-	3.45	3.45
33	-	-	3.45	1.15	-	-	3.45	-	-

Appendix B.4. Inductive Network

The electrical characteristics of the simulation network of scenario *inductive network* are listed in Table A5.

Table A5. Network characterization and electrical characteristics of the *inductive network* scenario

Line Number	From Node	To Node	Electrical Characteristics	
			R, [Ω]	X, [Ω]
1	1	2	0.04006939	0.01202082
2	1	3	0.01346870	0.00565685
3	1	4	0.02592725	0.00777817
4	2	5	0.02188664	0.00919239
5	3	6	0.05439065	0.02545584
6	3	7	0.04949748	0.01484924
7	4	8	0.04714045	0.01414214
8	5	9	0.03299832	0.00989949
9	5	10	0.07350375	0.00742462
10	5	11	0.15467957	0.01484924
11	6	12	0.20623942	0.01979899
12	7	13	0.01649916	0.00494975
13	8	14	0.14064354	0.01378858
14	8	15	0.08778731	0.01378858
15	9	16	0.01649916	0.00494975
16	11	17	0.17645850	0.00742462
17	11	18	0.06752870	0.01060660
18	12	19	0.02693740	0.01131371
19	13	20	0.10804592	0.01697056
20	13	21	0.34227504	0.02227386
21	14	22	0.85708413	0.03606245
22	15	23	0.18908035	0.02969848
23	16	24	0.03299832	0.00494975
24	18	25	0.11409168	0.00742462
25	19	26	0.01683587	0.00707107
26	20	27	0.13258249	0.01272792
27	23	28	0.66079129	0.02969848
28	24	29	0.13039049	0.00848528
29	26	30	0.03771237	0.00565685
30	27	31	0.15146227	0.01484924
31	28	32	0.22818336	0.01484924
32	31	33	0.11409168	0.00742462

References

1. Pérez-Arriagaa, I.; Knittel, C.; Bharatkumar, A.; Luke, M.; Birk, M.; Miller, R.; Burger, S.; et al. MIT Energy Initiative: Utility of the Future. In *Technical Report*; MIT: Cambridge, MA, USA, 2016.
2. Alotaibi, I.; Abido, M.A.; Khalid, M.; Savkin, A.V. A Comprehensive Review of Recent Advances in Smart Grids: A Sustainable Future with Renewable Energy Resources. *Energies* **2020**, *13*, 6269. [CrossRef]
3. Boscán, L.; Poudineh, R. Chapter 19—Business Models for Power System Flexibility: New Actors, New Roles, New Rules. In *Future of Utilities Utilities of the Future*; Sioshansi, F.P., Ed.; Academic Press: Boston, UK, 2016; pp. 363–382. [CrossRef]
4. Zhang, Y.; Chen, W.; Gao, W. A survey on the development status and challenges of smart grids in main driver countries. *Renew. Sustain. Energy Rev.* **2017**, *79*, 137–147. [CrossRef]
5. Flavia, S.; Julija, V.; COVRIG; Catalin-Felix; Maria, M.A.; Gianluca, F. Smart grid projects outlook 2017: Facts, figures and trends in Europe. In *Technical Report*; Joint Research Center (JRC): Ispra, Italy, 2017.
6. Prettico, G.; Flammini, M.; Andreadou, N.; Vitiello, S.; Fulli, G.; Masera, M. Distribution System Operators Observatory 2018. In *Technical Report JRC113926*; Joint Research Center (JRC): Ispra, Italy, 2019.
7. H2020 Project InteGrid. Available online: https://integrid-h2020.eu/ (accessed on 19 November 2020).

8. Rivero, E.; Sebastian-Viana, M.; Ulian, A.; Stromsather, J. The evolvDSO project: Key services for the evolution of DSOs roles. In Proceedings of the CIRED Lyon 2015 Workshop, Lyon, France, 15–18 June 2015.
9. FP7 Project evolvDSO. Available online: https://www.edsoforsmartgrids.eu/projects/edso-projects/evolvdso/ (accessed on 19 November 2020).
10. FP7 Project Grid+. Available online: https://www.edsoforsmartgrids.eu/projects/edso-projects/past-projects/grid/ (accessed on 19 November 2020).
11. Sigrist, L.; May, K.; Morch, A.; Verboven, P.; Vingerhoets, P.; Rouco, L. On Scalability and Replicability of Smart Grid Projects—A Case Study. *Energies* **2016**, *9*, 195. [CrossRef]
12. FP7 Project Grid4EU. Available online: https://ses.jrc.ec.europa.eu/grid4eu (accessed on 19 November 2020).
13. FP7 Project IGREENGRID. Available online: https://cordis.europa.eu/project/id/308864 (accessed on 19 November 2020).
14. H2020 Project InterFlex. Available online: https://interflex-h2020.com/ (accessed on 19 November 2020).
15. Cen(2012). CEN-CENELEC-ETSI Smart Grid Coordination Group. Smart Grid Reference Architecture. Available online: https://www.cencenelec.eu/standards/Sectorsold/SustainableEnergy/SmartGrids/Pages/default.aspx (accessed on 19 November 2020).
16. Uslar, M.; Rohjans, S.; Neureiter, C.; Pröstl Andrén, F.; Velasquez, J.; Steinbrink, C.; Efthymiou, V.; Migliavacca, G.; Horsmanheimo, S.; Brunner, H.; et al. Applying the Smart Grid Architecture Model for Designing and Validating System-of-Systems in the Power and Energy Domain: A European Perspective. *Energies* **2019**, *12*, 258. [CrossRef]
17. Pinto, R.; Bessa, R.J.; Matos, M.A. Multi-period flexibility forecast for low voltage prosumers. *Energy* **2017**, *141*, 2251–2263. [CrossRef]
18. André, R.; Lopes, D.; Fonseca, D.; Almeida, B.; Bessa, R.J.; Madureira, A.; Simões, M.; Silva, J.; Sampaio, G.; Andrade, J.; et al. InteGrid pilot in Portugal: Smart grid based flexibility management tools for LV and MV predictive grid operation. In Proceedings of the CIRED Berlin 2020 Workshop, Berlin, Germany, 22–23 September 2020.
19. Lopes, D.; André, R.; Moreira, J.; Simões, M.; Sampaio, G.; Rua, D.; Machado, P.; Bessa, R.J.; Abreu, C.; Madureira, A. From home energy management system local flexibility to low-voltage predictive grid management. In Proceedings of the CIRED 2020 Workshop, Virtual, Berlin, Germany, 22–23 September 2020.
20. Nilsson, A.; Wester, M.; Lazarevic, D.; Brandt, N. Smart homes, home energy management systems and real-time feedback: Lessons for influencing household energy consumption from a Swedish field study. *Energy Build.* **2018**, *179*, 15–25. [CrossRef]
21. Ursula, K.; Boris, T. Demonstration of the technical and commercial VPP concept: Slovenian demo in the InteGrid project. In Proceedings of the CIRED 2018 Workshop, Ljubljana, Slovenia, 7–8 June 2018.
22. Leimgruber, J.L.B.F.; Korner, C.; Gutschi, C. The Traffic Light System to support Flexibility Exploitation from stressed distribution grids. In Proceedings of the CIRED 2019 Madrid, Virtual, Madrid, Spain, 3–6 June 2019.
23. Bessa, R.; Coelho, F.; Rodrigues, X.; Alonso, A.; Soares, T.; Pires, G.; Matos, P.; Prates, I.; Shahrokni, H.; Mäkivierikko, A. Grid and Market Hub: Empowering Local Energy Communities in InteGrid. In Proceedings of the CIRED 2018 Workshop, Ljubljana, Slovenia, 7–8 June 2018.
24. Moreira, J.; Bernardo, R.; Prata, R.; Krisper, U.; Bessa, R.J.; Coelho, F.; Schwarzländer, F. Service catalyst providing a neutral framework for supporting grid operation, while promoting market-based services: Grid and market hub. In Proceedings of the CIRED 2020 Workshop, Virtual, Berlin, Germany, 22–23 September 2020.
25. U.S department of Energy. The Smart Grid, What Makes a Grid "Smart?". Available online: https://www.smartgrid.gov/the_smart_grid/smart_grid.html (accessed on 19 November 2020).
26. Edris, A.A.; D'Andrade, B.W. 2—Transmission Grid Smart Technologies. In *The Power Grid*; D'Andrade, B.W., Ed.; Academic Press: Cambridge, MA, USA, 2017; pp. 37–55. [CrossRef]
27. Bessa, R.J. Use Cases and Requirements. In *Technical Report D1.2, H2020 InteGrid Project*; Publisher Integrid: Lisboa, Portugal, 2017.
28. Baut, J.L.; Potenciano-Menci, S.; Herndler, B.; Korner, C.; Rao, B.; Henein, S.; Potenciano-Menci, S.; López, G.; Domingo, J.; et al. Technical Scalability and Replicability of the InteGrid Smart Grid Functionalities. Technical Report D8.1, H2020 InteGrid Project. 2019. Available online: https://www.mdpi.com/1996-1073/13/15/3818 (accessed on 19 November 2020).
29. Cossent, R.; Lind, L.; Correa, M.; Gómez, T.; Pimentel, N.; Baut, J.L.; Menci, S.P.; Bharath-Varsh, R., Silva, M., Ávila, J.P.; et al. Economic and regulatory scalability and replicability of the InteGrid smart grid functionalities. In *Technical Report D8.2, H2020 InteGrid Project*; Publisher Integrid: Lisboa, Portugal, 2020.
30. Menci, S.P.; Baut, J.L.; Domingo, J.M.; López, G.L.; Arín, R.C.; Silva, M.P. A Novel Methodology for the Scalability Analysis of ICT Systems for Smart Grids Based on SGAM: The InteGrid Project Approach. *Energies* **2020**, *13*, 3818. [CrossRef]
31. Baut, J.; Kadam, S.; Menci, S.; Stefan, M.; Costa, J.M.; Silva, M.; Cossent, R.; Lind, L.; Morgado, M.; Bessa, R.J.; et al. Definition of Scenarios and Methodology for the Scalability and Replicability Analysis. In *Technical Report MS9, H2020 InteGrid Project*; Publisher Integrid: Lisboa, Portugal, 2017.
32. Rodríguez Calvo, A. Scalability and Replicability of the Impact of Smart Grid Solutions in Distribution Systems. Ph.D. Thesis, Universidad Pontificia Comillas, Madrid, Spain, 2017.
33. Viana, J.; Sousa, J.; Bessa, R.J. Load forecasting benchmark for smart meter data. In Proceedings of the 13th IEEE PES PowerTech Conference, Milano, Italy, 23–27 June 2019.
34. Andrade, J.R.; Bessa, R.J. Improving renewable energy forecasting with a grid of numerical weather predictions. *IEEE Trans. Sustain. Energy* **2017**, *8*, 1571–1580. [CrossRef]

35. Costa, J.; Trocato, C.; Moreira, J.; Rua, D.; Madureira, A.; Fonseca, D. LV Network Control Architecture: H2020 InteGrid Case Study. In Proceedings of the CIRED 2018 Workshop, Ljubljana, Slovenia, 7–8 June 2018.
36. Simões, M.; Madureira, A.G. Predictive Voltage Control: Empowering Domestic Customers With a Key Role in the Active Management of LV Networks. *Appl. Sci.* **2020**, *10*, 2653. [CrossRef]
37. Abreu, C.; Soares, I.; Oliveira, L.; Rua, D.; Machado, P.; Carvalho, L.; Peças Lopes, J.A. Application of genetic algorithms and the cross-entropy method in practical home energy management systems. *IET Renew. Power Gener.* **2019**, *13*, 1474–1483. [CrossRef]
38. Simões, M.; Sampaio, G.; Madureira, A.; Bessa, R.; Pereira, J.; Lopes, D.; Fonseca, D.; Godinho Matos, P.; Pires, R. Avoid technical problems in LV networks: From data-driven monitoring to predictive control. In Proceedings of the CIRED 2019 Madrid, Virtual, Madrid, Spain, 3–6 June 2019.
39. Bessa, R.; Sampaio, G.; Miranda, V.; Pereira, J. Probabilistic Low-Voltage State Estimation Using Analog-Search Techniques. In Proceedings of the 2018 Power Systems Computation Conference (PSCC), Dublin, Ireland, 11–15 June 2018.
40. Ciric, R.M.; Feltrin, A.P.; Ochoa, L.F. Power flow in four-wire distribution networks-general approach. *IEEE Trans. Power Syst.* **2003**, *18*, 1283–1290. [CrossRef]
41. Glover, J.D.; Sarma, M.S.; Overbye, T.J. Power Distribution. In *Power Systems Analysis and Design*; Thomson: Stanford, CT, USA, 2007.

A.3.5 Research Paper 5 – *Privacy-preserving federated learning for residential short-term load forecasting*

Applied Energy 326 (2022) 119915

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Privacy-preserving federated learning for residential short-term load forecasting

Joaquín Delgado Fernández *, Sergio Potenciano Menci, Chul Min Lee, Alexander Rieger, Gilbert Fridgen

Interdisciplinary Centre for Security, Reliability and Trust (SnT), 29 Avenue John F.Kennedy, Luxembourg, 1855, Luxembourg

ARTICLE INFO

Keywords:
Deep neural networks
Differential privacy
Federated learning
Secure aggregation
Privacy-preserving federated learning
Short-term load forecasting

ABSTRACT

With high levels of intermittent power generation and dynamic demand patterns, accurate forecasts for residential loads have become essential. Smart meters can play an important role when making these forecasts as they provide detailed load data. However, using smart meter data for load forecasting is challenging due to data privacy requirements. This paper investigates how these requirements can be addressed through a combination of federated learning and privacy preserving techniques such as differential privacy and secure aggregation. For our analysis, we employ a large set of residential load data and simulate how different federated learning models and privacy preserving techniques affect performance and privacy. Our simulations reveal that combining federated learning and privacy preserving techniques can secure both high forecasting accuracy and near-complete privacy. Specifically, we find that such combinations enable a high level of information sharing while ensuring privacy of both the processed load data and forecasting models. Moreover, we identify and discuss challenges of applying federated learning, differential privacy and secure aggregation for residential short-term load forecasting.

1. Introduction

As the supply from intermittent and difficult-to-forecast renewable power sources increases, load forecasting – and especially residential short-term load forecasting (STLF) – is becoming ever more crucial for the reliability of modern power systems [1,2]. Residential STLF covers forecasting windows from a few minutes to a week ahead [2,3]. It plays an important role for many operational processes in the power system, such as planning, operating, and scheduling [4,5]. For instance, it enables energy providers to identify gaps between supply and demand in their customer portfolios. These gaps typically lead to high imbalance costs and ultimately to higher electricity prices for residential customers [6,7].

Traditionally, residential STLF has relied on aggregated load data and reference load profiles [5,8,9]. Yet, aggregation and reference profiles are often ill-suited for power systems with a high share of distributed generation and active demand-side management [5,8]. Moreover, they have become less reliable with residential heating and mobility being increasingly electric [10,11] and consumption patterns growing more dynamic, for instance, due to fluctuating levels of remote work [12]. These trends make accurate forecasting of individual residential loads an important priority.

There are various traditional methods for more granular STLF, but most build on limiting linearity assumptions (correlation between values and past values) even though residential load patterns are often highly dynamic [5]. Examples include time series models that rely on seasonal autoregressive integrated moving averages (ARIMA) [5,13], exponential smoothing, or linear transfer functions. Residential STFL is thus increasingly relying on methods that can work with non-linear dependencies, such as many Artificial Intelligence (AI) models [14–18].

A core challenge for any of these methods is the availability of granular data [19]. In many countries, this 'data scarcity' problem is tackled by pushing for advanced metering infrastructure (AMI), which substantially increases the resolution of residential load data [20]. STLF methods can make use of this data using either 'centralized' or 'decentralized' approaches. Centralized approaches transfer smart meter data to a central forecasting system. While these forecasting systems promise very accurate results, they face a twofold problem. First, they are subject to substantial privacy challenges because smart meter data are often easily attributable to natural persons. That is, data collected from smart meters can be detailed enough to permit the identification of specific customers [21]. The transfer and aggregation of smart meter

* Corresponding author.
E-mail address: joaquin.delgadofernandez@uni.lu (J.D. Fernández).

https://doi.org/10.1016/j.apenergy.2022.119915
Received 21 April 2022; Received in revised form 6 July 2022; Accepted 28 August 2022
Available online 15 September 2022

data is thus typically subject to data privacy regulations such as the European Union's General Data Protection Regulation (GDPR) and its obligations and requirements for processing personal data [22,23]. Second, there are considerable regulatory uncertainties. In particular, it is often unclear how device ownership (who owns the smart meter) and aggregation impact data ownership. Moreover, specific regulations for smart meter data are typically absent [24,25]. These regulatory uncertainties often mean that centralized approaches such as Belgium's Atrias [26], or Norway's Elhub [27], which provide so-called *data lakes*, may not be desirable.

Decentralized approaches aim to tackle some of these issues by processing smart meter data locally. A particularly promising of these decentralized approaches is Federated Learning (FL) [28,29]. Federated Learning is a machine learning technique that offers a collaboration framework for clients. In a so-called 'federation' clients jointly train and share prediction models instead of training data. Although FL cannot guarantee privacy by itself [30,31], it can be combined with privacy-preserving techniques such as differential privacy (DP) and secure aggregation (SecAgg).

Even though such a combination could substantially benefit residential STLF, academic attention to FL has been limited so far [32–43] and the two components have mostly been considered mostly in isolation [44–46]. With this paper, we seek to close several gaps in the literature on FL-based STLF: Firstly, we aim to deepen the understanding of FL-based STLF by examining the effects of clustering based on Pearson correlation and the effects of architectural complexity. Secondly, we analyze the privacy and performance effects of adding privacy-preserving techniques (DP and SecAgg) to FL. Third, we identify key challenges associated with using a combination of FL and privacy-preserving techniques.

To do so, we conduct the following analysis: Initially, we identify promising NN architectures from a review of the recent FL literature. Subsequently, we select the most effective of these architectures and investigate six scenarios using real-world historical data. In a first scenario, we evaluate the performance of the selected architecture in a 'centralized' setting to establish a performance benchmark for the remaining five FL scenarios. In the second scenario, we investigate the performance and computational cost effects of moving from a centralized setting to a FL setting. In a third scenario, we then examine the effects of using correlated training data based on Pearson correlation and socio-economic factors. Correlation is typically avoided in non-federated ML models to increase data variability. Yet, for FL models, correlated data may increase forecasting accuracy [35] and mitigate problems with non-IID (non-independent and non-identically distributed) data. In the fourth scenario, we reflect on the trend to work with ever more complex models and explore the effects of increasing the complexity of the NN's architecture. In scenarios 5 and 6, we study how privacy-preserving techniques affect the training and performance of federated models. Specifically, we investigate the effect of different DP implementations (i.e., clipping techniques) and SecAgg on accuracy, privacy, and computational costs.

The remainder of the paper is structured as follows. Section 2 provides an overview of related work on the use of NNs for STLF, FL, and privacy-preserving techniques. Section 3 covers our evaluation method, including the simulation environment, dataset and evaluation metrics. Section 4 describes our evaluation design. It covers the selection of the baseline NN architecture, the specification of the analyzed differential privacy and secure aggregation techniques, the training process for the federated learning models, and the design of six evaluation scenarios. Section 5 presents the evaluation results for the six scenarios. Finally, Section 6 provides a synthesis of our results and points out directions for further research.

2. Related work

2.1. Federated learning

In most fields, AI-based methods have already proven their value. However, their performance is highly dependent on the quantity and quality of available training data. Generally speaking, AI-based methods are typically limited by data fragmentation and isolation — mostly due to competitive pressure and tight regulatory frameworks (related to data privacy and security). To address these challenges, McMahan et al. proposed a new technique, FL [28,29]. The main idea of FL is to collaboratively train machine learning models between multiple independent clients without moving or revealing the training data. In other words, FL allows competing participants to leverage each others' datasets without revealing their own individual datasets. In doing so, models trained with FL enable more accurate forecasts than models that were independently trained by each client. To date, there are two canonical training algorithms for FL and four different configurations for the distribution of data and errors.

The two canonical training algorithms are: federated stochastic gradient descent (Fed-SGD) and federated averaging (Fed-Avg) [28]. Fed-SGD works by averaging the client's gradients after every pass through a local data batch. More specifically, Fed-SGD clients compute gradients of their 'loss' for a sub-set of their data. The loss is a non-parametric function that penalizes bad predictions and to minimize it, the clients need to move toward the empirical minimum by taking steps in the opposite direction of the gradient. Clients subsequently send their locally computed gradients to a central server. The central server aggregates and averages them – either equally or in a weighted manner – to update the model weights. These updated weights are again sent to the clients and each client trains their local model with the updated weights. Training continues in an iterative manner until a pre-defined number of so called communication rounds have been reached or a common goal is achieved. In Fed-SGD, a communication round represents a full pass through all batches.

In Fed-Avg, the clients send their model weights instead of their gradients. Once the central server has received the weights, it aggregates and averages them to arrive at a new 'consensus' that will be sent back to the clients for the next training round. Unlike Fed-SGD, Fed-Avg does not split the training data into batches, which has two effects: the number of communication rounds is reduced substantially (only once per epoch) and an improvement in forecasting accuracy [28,39]. As in Fed-SGD, the training process continues until the pre-defined number of epochs has been reached or a common goal is achieved.

Besides different algorithms, FL applications can also differ in their configurations. These configurations depend on how the data is structured. More specifically, they depend on the configuration of the feature space $\mathcal{X}$, the label space $\mathcal{Y}$, and the space formed by the identifiers $\mathcal{I}$. Different setups of the triplet $(\mathcal{X}, \mathcal{Y}, \mathcal{I})$ can be classified as Horizontal, Vertical, Transfer and Assisted Federated Learning [47]. Take for instance two clients i and j.

- Horizontal Federated Learning is when i and j share the same feature space such that $\mathcal{X}_i = \mathcal{X}_j$ but their label spaces $\mathcal{Y}$ are different so that $\mathcal{Y}_i \neq \mathcal{Y}_j$. In our residential STLF example, Horizontal FL would be applicable when the model is to be trained on smart meter data from a range of clients with the same feature set (consumption, weather profile, etc.) and the data is held by different companies.
- Vertical Federated Learning is when $\mathcal{I}_i = \mathcal{I}_j$, but $\mathcal{X}_i \neq \mathcal{X}_j$ and $\mathcal{Y}_i \neq \mathcal{Y}_j$. This would be the case, for instance, when two companies have access to the same client but each of them holds a different feature set regarding the client.
- Federated Transfer Learning happens when $\mathcal{X}_i \neq \mathcal{X}_j$, $\mathcal{Y}_i \neq \mathcal{Y}_j$, $\mathcal{I}_i \neq \mathcal{I}_j$, $\forall \mathcal{D}_i, \mathcal{D}_j, i \neq j$. Federated Transfer Learning can be used, for instance, when two companies have different clients and feature sets but want to nevertheless collaboratively train a model.

- Assisted Learning (AL) is done through collided data between clients. Xian et al. [48] define collision as when clients with the same data entries of a dataset $\mathcal{D}$ have different feature spaces $\mathcal{I}_i = \mathcal{I}_j, \mathcal{X}_i \neq \mathcal{X}_i \; \forall \mathcal{D}_i, \mathcal{D}_j, i \neq j$. One client may use the errors of another for their own benefit by increasing their training performance.

Regardless of the chosen algorithm and configuration, FL is vulnerable to moral hazard [49] or so-called 'soft' attacks on the contextual integrity of the shared data. Moral hazard arises because FL is by nature collaborative [50]. Multiple clients must work together to train models iteratively using the respective data at their disposal. If one or several of these clients manipulate the joint training process, it does not work. In effect, federated learning requires trust between the clients involved.

2.2. FL-based short term Load forecasting

Short-term load forecasting is a complex, multivariate time series problem. Its complexity is high because residential load data is often replete with irregularities, missing or inaccurate values, and seasonality. Petropoulus et al. [2] provide an in-depth overview of these challenges. Yet, they also point out the increasing importance and momentum that STLF has gained over recent years. STLF is crucial because system operators require it for unit commitment and optimal power flow calculations [2,4,51]. Moreover, it enables utilities, energy suppliers, and distribution grid operators (DSOs) to optimize their customer portfolios, design tariffs, and strategically adapt flexibility offerings [2,4].

STLF typically build on three groups of methods: traditional methods, AI-based methods, and hybrid methods that integrate traditional and AI-based components [2]. Traditional methods such as ARIMA can capture seasonal trends but fall short when it comes to non-linear patterns and non-aggregated data. At the same time, they are simple to use and have light computational costs [2]. AI-based methods, in turn, are well suited to identifying non-linear patterns and work well with individual (i.e., residential level) and aggregated data (i.e., substation level) [5,52].

Within the larger group of AI-based methods, FL is a relatively new but increasingly popular method for STLF. Our following overview of these FL studies which follows is based on a search in Semantic Scholar using the following search terms: *short-term load forecasting neural networks* and *Federated Learning for Residential Short Term Load Forecasting*.

The first group of studies employ Fed-SGD [34,41]. He et al. [34] additionally use k-means clustering and compare performance between six scenarios with a different number of clusters in each scenario. Their results suggest that grouping data based on comparable load patterns substantially improves the performance of FL models. Lin et al. [41], in turn, focus on limiting the high computational cost of Fed-SGD. To this end, they introduce an asynchronous stochastic gradient descent algorithm with delay computation (ASGD-DC). Specifically, their algorithm uses a Taylor expansion to compensate for the delay of clients with lower computational power.

The second and substantially larger group of studies employ Fed-Avg. Similar to He et al. [34], Briggs et al. [32], Savi et al. [33], Afaf et al. [35], and Biswal et al. [36] investigate different forms of clustering for Fed-Avg. Their findings suggests that clustering based on k-means and socio-economic factors can also substantially improve the performance of Fed-Avg. With certain caveats, their findings also suggest that its possible to train good models with a small number of clients. Li et al. [37], in turn, use Fed-Avg to compare the effects of different federation sizes, ranging the number of clients from 2, to 4, and 6. They also vary the number of training rounds (epochs) from 5 to 15. Their results suggest performance is increased by increasing the number of clients and training rounds.

Xu et al. [38] as well as Husnoo et al. [42] investigate the effect of increasing the number of clients participating in the training rounds. Their results show a considerably drop in performance for the higher participation cases. This drop appears to be the result of non-IDD consumption data between the clients.

Khalil et al. in [43] use Fed-Avg to train a FL model for building control, replicating the use of FL for household training. They consider six floors of a seven-story building as clients. They later personalize the global FL model for the 7th floor – not used in the FL training – by running locally five additional rounds (epochs) and not sharing the data with the global model. Their results suggest that even the personalized FL model can help a smart building controller reduce total electricity consumption using FL.

In terms of relative performance, Fekri et al. [39] find that Fed-Avg provides more accurate results for STLF than Fed-SGD. Shi et al. [40],in turn, look beyond canonical FL and use a multiple kernel variant of maximum mean discrepancies (MK-MMD) to fine-tune the central server model (global). They train for several rounds using transfer learning to adapt the global model to specific customers. Their results indicate better performance than a canonical Fed-avg implementation.

The works of [32–43] provide important stepping-stones in FL-based STLF. In particular, they clearly indicate the prospect of using collaborative training to create accurate forecasting models. However, they provide only limited insights into the challenges of using FL. In particular, it is not yet clear if different but simpler clustering techniques such as Pearson correlation are also effective. Also, prior literature has not yet looked at the effect of architectural complexity. Moreover, existing studies do not or only in a very limited way account for matters of privacy. Thus, this paper aims to provide a better understanding of clustering and architectural complexity and explores the addition of different privacy preserving techniques.

2.3. NN architectures for FL-based short term load forecasting

The studies presented on FL-based STLF use a range of different NN architectures (Table 1). Overall, the architectures have become deeper (i.e., multi-layered) over time as depth is typically associated with more accurate results [52]. In terms of layer design, we found Fully Connected layers (FCL), Long Short-term Memory (LSTM) Layers [53] and Convolutional Neural Networks (CNN). LSTMs have feedback connections which understand the dependence between items in a sequence and which make them suitable for temporal pattern recognition. CNN layers emulate human retinas and can capture the spatial distribution of graphic patterns. Moreover, we found Encoder–Decoder or autoencoder architectures [54]. In these architectures, the NN is provided with a sequence (a vector) as an input and maps this sequence to another sequence. Encoder–Decoder architectures reduce the effects of outliers because they transpose the original input space into a differently encoded space [55,56]. Sehovac et al. [57] present a particular interesting example of a Seq2Seq architecture that includes an attention mechanism to help the decoder extract additional information.

Aside from different layer designs, we also identified hybrid designs. For instance, Kim et al. [58] use CNN with LSTM layers to find both spatial and temporal patterns. Building on their work, Tuong et al. [59] add a bi-directional LSTM layer to identify temporal trends both forward and backwards in time. Similarly, Zulfiqar Ahmad et al. [14] combine Seq2Seq from [54] with a CNN layer design. This combination allows for the capture of both temporal and spatial patterns and offers protection against outliers. Shi et al. [60] take a different path by clustering and pooling the training data to increase variability and reduce overfitting.

2.4. Privacy preserving techniques for federated learning

Privacy-preserving techniques can support the design of forecasting systems that comply with privacy requirements and regulations

Table 1
Neural network architectures for FL-based and non FL-based STLF.

Method	Dataset	Neural network architecture	Year
Marino et al. [54]	UCI - Individual household electric power consumption	LSTM + Repeat vector + LSTM + 2x FCL	2016
Kong et al. [61]	Australia SGDS Smart Grid Dataset	Stacked LSTM + FCL	2017
Li et al. [62]	Fremont, CA 15 min Retail building electricity load	Missing or incomplete architecture description	2017
Shi et al. [60]	Irish CBTs - Residential and SMEs	Stacked LSTM + Pooling mechanism	2018
Yan et al. [63]	UK-DALE Domestic Appliance-Level Electricity dataset	2x Conv + 1x LSTM + FCL	2018
Kim and Cho [64]	UCI - Individual household electric power consumption	Missing or incomplete architecture description	2019
Kim and Cho [58]	UCI - Individual household electric power consumption	2x Conv + LSTM + 2x FCL	2019
Le et al. [59]	UCI - Individual household electric power consumption	2x Conv + Bi + LSTM + 2x FCL	2019
Khan et al. [14]	UCI - Individual household electric power consumption	2x Conv + 2x LSTM (Encoder) + 2x LSTM (Decoder) + 2x FCL	2020
Afaf et al. [35]	Pecan Street Research Institute	2x LSTM (same size) + FCL	2020
Sehovac et al. [57]	Non-disclosed or private data	Sequence to Sequence with attention	2020
Li et al. [37]	Global Energy Forecasting Competition 2012	Missing or incomplete architecture description	2020
Xu et al. [38]	Pecan Street Research Institute	Missing or incomplete architecture description	2021
Briggs et al. [65]	Low Carbon London Dataset	2x LSTM (same size) + FCL	2021
He et al. [34]	Australia SGDS Smart Grid Dataset	2x LSTM (same size) + FCL	2021
Savi et al. [33]	Low Carbon London Dataset	LSTM (64) + LSTM (32) + FCL	2021
Zhao et al. [66]	Pecan Street Research Institute	2x LSTM (same size) + FCL	2021
Biswal et al. [36]	Commission for Energy Regulation (CER)	Missing or incomplete architecture description	2021
Khalil et al. [43]	CU-BEMS, smart building electricity consumption and indoor environmental sensor datasets	Missing or incomplete architecture description	2021
Shi et al. [40]	Low Carbon London Dataset	Missing or incomplete architecture description	2022
Lin et al. [41]	Commission for Energy Regulation (CER)	Missing or incomplete architecture description	2022
Husnoo et al. [42]	Solar Home Electricity Data from Eastern Australia	LSTM (256) + LSTM (128) + FCL	2022

[22,67,68]. From an organizational perspective, these techniques allow competing agents like energy providers to cooperate and integrate with utilities and DSOs [23,67]. Furthermore, their use might facilitate the creation of local markets that support the energy transition [69].

Privacy-preserving techniques are especially relevant for FL. Although FL offers considerable improvements over centralized ML methods, it does not guarantee privacy. Firstly, the shared data (gradients or model weights) may allow inadvertent attribution, and secondly, privacy can be compromised through the communication between clients and the central server. For instance, Zhu et al. found a way to use gradient updates to reconstruct the training data of a client [30]. This effectively means that gradient updates are to be treated as personal data and that FL requires additional measures when data privacy is required. In the following, we describe two such measures: DP as a way to anonymize training data and SecAgg as a mechanism to enable privacy-sensitive communication between clients and the central server.

Dwork [70] introduces DP as a technique to guarantee privacy when retrieving information from a dataset. As described in [71], "differential privacy addresses the paradox of knowing nothing about an individual while learning useful information about a population". DP hides individual data trends by using additive noise. In more technical terms, Dwork [70] introduced epsilon differential privacy (ϵ-DP) as follows: *"For every pair of inputs x and y that differ in one row, for every output in S, an adversary should not be able to use the output in S to distinguish between any x and y"*. The privacy budget (ϵ) determines how much of an individual's privacy a query may use, or to what extent it may increase the risk of breaching an individual's privacy. A value of $\epsilon = 0$ represents perfect privacy, which means that privacy cannot be compromised through any analysis on a dataset in question [72]. Jayaraman et al. [73] extended the concept of (ϵ-DP) to (ϵ, δ-DP) where δ is the failure probability to better control for the tails of the privacy budget.

DP is typically implemented by adding random noise to data queries. This noise is usually sampled from a Laplacian or Gaussian distribution [71]. Finding an adequate noise level is crucial but not trivial — especially for FL. Too much noise can not only hide patterns in the data but also complicate convergence of the local models due to the random updates of the patterns during training. Simply speaking, more noise means more privacy, but more noise also means less accuracy.

An alternative to adding noise to the training process or the data is using secure multi-party computation (SMPC) protocols, which enable privacy-preserving communication. One such protocol is SecAgg [74]. SecAgg uses cryptographic primitives that prevent the central server from reconstructing each client's involvement and contribution. In more technical terms, SecAgg allows a set of distributed, unknown clients to aggregate a value x without revealing the value to the other clients. The backbone of SecAgg is Shamir's *t-out-of-n* Secret Sharing. It enables a user to split a secret s into n shares [75]. To reconstruct the secret, more than $t-1$ shares are needed to retrieve the original secret s. Any allocation with less than $t-1$ shares will provide no information about the original secret. SecAgg implies two main algorithms: sharing and reconstruction. The sharing algorithm transforms a secret into a set of shares of the secret that are each associated with a client. Following [75], these shares are constructed in such a way that collusion between $t-1$ participants (t being the total number of participants) is insufficient to disclose other clients' private information. The reconstruction algorithm works in the opposite direction. It takes the mentioned shares from the clients and reconstructs the shared secret.

Of the two privacy-preserving techniques, only DP has so far been examined in the context of residential STLF. Chhachhi et all. [46], Eibl et al. [76], and Zhao et al. [77] use DP to train a 'centralized' machine learning model. More specifically, they perturb the datasets by adding noise drawn from either a Gaussian or Laplacian distribution before each training round of the model. To the best of our knowledge, Zhao et al. [66] are the first to combine FL and DP for STLF. Specifically, they include DP in the training process of a Fed-Avg model. However, they do not systematically analyze different DP parameters. Moreover, they do not look at secure multi-party computation protocols, such as SecAgg.

3. Method

3.1. Simulation environment

The evaluations in this paper are based on simulations we ran on the IRIS Cluster of the high performance computer (HPC) facilities of the

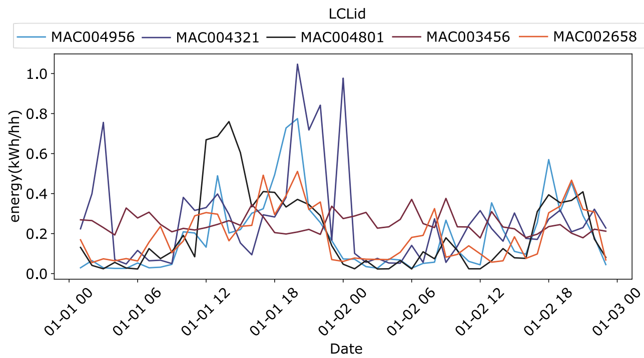


Fig. 1. Energy consumption (kWh/h) of 4 LCLIds from 01 January 2013 to 03 January 2013.

University of Luxembourg [78]. The simulations ran in an environment with 32 Intel Skylake cores and two NVIDIA Tesla V100 with 16 GB or 32GV depending on the allocation. We programmed the federation code in Python and based it on the machine learning framework provided by Tensorflow-Federated, [1] (TFF). The DL models are written in Keras [79].

3.2. Dataset

For our simulations, we used a large dataset from the Low Carbon London project, which was conducted by UK Power Networks between November 2011 and February 2014 in London, United Kingdom (herein LCL dataset) [80]. It contains the electrical consumption [kWh] data from 5567 households in a half-an hour resolution. The LCL dataset also contains a socio-technical classification of the households following the ACORN scheme [81] and is divided into individual household entries known as LCLid (Low Carbon London id).

To make the dataset ready for our simulations, we treated it in a 4-step procedure. First, we reduced the resolution of the LCL dataset to hourly values. The down-scaled values in the treated data set are the sum of two subsequent half-hour values in the original data set. This treatment significantly reduced the computational burden of our simulations. Secondly, we trimmed outliers or null values. Thirdly, we scaled all variables to have the same range using a Min–Max scaler. This re-scaling was necessary to ease the FL learning process as all values have to be in a known range, in our case: 0 to 1. Fourthly and finally, we split the dataset into a training and validation dataset. The training dataset (75%) contains electrical consumption data from January to December 2013 and the validation set (25%) covers data from January 2014 to March 2014. In Fig. 1, we provide an example of the processed data. It visualizes the electricity consumption [kWh] of 5 randomly selected households for a 2 day period using 1 h timestamps.

3.3. Evaluation metrics

Evaluation metrics offer an important means for the training and testing of forecasting models. However, the use of certain metrics can lead to undesirable results because FL models are known to converge to a *middle point* [82]. More specifically, FL models optimize the error of prediction with respect to the ground truth. In a distributed environment where there are *many such truths*, the models tend to minimize the mean of the loss across datasets. This tendency can provoke FL models to predict the average of each of the datasets and hence offer promising mean squared errors (MSE, Eq. (1)) and mean absolute errors (MAE, Eq. (2)). Such predictions, however, mean that the FL model did not learn local patterns in the data.

[1] https://github.com/tensorflow/federated

Therefore, MSE and MAE are typically not enough to evaluate the performance of a FL model and additional metrics, such as mean absolute percentage error (MAPE, Eq. (3)) and root mean square error (RMSE, Eq. (4)), are needed to quantify deviations of model predictions from the ground truths. The formal equations for these four metrics are as follows:

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2 \tag{1}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - x_i| \tag{2}$$

$$MAPE = \frac{100}{n}\sum_{t=1}^{n}\left|\frac{x_i - y_i}{x_i}\right| \tag{3}$$

$$RMSE = \sqrt{\left(\frac{1}{n}\right)\sum_{i=1}^{n}(y_i - x_i)^2} \tag{4}$$

4. Evaluation

4.1. Selection of a baseline neural network architecture

One crucial aspect for any AI method and specifically FL is the selection of the underlying NN architecture. To pick an architecture for our evaluation, we compared those in Table 1 that had a clear ‘implementation guide’ we could replicate. For this comparison, we used the metrics described in Section 3.3, trained the architectures with a maximum of 300 epochs on the training dataset and evaluated them on the evaluation dataset. We used the authors’ codes where available and otherwise implemented the architecture ourselves. To limit computational costs, we used an early stopping mechanism for the training, that ended the training when the evaluation metrics did not improve over 10 epochs.

In Fig. 2, we illustrate the evaluation results for the twelve architectures we could replicate. Some architectures behaved worse on our dataset than on the dataset used by the respective authors. One possible reason for these differences could be scaling. Kim et al. [58,59], for instance, worked with a non-scaled dataset. This means that depending on the standard deviation of the dataset σ, the error metrics can differ substantially. For instance, the MSE scales proportionally with the standard deviation: $MSE_{scaled} = MSE_{non-scaled} * \sigma$. To avoid this scaling effect, we calculated all metrics using standardized data (Section 5).

Overall, the architectures in [33,34,42,54,61,63,66] had the lowest MAPE, from 6.7 to 7.1. From these, we selected Marino et al.’s [54] autoencoder architecture. Autoencoders are known to perform well even with non-idd data, so we selected the most performant autoencoder architecture among our shortlist of architectures. Marino et al.’s [54] architecture uses a 50-neuron encoder layer, a 12-neuron latent space, a 50-neurons decoder layer, and two final layers with 100 and 1 neurons respectively.

For our investigation of the effects of architectural complexity, we selected Khan et al.’s [14] architecture as it performed best among the more complex architectures in our sample. Khan et al.’s [14] architecture is different from Marino et al.’s [54] in that it uses convolutional layers and LSTM.

4.2. Fl, differential privacy and secure aggregation set-up

For our simulations, we selected Fed-Avg over Fed-SGD as it requires fewer communication rounds and has better performance [39, 83]. Moreover, we used a horizontal FL configuration as our clients represent different LCLIds but share the same feature space.

To implement DP, we followed the steps proposed by McMahan et al. [84] rather than those of Chhachhi et al. [46] and Lu et al. [85],

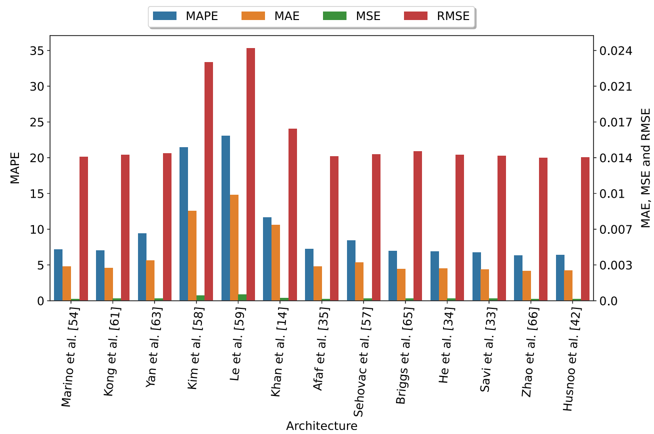


Fig. 2. RMSE, MSE, MAE, MAPE of the current literature applied to this paper's dataset.

in which noise is added to the dataset before the training. McMahan et al. [84] propose the central server to add noise after aggregating the updates of the model weights at every training round (in Fed-Avg). In other words, it differs from canonical Fed-Avg, which aggregates model weights.

The process proposed by McMahan et al. requires the definition of a query function sensitivity ($\mathbb{S}$) and a clipping strategy. The sensitivity of the query function determines the *actuation range* of the added noise. It represents the Euclidean distance between two datasets (C) differing in at most one element k: $\mathbb{S}(\tilde{f}) = max_{C,k} \left\| \tilde{f}(C \cup \{k\}) - \tilde{f}(c) \right\|_2$ [71]. Considering McMahan et al.'s first lemma [84] and assuming all clients are equally weighted, the sensitivity $\mathbb{S}$ is bounded as $\mathbb{S}(\tilde{f}(c)) \leq S/n$, with n being the number of clients. The vectors in Δ_k include the different model updates computed among the clients.

To bound the sensitivity of the query function, we needed to maintain the models' updates in a known range. One approach to ensure this range control is clipping model updates by a defined value before averaging. There are two strategies to clip the values of a neural network: 'per layer clipping', which applies clipping on a layer basis or 'flat clipping' which applies a clipping value to all the network parameters. Both clipping strategies project the values of the updates into a l2 sphere with the norm determined by the clipping value.

For both, per layer and flat clipping, there are two sub-strategies. One is to clip values using a fixed norm, known as fixed clipping. The second sub-strategy is called adaptive clipping [86]. It adapts the clipping norm based on a target quantile (i.e., 0.5) of the data distribution [86].

For the sake of simplicity, we used flat clipping as $\Delta'_k = \pi(\Delta_k, S)$ with S being the overall clipping value for the model updates. At the same time, we implemented both fixed and adaptive flat clipping strategies.

Once we had defined the query sensitivity and applied a flat clipping strategy, we evaluated how noise levels scale with the query sensitivity to obtain the minimum level of noise with a privacy guarantee. We added Gaussian noise as defined by: $N(0, \sigma^2)$ for $\sigma = z \cdot \mathbb{S}$, where z is the noise scale and $\mathbb{S}$ is the sensitivity of the query.

The addition of noise determines the overall privacy protection (ϵ) provided by DP. ϵ varies depending on the amount of noise added and the ratio of clients involved in the training (Q). Q is the ratio of clients selected out of the total which will participate in the next round of training. More noise naturally means more privacy and a lower ϵ. A higher Q, in turn, means less privacy and a higher ϵ [87].

To compute the privacy protection after a query, that is, each training round of our model, we used the privacy accountant provided by Renyi Differential Privacy (RDP) [88] as it provides a more detailed analysis of the privacy budget than the one created by [84].

For SecAgg, we used the implementation provided by Bonawitz et al. [74]. Their SecAgg implementation works as a plug-and-play algorithm that does not require any modification. We used SecAgg to ensure privacy-preserving communication between the central server and the clients. By using SecAgg in FL, clients can share their model weights without the central server or another client being able to reconstruct their weights [75].

Table 2
Scenarios considered.

Scenario	Privacy-Preserving technique	NN Architecture	Imposed correlation
0	–	Marino et al. [54]	✗
A	–	Marino et al. [54]	✗
B	–	Marino et al. [54]	✓
C	–	Khan et al. [14]	✗
D	Differential Privacy	He et al. [34]	✗
E	Secure Aggregation	Marino et al. [54]	✗

Table 3
Hyperparameters for scenarios A,B,C and E. Those marked with * the ones used in scenario 0.

Parameter	Value
Number of internal rounds before averaging	5
NN architecture	Marino et al. [54] * and Khan et al. [14]
Ratio of clients involved per round (Q)	1
Total number of clients (ω)	Subject to federation size
Optimizer	Adam *
Optimizer learning rate (L_r)	0.01 *
Batch size	256 *
Number of communication rounds	300 *
Number of internal epochs after training	Not applicable

4.3. Model operation

In this subsection, we describe how we trained the FL models. For this training, we used 6 steps. We illustrate these steps as well as the additional step that FL-DP requires in Fig. 3. FL-SecAgg requires a different additional step, namely the initial sharing of public keys between the clients and central server. Fig. 3 does not illustrate this additional public key sharing.

In step 1, the central server initializes the model using Glorot initialization [89]. In step two, the central server shares the model with the participating clients. In step three, a subset of clients are selected based on the ratio (Q). Each of these clients in this sub-set then trains the received model on its data. In step four, clients send their model updates to the central server. In step five, the central server averages the aggregated updates and adds noise drawn from a Gaussian distribution in the case of DP (5' in Fig. 3). In step six, the central server returns the averaged updates to the clients. The central server and the clients repeated steps 2 to 6 until they reached 300 epochs.

4.4. Scenario design

Overall, we designed a set of six scenarios for our evaluation. Scenario 0 represents a hypothetical scenario in which all clients share their training data with the central server. This 'centralized setting' serves as a benchmark for the other scenarios. In Scenario A, we study the effects of moving from a centralized to a FL setting. In scenario B, we analyze the performance effect of clustering clients based on Pearson correlation. In scenario C, we evaluate the effect of a more complex NN architecture. Lastly, in Scenarios D and E, we study the effects of adding DP and SecAgg to the FL model. We summarize the specifications of the six scenarios in Table 2.

For scenarios 0, A, B, C and E, we ran eight simulations. These simulations evaluate the models' performance with a growing number of clients (federation size). We used the following eight federation sizes: 2, 5, 8, 11, 14, 17, 20, and 23 clients. Each of these clients worked with data from one LCLid. We had to limit the maximum number of clients

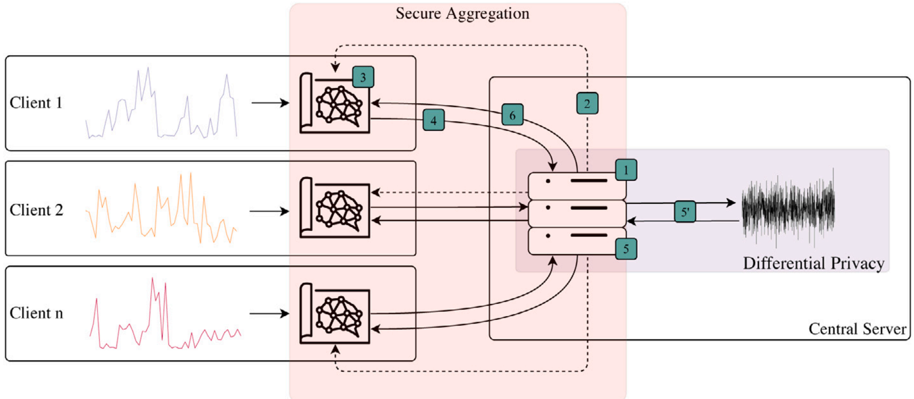


Fig. 3. Visual representation of our implementation of Federated Learning with privacy-preserving techniques.

Table 4
Hyperparameters for scenario D.

Parameter	Value
Number of internal rounds before averaging	5
NN Architecture	He et al. [34]
Ratio of clients involved per round (Q)	0.1
Total number of clients (w)	100
Optimizer	Adam
Optimizer learning rate (L_r)	0.01
Batch size	64
Number of communication rounds	100
Number of internal epochs after training	1

to 23 to control for computational cost as we simulated all clients and the communication between them in one virtual environment. In effect, every additional client did not add computational power but computational overhead.

We provide an overview of the hyperparameters for scenarios 0, A, B, C and E in Table 3. Table 4 provides the hyperparameters for the DP implementation in Scenario D.

5. Evaluation results

5.1. Scenario 0: Centralized setting

Scenario 0 analyzes the performance of a centralized setting, in which the clients send their data to a central server that trains a single model on the aggregated data. Scenario 0 uses the NN architecture presented by Marino et al. [54]. Similar to the architecture selection process, we employed an early stopper for Scenario 0 that terminated the training when there was no improvement in the validation metrics for more than 10 epochs.

In Table 5, we collect the simulation results for scenario 0. The MSEs, RMSEs and MAEs are expressed in absolute values, the MAPEs in percentage points, and the average training time per epoch in second [s]

Table 5 highlights that the overall performance of the centralized setting is very good, and that it remains almost constant for more than five clients with no evident variation in any of the metrics. The poor results in the two-client case could be the result of substantially different consumption patterns.

5.2. Scenario A: standard federated learning setting

We designed Scenario A to compare the ‘centralized setting’ in Scenario 0 with a FL setting, and to obtain a reference point for the other FL scenarios. Scenario A uses the NN architecture presented in [54] and does not apply privacy-preserving techniques. Furthermore, we did not impose data correlation among the clients.

Table 5
Validation error metrics and computation time for one-hour-ahead prediction: Scenario 0.

Central dataset size	MSE	RMSE	MAE	MAPE	Time per epoch [s]
2	0.00013	0.01158	0.00468	29.046	1.85
5	0.00012	0.01113	0.00308	9.068	6.01
8	0.00042	0.02067	0.00611	9.734	6.19
11	0.00028	0.01681	0.00437	8.561	8.18
14	0.00022	0.01514	0.00390	7.500	10.52
17	0.00023	0.01519	0.00383	6.850	12.56
20	0.00022	0.01498	0.00387	9.017	14.59
23	0.00019	0.01388	0.00330	7.144	16.82

Table 6
Validation error metrics and computation time for one-hour-ahead prediction: Scenario A.

Federation size	MSE	RMSE	MAE	MAPE	Time per round [s]
2	0.00015	0.01240	0.00516	30.1461	3.13
5	0.00022	0.01496	0.00468	16.2269	11.54
8	0.00058	0.02407	0.00745	11.9892	10.72
11	0.00042	0.02049	0.00538	10.1082	13.39
14	0.00035	0.01872	0.00542	10.1077	18.58
17	0.00032	0.01787	0.00469	8.5392	21.05
20	0.00031	0.01775	0.00479	11.2933	25.10
23	0.00028	0.01701	0.00478	10.8257	29.39

Table 6 presents the simulation results for Scenario A. The error metrics are expressed in absolute values and the average training time per epoch is expressed in seconds [s].

Table 6 highlights that performance of FL models varies depending on the federation size. While MSEs, MAEs and RMSEs remain almost constant, there is a clear improvement in MAPEs. These results are in line with those by Savi et al. [33] and Fekri et al. [39] and indicate that larger federation sizes lead to more accurate FL models.

To better illustrate this effect, we plot how the MAPEs evolved for the eight federation sizes along the training rounds in Fig. 4. Overall, we can observe a *quasi-exponential* decrease over the 300 rounds, approaching final values between 6.8 and 29, which indicate reasonably good forecasts [90].

In comparison to Scenario 0, we can observe an average performance decrease between 20% to 40%. FL appears to perform significantly worse than a ‘centralized’ setting, which is in line with other comparable studies [32,41,42].

Table 6 also highlights a trade-off between accuracy and computational time for federation size. As the number of clients increases, so does performance, but also computation time. This trade-off can present an important limitation for the use of FL.

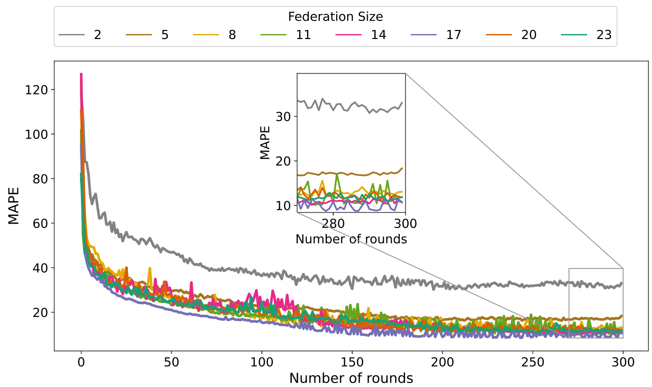


Fig. 4. Validation Mean Absolute Percentage Error (MAPE) per federation size in terms of training rounds for scenario A.

5.3. Scenario B: standard federated learning setting with imposed correlation

In scenario B, we analyzed the performance of a standard FL setting with imposed correlation among the clients in the federation. We followed Lee et al. [91] and used Pearson correlation to identify and bundle clients (or LCLids) by correlated data. This way of bundling differs from the dominant k-means approach in prior literature and offers a more direct and simple view of the correlation between clients. More specifically, we pre-filtered our dataset for specific ACORNs (H and L). For these ACORNS, we then calculated all possible non-repeated combinations and calculated their correlations. For each federation size, we selected those combinations of clients with the highest correlations.

We present the simulation results for Scenario B in Table 7. The error metrics and the correlation rate are both expressed in absolute values. We omit the computation time because it was basically the same as in scenario A 5.2.

FL with imposed correlation performed better in almost every metric than FL without imposed correlation (Scenario A). The MSEs decreased by an average 35.87%; RMSEs by 21.81%; MAEs by 25.57% and the MAPEs by 27.61%. They nevertheless still trail Scenario 0 by 6.35% on average. Moreover, these values are subject to some caveats. Our model with two clients had a correlation rate of 0.62, which led to a 75% better performance than the two-client case in Scenario A. Moreover, the performance of the model with 17 clients was worse than the same model in Scenario A, and 45% of the error metrics in Scenario B were better than those in scenario 0.

These results align well with similar studies, such as [34,36,39] or [33], where the application of k-means to cluster customers leads to performance improvements between 10% and 15%.

Overall, scenario B suggests that clustering based on Pearson correlation among the clients in a federation can substantially improve the performance of FL-based STLF. Specifically, utilities, energy providers, and DSOs could leverage simple socio-economic factors (ACORNS) and historical, individual smart meter data to cluster their residential customers into correlated groups. Each cluster can use a different FL model to reduce imbalance costs for inaccurate forecasts and offer tailored demand-side management programs.

5.4. Scenario C: standard federated learning setting with a more complex neural network architecture

In scenario C, we explore how a more complex NN architecture [14] impacts the performance of FL-based STLF. The motivation for scenario C is rooted in the trend to use ever more complex machine learning architectures in the hope of catching patterns invisible to less complex architectures. At the same time, it is unclear whether larger architectures increase performance.

Table 7
Validation error metrics and correlation rates for one-hour-ahead prediction: Scenario B.

Federation size	MSE	RMSE	MAE	MAPE	Correlation rate
2	0.00002	0.00463	0.00170	4.54	0.62
5	0.00015	0.01238	0.00373	9.77	0.51
8	0.00022	0.01513	0.00426	8.91	0.49
11	0.00021	0.01465	0.00402	8.23	0.45
14	0.00020	0.01429	0.00390	8.66	0.42
17	0.00032	0.01805	0.00465	8.22	0.37
20	0.00029	0.01726	0.00428	8.38	0.34
23	0.00026	0.01640	0.00432	9.95	0.31

Table 8
Validation error metrics and computation time for one-hour-ahead prediction: Scenario C.

Federation size	MSE	RMSE	MAE	MAPE	Time per round [s]
2	0.00024	0.01550	0.00720	31.50674	6.25
5	0.00052	0.02289	0.01282	33.42653	21.10
8	0.00117	0.03433	0.01754	20.92209	20.43
11	0.00115	0.03398	0.01495	21.93438	30.34
14	0.00087	0.02955	0.01404	18.44877	34.52
17	0.00077	0.02783	0.01080	13.80498	40.59
20	0.00081	0.02858	0.01435	24.28874	50.19
23	0.00061	0.02486	0.01059	19.02717	59.76

To account for the size of the model in [14] and its computational burden, we implemented three modifications to the set-up of our simulation environment. The first modification concerns the GPUs. For each of the Nvidia Tesla allocated on the HPC, we created two virtual cards, resulting in four cards we could use for our simulation. The second modification is related to the batch size, which we increased from 100 to 200. Increasing the batch size can help to prevent or limit overfitting since there are more data entries available to compute the loss of the model. Finally, we modified the model in [14] by transforming the initially proposed LSTM layers to CuDNNLSTM [92]. The transformation enabled the LSTMs to use the Compute Unified Device Architecture (CUDA) kernel of our Tesla GPUs.

The simulation results of scenario C are presented in Table 8. The results clearly indicate the increased computational costs of training a FL model with a complex architecture. The computational time is almost twice as high as in scenarios A and B. On the other hand, the performance of the model with the more complex architecture was worse that of the smaller model's for all federation sizes and all metrics, ranging from 50% up to 142%.

These results suggest a clear case of overfitting. Overfitting is generally defined as the lack of generalization of a model. An overfitted model crosses the line between learning tendencies or patterns and *memorizing* the data received as input.

Fig. 5 provides a visualization of this overfitting. The performance on the training subset is represented by the solid lines, while the performance on the validation subset is visualized by the dotted lines. The dotted lines begin to increase again after round 120, whereas the solid lines decrease as the model is over-fitted to the training data. .

In effect, scenario C offers a cautionary tale for utilities, energy providers, and DSOs that want to use FL for short-term load forecasting. Not only are more complex FL architectures more expensive and detrimental to the environment [93], they are also more sensitive to handle.

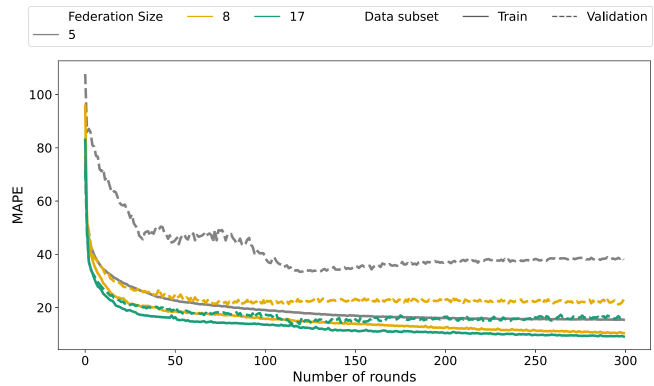


Fig. 5. Validation and Training MAPEs for federation sizes 5,8, and 17 in Scenario C.

5.5. Scenario D: privacy-preserving federated learning setting with differential privacy

Scenario D focuses on adding DP to FL and how this impacts the performance of FL-based STLF. Furthermore, we compare two *flat clipping* approaches: fixed and adaptive clipping, as described in Section 4.2.

In scenarios A and B, we used Marino et al.'s model [54] as the baseline architecture. Encoder–decoder architectures can cope well with outliers due to their capacity to abstract information into the latent space. This capacity is very beneficial for FL where different clients can have substantially different data points. However, we found that these architectures are substantially more vulnerable to noise than standard stacked LSTM networks. One reason for this vulnerability could be that they compact information from a higher dimensional space into a smaller one. Adding noise to the weights of this latent space will have a multiplicative effect on the model's output in the decoder phase. To avoid such encoder–decoder noise problems for our DP simulation, we changed the architecture in Scenario D to a two-layer LSTM with 50 neurons each, and a final dense layer as in He et al. [34].

DP offers two approaches to obtain a high privacy budget given a defined amount of noise: reduce the ratio of clients that participate in each training round (Q), retrain the model locally for several epochs on client data, find a lower δ, and/or increase the noise scale (z). For Scenario D, we employed a ratio of $Q = 0.1$. With $Q = 0.1$, a total of 100 clients and without the addition of privacy preserving techniques, our model had a MAE of 0.00300, a MSE of 0.012, a RMSE of 0.01114, and a MAPE of 8.3846, which matches results in Scenario A.

Moreover, we considered recommendations by Zhao et al. [66] and Xu et al. [38] to introduce local re-training. Specifically, they propose to conduct several local training rounds on each client between each aggregation with DP to better fit the local models. Yet, we found that these repeated rounds did not improve performance so we chose to use just one local training round. However, we did optimize the δ to $\delta = 4e^{-3}$ as proposed by Zhao et al. [66].

The first strategy we implemented was fixed clipping following the two main steps in McMahan et al. [84]. In the first step, we determined the lowest possible clipping value (S) as being too low clipping values can negatively affect the convergence rate as they clip all values bigger than S. We treated S as a hyper-parameter and used an iterative approach to find the lowest possible clipping value. Specifically, we followed McMahan et al. [84] and used iterative steps of 0.1 for S, starting with $S = 0.1$ until $S = 0.7$. We present the error metrics for the different S values in Table 9.[2]

[2] Setting a fixed value for the clipping slows the training process significantly. The values in Table 9 are the validation metrics after 2000 communication rounds. Without any clipping strategy, the models converge at an earlier rate (see Fig. 4).

Table 9
Validation error metrics for different clipping values for one-hour-ahead prediction with the sample client ratio $Q = 0.1$ and total number of clients $w = 100$: Scenario D.

S	MSE	RMSE	MAE	MAPE
0.10	0.00043	0.02094	0.00628	10.69357
0.20	0.00035	0.01884	0.00502	8.89023
0.30	0.00038	0.01969	0.00496	8.00244
0.40	0.00038	0.01963	0.00486	7.71642
0.50	0.00039	0.01978	0.00493	7.92688
0.60	0.00034	0.01869	0.00477	7.81763
0.70	0.00036	0.01915	0.00484	7.53057

Table 10
Exploration of the different noise levels, in bold the hyper-parameter **z** that defines the amount of noise.

Qw	S	$\mathbb{S} = S/Qw$	z	$\sigma = z \cdot S$
10	0.3	0.03	0.1	0.003
10	0.3	0.03	0.2	0.006
10	0.3	0.03	0.3	0.009
10	0.3	0.03	0.4	0.012
10	0.3	0.03	0.5	0.015
10	0.3	0.03	0.6	0.018
10	0.3	0.03	0.7	0.021
10	0.3	0.03	0.8	0.024
10	0.3	0.03	0.9	0.027

Based on these iterations, we selected $S \approx 0.3$ as our fixed clipping value. It is the lowest clipping value with comparatively good error metrics and the marginal increase in error metrics from lowering S increases disproportionately below ≈ 0.3.

Once we had identified the lowest possible clipping value S, the second step was to identify a tolerable level of noise. With $S = 0.3$, a total number of clients $w = 100$, and $Q = 0.1$, we applied $\mathbb{S} = S/Qw$ to calculate the standard deviation of the noise level $\sigma = z \cdot \mathbb{S}$. Similarly with the approach that we took with S, we treated z as a hyper-parameter and ranged it from 0.1 to 0.9

In Table 10, we present the performance metrics for each of the z variations. Each of the explored z values represents a different level of noise added to the federated model. Intuitively, there is a trade-off between the amount of noise and performance, whereby more noise (increase in z) reduces performance. This trade-off dynamic is clear from the error metrics in Table 11. Nevertheless, the overall error metrics for DP based on fixed clipping are generally low and indicate good forecasting performance.

Concurrently, more noise also means better privacy, as indicated by the increasing privacy guarantees in column three of Table 11. We calculated these guarantees using the Rényi Differential Privacy Accountant [88]. The highest amount of noise we examined (z=0.9) provides a privacy guarantee of (4.2, $4e^{-3}$), which is close to perfect privacy ($\epsilon = 0$). In effect, scenario D demonstrates that adding DP to FL maintains comparatively good performance and offers high privacy guarantees.

The second clipping strategy that we analyzed is adaptive clipping. With adaptive clipping, clipping value are calculated automatically. To evaluate this approach, we used Andrew et al.'s adaptive clipping implementation [86], in which the algorithm iteratively (per communication round) adjusts the norm clip, trying to approximate it to a predefined quantile (0.5 in our case).

This data quantile approximation expends privacy budget as it queries the data. To prevent this *privacy leakage* Andrew et al. [86] propose to add noise during the approximation. This noise (σ_b) is defined by 0.05 times the number of clients per round, in our case $\sigma_b = 0.5$. This addition of noise has a slight affect on the total privacy guarantee of the model. It results in increased effective noise as $z_\Delta = (z^{-2} - (2\sigma_b)^{-2})^{-1/2}$.

Fig. 6 highlights the adaptive adjustments of the clipping value over the training rounds. There is a sharp increase in the clipping norm at

Table 11
Validation error metrics with S = 0.3 and a varying noise scale **z** from 0.1 to 0.9 for one hour-ahead-prediction with the sample client ratio $Q = 0.1$ and total number of clients $w = 100$ after one epoch of local training.

Noise scale (**z**)	Privacy guarantee (ϵ, δ)	MSE	RMSE	MAE	MAPE	Timer per round [s]
0.1	(911, $4e^{-3}$)	0.00010	0.00946	0.00272	7.5426	86.74
0.2	(190, $4e^{-3}$)	0.00010	0.00957	0.00312	8.8930	85.11
0.3	(69.3, $4e^{-3}$)	0.00010	0.00959	0.00309	8.4391	87.48
0.4	(32.4, $4e^{-3}$)	0.00010	0.00962	0.00321	9.1156	84.66
0.5	(17.9, $4e^{-3}$)	0.00011	0.00971	0.00340	9.7164	88.52
0.6	(11.2, $4e^{-3}$)	0.00011	0.00972	0.00344	9.9693	84.28
0.7	(7.58, $4e^{-3}$)	0.00011	0.00979	0.00354	10.0378	81.46
0.8	(5.5, $4e^{-3}$)	0.00013	0.01075	0.00519	15.6755	82.08
0.9	(4.2, $4e^{-3}$)	0.00011	0.00991	0.00372	10.6031	87.48

Table 12
Validation error metrics with adaptive clipping at different noise levels from 0.1 to 0.9 using as initial clipping value $C^0 = 0.1$ and the step factor for the geometric updates $\eta C = 0.2$ for one hour ahead prediction with the sample client ratio $Q = 0.1$ and total number of clients $w = 100$ after one epoch of local training.

Noise scale (**z**)	Effective noise (z_Δ)	Privacy guarantee (ϵ, δ)	MSE	RMSE	MAE	MAPE	Time per round [s]
0.1	0.100	(910.0, $4e^{-3}$)	0.00010	0.00936	0.00276	7.9966	84.39
0.2	0.200	(189.4, $4e^{-3}$)	0.00010	0.00930	0.00260	7.3866	88.41
0.3	0.300	(68.7, $4e^{-3}$)	0.00009	0.00930	0.00257	7.0985	85.30
0.4	0.402	(31.9, $4e^{-3}$)	0.00010	0.00945	0.00292	8.2810	86.92
0.5	0.504	(17.5, $4e^{-3}$)	0.00010	0.00948	0.00301	9.0461	88.57
0.6	0.607	(10.8, $4e^{-3}$)	0.00010	0.00955	0.00302	8.8343	86.27
0.7	0.711	(7.2, $4e^{-3}$)	0.00010	0.00961	0.00317	9.4312	87.68
0.8	0.817	(5.2, $4e^{-3}$)	0.00010	0.00955	0.00325	9.6126	88.27
0.9	0.924	(3.9, $4e^{-3}$)	0.00010	0.00955	0.00319	9.2953	87.93

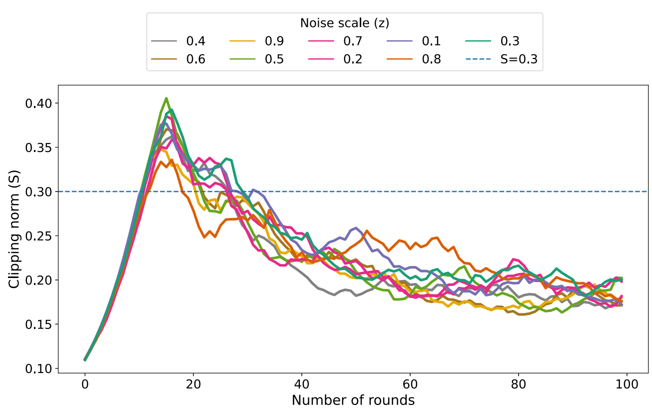


Fig. 6. Evolution of the adaptive clipping norm at different noise levels z (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9) using as initial clipping value $C^0 = 0.1$ and the step factor for the geometric updates $\eta C = 0.2$.

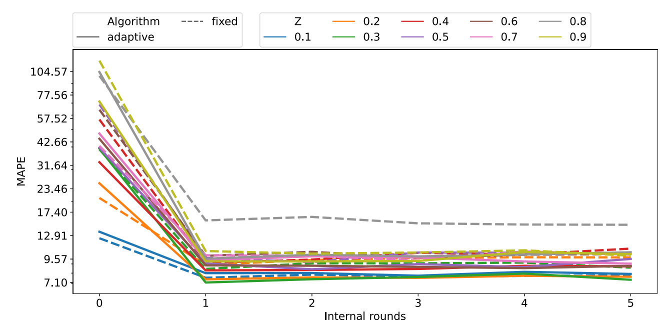


Fig. 7. Validation Mean Absolute Percentage Error (MAPE) per local training epoch for adaptive and fixed DP.

the beginning of the training rounds due to the low initial clipping value $C^0 = 0.1$. Such a low quantile allows only a few data points to participate in selecting the clipping value. The smaller the quantile, the fewer data points participate and thus, it is more difficult to estimate the optimal clipping value.

As in our case, the adaptive clipping algorithm may overshoot as a result and increase the clipping norm to higher values. After this overshot, the adaptive clipping algorithm correctly approximates the optimal clipping value $S \approx 0.2$.

We present the simulation results for adaptive clipping in Table 12. On average, adaptive clipping outperformed fixed clipping by 9%. Moreover, the privacy guarantee is close to perfect privacy (3.9, $4e^{-3}$)

Adaptive clipping appears not only more attractive from a performance and privacy perspective. It is also easier to use in terms of performance and privacy. Fixed clipping requires an initial and computationally expensive manual step to identify an appropriate clipping value, whereas, in adaptive clipping, this value is calculated automatically in the training rounds. Thus, DP with adaptive clipping presents the more convenient choice for residential STLF.

The results we present in Tables 11 and 12 are those after the local training round suggested by Zhao et al. [66]. Unlike Zhao et al. [66], who worked with five local training round, we used only one as additional rounds did not significantly improve performance (Fig. 7). Nevertheless, clients profited from local training with negligible computational overhead.

5.6. Scenario E: privacy-preserving federated learning setting with secure aggregation

In this scenario, we examine SecAgg as an alternative technique to add privacy to FL. Whereas DP adds random noise to model updates, SecAgg targets the communication and aggregation of the clients' model updates. Hence, there is no trade-off as in scenario D, where it is important to find an adequate noise level.

Similar to scenarios A, B and C, we present the simulation results for the eight federation sizes in Table 13. We express the error metrics in absolute values and the average computation time in seconds [s].

Table 13
Error metrics and computation time for one-hour-ahead prediction using SecAgg: Scenario E on test set.

Federation size	MSE	RMSE	MAE	MAPE	Time per round [s]
2	0.00017	0.01324	0.00532	31.01177	4.54
5	0.00018	0.01348	0.00431	15.60893	13.23
8	0.00060	0.02457	0.00759	12.28532	13.34
11	0.00039	0.01996	0.00523	9.65965	18.21
14	0.00034	0.01864	0.00503	9.67057	22.25
17	0.00033	0.01820	0.00466	8.25973	26.70
20	0.00033	0.01836	0.00522	12.88359	34.64
23	0.00028	0.01683	0.00453	10.19247	38.10

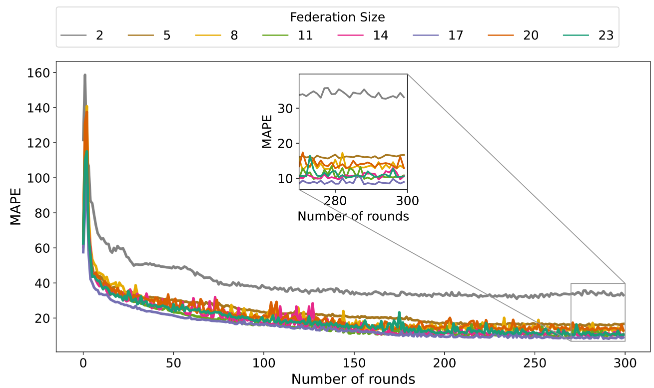


Fig. 8. Validation Mean Absolute Percentage Error (MAPE) per LCLids federation size in terms of training rounds for Scenario E.

Furthermore, we complement the results with Fig. 8. It depicts the MAPE, following a similar curve as in Scenario A.

Table 13 shows that the use of SecAgg affects computation time only marginally. As SecAgg does not add any noise, it also provides less burden than DP. Consequently, SecAgg presents a more performant alternative for residential STLF with the cost of an extra 30% of computation time. However, it is important to note that SecAgg does not provide complete privacy because latent patterns could still point toward the original data subject. More specifically, Model Inversion (MI) attacks could reconstruct the original training data from the model parameters [94].

5.7. Comparison across the scenarios

We summarize our results for scenarios 0, A, B, C, and E in Figs. 9 and 10. We omitted scenario D from these figures because in scenario D we only varied the noise scale and not the federation size.

Overall, the two figures suggest an inherent trade-off between performance and privacy in residential STLF. Yet, FL models can successfully mediate this trade-off and provide high levels of performance and privacy, especially when trained on correlated data, avoid unduly complex architectures, and employ SecAgg.

6. Conclusions

This paper analyses the use of FL and its combination with privacy preserving techniques for short-term forecasting of individual residential loads. Such a combination offers an innovative approach to accommodate both accuracy and privacy. In particular, it allows those who depend on accurate forecasts of residential loads (such as utilities, energy providers, and DSOs) to train in a collaborative fashion forecasting models with granular smart meter data without having to share this data.

Our analysis builds on historical smart meter data and consists of six scenarios. While the first two scenarios set the baseline scenarios,

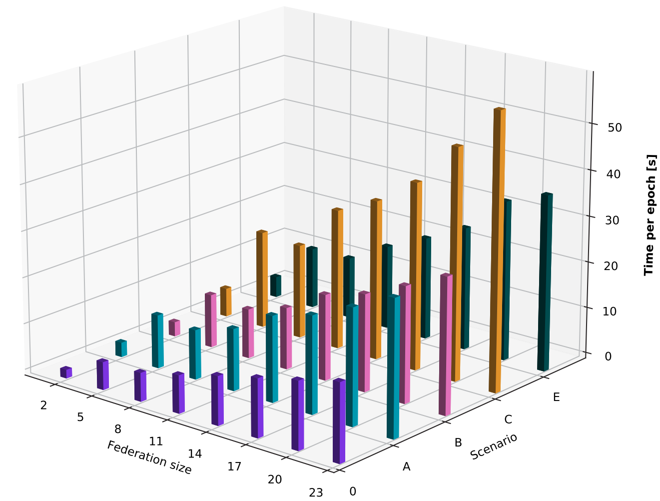
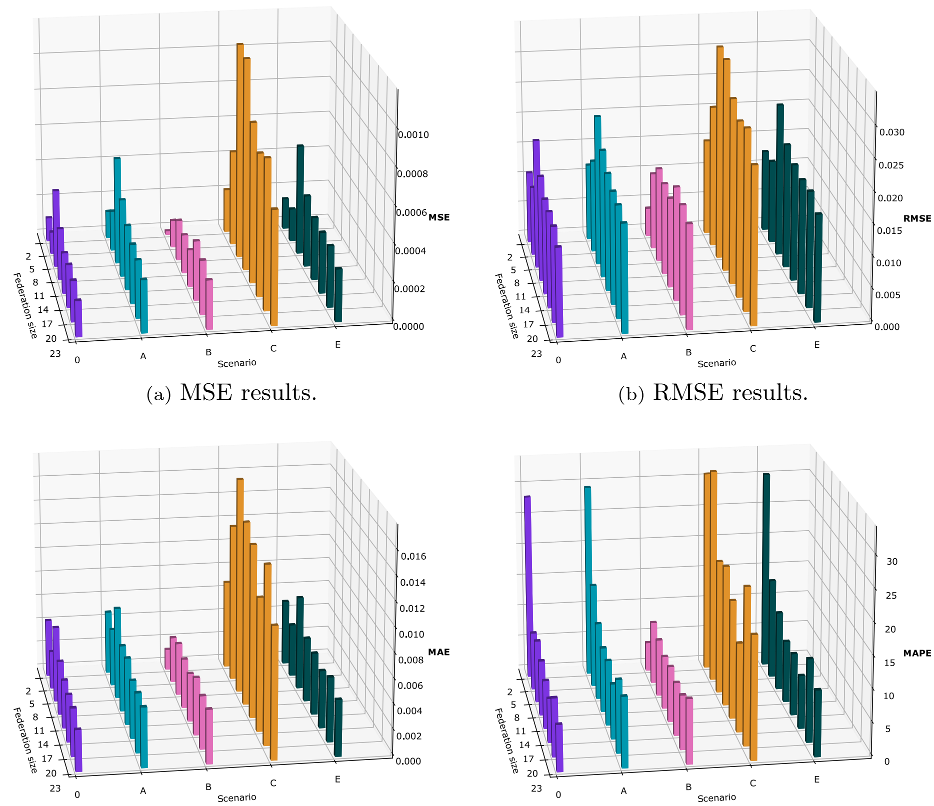


Fig. 9. Comparison of computation time across Scenarios 0, A, B, C, and E.

each of the subsequent four scenarios have a particular analytical focus. Specifically, these scenarios investigate the effects of data correlation, neural network architecture complexity, differential privacy, and secure aggregation on performance, computation time, and privacy guarantee levels. In each scenario, we also explore the effects of different federation sizes. From our analysis, we can posit the following:

1. Collaborative training of AI models with federated learning reduces forecasting accuracy as compared to a 'centralized' setting. However, it makes it easier to account for data privacy concerns through the addition of privacy-preserving techniques.
2. As the number of participating clients (smart meters) in a federation increases, forecasting accuracy tends to also increase. However, while a greater number of clients leads to greater accuracy, this also implies higher computational costs that may no always be justified.
3. Customer segmentation with Pearson correlation along socio-economic factors (e.g., with the ACORN methodology) substantially improves forecasting accuracy for FL models.
4. Complex neural network architectures imply high computational costs, difficulties in handling the architecture, and a potential risk of overfitting. It is thus important to balance accuracy and usability when selecting of model architectures.
5. Complementing federated learning with differential privacy or secure aggregation does not significantly reduce forecasting accuracy but does enable very high levels of privacy.
6. Adaptive and fixed clipping approaches to differential privacy provides similar performance. Adaptive clipping is easier to use as it does not require manual pre-selection of good clipping values, and it facilitates faster model convergence.
7. Combining autoencoder architectures with DP complicates the training of FL models. The design of these architectures magnifies the noise added by DP, which restricts the training process.
8. Secure aggregation is superior to DP in terms of usability, performance and computational burden. It can be added as a simple plug-and-play component, does not reduce performance by adding noise, and permits faster training.

Overall, our analysis suggests that a combination of federated learning with privacy-preserving techniques can be a highly promising alternative for residential short-term load forecasting. However, is not free from technical challenges. Differential privacy requires careful configuration of noise size, clipping values and client ratios to balance accuracy and privacy. Secure aggregation does not require such configuration but its cryptographic set-up can also be challenging as well.



(a) MSE results. (b) RMSE results.

(c) MAE results. (d) MAPE results.

Fig. 10. Comparison of evaluation metrics across Scenarios 0, A, B, C, and E.

Furthermore, computational costs limit the number of clients that can be used for training.

More broadly, our study contributes to a better understanding of the use of FL and privacy-preserving techniques for residential short-term load forecasting. It makes an important contribution to the growing literature on the applications of federated learning in electric power systems by testing different NN under distributed settings, examining the implications of privacy preserving techniques, and identifying technical challenges in using FL.

Naturally, our analysis is not free from limitations. In particular, computational costs have considerably limited the size of our federations. Even though larger federation sizes may result in somewhat different results, nevertheless we believe that our overall results are robust, as we have explored several settings in terms of: number of clients, baseline NN architectures, and dataset characteristics.

Further research may nevertheless want to (1) assess larger federation size settings with additional correlation indicators, such as the existence of distributed energy resources (i.e., photovoltaics, electric vehicles, or home energy management systems), (2) investigate data input disruptions produced by hostile agents or errors caused by malfunctions of a smart metering device, and (3) examine other, innovative NN architectures with attention mechanisms and multi-variate input data. After all, FL is highly collaborative and iterative and perfect data and operation may not always be possible in real-world applications.

CRediT authorship contribution statement

Joaquín Delgado Fernández: Conceptualization, Methodology, Data curation, Writing – original draft, Software, Writing – review & editing, Visualization. **Sergio Potenciano Menci:** Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Chul Min Lee:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Alexander Rieger:** Writing – review & editing, Supervision. **Gilbert Fridgen:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

We would like to acknowledge Tom Josua Barberau and Orestis Papageorgiou for their valuable feedback on the first draft of this paper. Moreover, we would like to acknowledge the support of the European Union (EU) within its Horizon 2020 programme, project MDOT (Medical Device Obligations Taskforce), Grant agreement 814654. Additionally, this project was supported by the Kopernikus-project "SynErgie" of the German Federal Ministry of Education and Research (BMBF), by PayPal and the Luxembourg National Research Fund FNR (P17/IS/13342933/PayPal-FNR/Chair in DFS/Gilbert Fridgen) as well as by the Luxembourg National Research Fund (FNR) -FiReSpARX Project, ref. 14783405. All authors have read and agreed to the published version of the manuscript.

References

[1] Nti IK, Teimeh M, Nyarko-Boateng O, Adekoya AF. Electricity load forecasting: a systematic review. J Electr Syst Inf Technol 2020;7(1):13. http://dx.doi.org/10.1186/s43067-020-00021-8.

[2] Petropoulos F, Apiletti D, Assimakopoulos V, Babai MZ, Barrow DK, Taieb SB, et al. Forecasting: theory and practice. Int J Forecast 2022;38(3):705–871. http://dx.doi.org/10.1016/j.ijforecast.2021.11.001.

[3] ENTSO-E. Enhanced load forecasting. 2021, URL https://www.entsoe.eu/Technopedia/techsheets/enhanced-load-forecasting.

[4] Muñoz A, Sánchez-Úbeda EF, Cruz A, Marín J. Short-term forecasting in power systems: A guided tour. In: Handbook of power systems II. Berlin, Heidelberg: Springer Berlin Heidelberg; 2010, p. 129–60. http://dx.doi.org/10.1007/978-3-642-12686-4_5.

[5] Lusis P, Khalilpour KR, Andrew L, Liebman A. Short-term residential load forecasting: Impact of calendar effects and forecast granularity. Appl Energy 2017;205:654–69. http://dx.doi.org/10.1016/j.apenergy.2017.07.114.

[6] Commission for Regulation of Utilities. Energy supply costs information paper. Tech. rep., (CRU17291). Commission for Regulation of Utilities - CRU; 2017, URL https://www.cru.ie/wp-content/uploads/2017/10/CRU17291-RFI-Information-paper.pdf [Accessed on 16 Feb 2022].

[7] Specht JM, Madlener R. Energy supplier 2.0: A conceptual business model for energy suppliers aggregating flexible distributed assets and policy issues raised. Energy Policy 2019;135:110911. http://dx.doi.org/10.1016/j.enpol.2019.110911.

[8] Maltais L-G, Gosselin L. Forecasting of short-term lighting and plug load electricity consumption in single residential units: Development and assessment of data-driven models for different horizons. Appl Energy 2021;118229. http://dx.doi.org/10.1016/j.apenergy.2021.118229.

[9] Wang Y, Chen Q, Hong T, Kang C. Review of smart meter data analytics: Applications, methodologies, and challenges. IEEE Trans Smart Grid 2019;10(3):3125–48. http://dx.doi.org/10.1109/TSG.2018.2818167.

[10] Keramidas K, Diaz Vazquez A, Weitzel M, Vandyck T, Tamba M, Tchung-Ming S, et al. Global energy and climate outlook 2019: Electrification for the low carbon transition. Publications Office of the European Union, Joint Research Center: Luxembourg; 2020, URL https://op.europa.eu/s/wWQS.

[11] International Energy Agency. Electricity final consumption by sector, wolrd. IEA; 2021, URL https://www.iea.org/fuels-and-technologies/electricity (Accessed on 21 June 2021).

[12] Bielecki S, Skoczkowski T, Sobczak L, Buchoski J, Maciąg L, Dukat P. Impact of the lockdown during the COVID-19 pandemic on electricity use by residential users. Energies 2021;14(4). http://dx.doi.org/10.3390/en14040980.

[13] Kaur H, Ahuja S. Time series analysis and prediction of electricity consumption of health care institution using ARIMA model. In: Proceedings of sixth international conference on soft computing for problem solving. Springer; 2017, p. 347–58. http://dx.doi.org/10.1007/978-981-10-3325-4_35.

[14] Khan ZA, Hussain T, Ullah A, Rho S, Lee M, Baik SW. Towards efficient electricity forecasting in residential and commercial buildings: A novel hybrid CNN with a LSTM-AE based framework. Sensors 2020;20(5). http://dx.doi.org/10.3390/s20051399.

[15] Kalimoldayev M, Drozdenko A, Koplyk I, Marinich T, Abdildayeva A, Zhukabayeva T. Analysis of modern approaches for the prediction of electric energy consumption. Open Eng 2020;10(1):350–61. http://dx.doi.org/10.1515/eng-2020-0028.

[16] Alfares HK, Nazeeruddin M. Electric load forecasting: Literature survey and classification of methods. Internat J Systems Sci 2002;33(1):23–34.

[17] Hippert H, Pedreira C, Souza R. Neural networks for short-term load forecasting: a review and evaluation. IEEE Trans Power Syst 2001;16(1):44–55. http://dx.doi.org/10.1109/59.910780.

[18] Ardabili S, Mosavi A, Várkonyi-Kóczy AR. Advances in machine learning modeling reviewing hybrid and ensemble methods. 2019, http://dx.doi.org/10.1007/978-3-030-36841-8_21.

[19] Negnevitsky M, Mandal P, Srivastava AK. An overview of forecasting problems and techniques in power systems. In: 2009 IEEE power energy society general meeting. 2009, p. 1–4. http://dx.doi.org/10.1109/PES.2009.5275480.

[20] Rashed Mohassel R, Fung A, Mohammadi F, Raahemifar K. A survey on advanced metering infrastructure. Int J Electr Power Energy Syst 2014;63:473–84. http://dx.doi.org/10.1016/j.ijepes.2014.06.025.

[21] Hinterstocker M, Schott P, von Roon S. Disaggregation of household load profiles. Vienna: Internationale Energiewirtschaftstagung; 2017, URL https://www.fim-rc.de/Paperbibliothek/Veroeffentlicht/788/wi-788.pdf.

[22] McKenna E, Richardson I, Thomson M. Smart meter data: Balancing consumer privacy concerns with legitimate applications. Energy Policy 2012;41:807–14. http://dx.doi.org/10.1016/j.enpol.2011.11.049.

[23] Kowarik A, Stolze P, Grondal O, Ilves M, Kirt T, Jansson I, et al. Report on data access and data handling. Tech. rep., ESSnet Big Data; 2016, URL https://ec.europa.eu/eurostat/cros/content/WP3_Report_1_1_en.

[24] European Commission, Directorate-General for Energy, Küpper G, Cavarretta M, Ehrenmann A, Naffah E, Szilagyi J, et al. Format and procedures for electricity (and gas) data access and exchange in member states. Publications Office; 2020, http://dx.doi.org/10.2833/719689.

[25] Haney A, Jamasb T, Pollitt M. Smart metering and electricity demand: Technology, economics and international experience. In: Faculty of economics. Cambridge working papers in economics, University of Cambridge; 2009, URL https://www.cambridge.org/core/books/future-of-electricity-demand/smart-metering-technology-economics-and-international-experience/82C8C2C82CFE1FE9D513CFB17F356C9C.

[26] Atrias. The central hub in providing information in the energy market. 2021, URL https://www.atrias.be/ [Accessed: 28 May 2021].

[27] Elhub. Netural data hub fir metering data and market processes.. 2021, URL https://elhub.no/en/# [Accessed: 28 May 2021].

[28] McMahan B, Moore E, Ramage D, Hampson S, y Arcas BA. Communication-efficient learning of deep networks from decentralized data. In: Artificial intelligence and statistics. PMLR; 2017, p. 1273–82, URL https://proceedings.mlr.press/v54/mcmahan17a/mcmahan17a.pdf.

[29] Konečný J, McMahan HB, Ramage D, Richtárik P. Federated optimization: Distributed machine learning for on-device intelligence. 2016, ArXiv, arXiv:1610.02527.

[30] Zhu L, Liu Z, Han S. Deep leakage from gradients. In: Wallach H, Larochelle H, Beygelzimer A, dÁlché Buc F, Fox E, Garnett R, editors. Advances in neural information processing systems, Vol. 32. Curran Associates, Inc.; 2019, URL https://proceedings.neurips.cc/paper/2019/file/60a6c4002cc7b29142def8871531281a-Paper.pdf.

[31] Geiping J, Bauermeister H, Dröge H, Moeller M. Inverting gradients-how easy is it to break privacy in federated learning? Adv Neural Inf Process Syst 2020;33:16937–47, URL https://proceedings.neurips.cc/paper/2020/file/c4ede56bbd98819ae6112b20ac6bf145-Paper.pdf.

[32] Briggs C, Fan Z, Andras P. Federated learning for short-term residential energy demand forecasting. 2021, ArXiv, arXiv:2105.13325.

[33] Savi M, Olivadese F. Short-term energy consumption forecasting at the edge: A federated learning approach. IEEE Access 2021;9:95949–69. http://dx.doi.org/10.1109/ACCESS.2021.3094089.

[34] He Y, Luo F, Ranzi G, Kong W. Short-term residential load forecasting based on federated learning and load clustering. In: 2021 IEEE international conference on communications, control, and computing technologies for smart grids. 2021, p. 77–82. http://dx.doi.org/10.1109/SmartGridComm51999.2021.9632314.

[35] Taïk A, Cherkaoui S. Electrical load forecasting using edge computing and federated learning. In: ICC 2020-2020 IEEE international conference on communications. IEEE; 2020, p. 1–6. http://dx.doi.org/10.1109/ICC40277.2020.9148937.

[36] Biswal MK, Tayeen ASM, Misra S. AMI-FML: A privacy-preserving federated machine learning framework for AMI. 2021, ArXiv, arXiv:2109.05666.

[37] Li J, Ren Y, Fang S, Li K, Sun M. Federated learning-based ultra-short term load forecasting in power internet of things. In: 2020 IEEE international conference on energy internet. 2020, p. 63–8. http://dx.doi.org/10.1109/ICEI49372.2020.00020.

[38] Xu Y, Jiang C, Zheng Z, Yang B, Zhu N. LSTM short-term residential load forecasting based on federated learning. In: 2021 international conference on mechanical, aerospace and automotive engineering. 2021, http://dx.doi.org/10.1145/3518781.3519181.

[39] Fekri MN, Grolinger K, Mir S. Distributed load forecasting using smart meter data: Federated learning with recurrent neural networks. Int J Electr Power Energy Syst 2021;107669. http://dx.doi.org/10.1016/j.ijepes.2021.107669.

[40] Shi Y, Xu X. Deep federated adaptation: An adaptative residential load forecasting approach with federated learning. Sensors (Basel, Switzerland) 2022;22. http://dx.doi.org/10.3390/s22093264.

[41] Lin J, Ma J, Zhu J. Privacy-preserving household characteristic identification with federated learning method. IEEE Trans Smart Grid 2022;13:1088–99. http://dx.doi.org/10.1109/TSG.2021.3125677.

[42] Husnoo MA, Anwar A, Hosseinzadeh N, Islam SN, Mahmood AN, Doss RRM. FedREP: Towards horizontal federated load forecasting for retail energy providers. 2022, ArXiv, arXiv:2203.00219.

[43] Khalil M, Esseghir M, Merghem L. Federated learning for energy-efficient thermal comfort control service in smart buildings. In: 2021 IEEE global communications conference. 2021, p. 01–6. http://dx.doi.org/10.1109/GLOBECOM46510.2021.9685286.

[44] Barbosa P, Brito A, Almeida H. A technique to provide differential privacy for appliance usage in smart metering. Inform Sci 2016;370–371:355–67. http://dx.doi.org/10.1016/j.ins.2016.08.011.

[45] Eibl G, Engel D. Differential privacy for real smart metering data. Comput Sci - Res Dev 2017;32. http://dx.doi.org/10.1007/s00450-016-0310-y.

[46] Chhachhi S, Teng F. Market value of differentially-private smart meter data. In: 2021 IEEEpower energy society innovative smart grid technologies conference. 2021, p. 1–5. http://dx.doi.org/10.1109/ISGT49243.2021.9372228.

[47] Yang Q, Liu Y, Chen T, Tong Y. Federated machine learning: Concept and applications. ACM Trans Intell Syst Technol (TIST) 2019;10(2):1–19. http://dx.doi.org/10.1145/3298981.

[48] Xian X, Wang X, Ding J, Ghanadan R. Assisted learning: A framework for multi-organization learning. Adv Neural Inf Process Syst 2020;33:14580–91, URL https://papers.nips.cc/paper/2020/file/a7b23e6eefbe6cf04b8e62a6f0915550-Paper.pdf.

[49] Kairouz P, McMahan HB, Avent B, Bellet A, Bennis M, Bhagoji AN, et al. Advances and open problems in federated learning. Found Trends® Mach Learn 2021;14(1–2):1–210. http://dx.doi.org/10.1561/2200000083.

[50] McMahan HB, Moore E, Ramage D, y Arcas BA. Federated learning of deep networks using model averaging. 2016, CoRR, abs/1602.05629 arXiv:1602.05629.

[51] Li C. Designing a short-term load forecasting model in the urban smart grid system. Appl Energy 2020;266:114850. http://dx.doi.org/10.1016/j.apenergy.2020.114850.

[52] Vos M, Bender-Saebelkampf C, Albayrak S. Residential short-term load forecasting using convolutional neural networks. In: 2018 IEEE international conference on communications, control, and computing technologies for smart grids, smartgridcomm 2018. 2018, http://dx.doi.org/10.1109/SmartGridComm.2018.8587494.

[53] Hochreiter S, Schmidhuber J. Long short-term memory. Neural Comput 1997;9(8):1735–80. http://dx.doi.org/10.1162/neco.1997.9.8.1735.

[54] Marino DL, Amarasinghe K, Manic M. Building energy load forecasting using deep neural networks. In: IECON 2016-42nd annual conference of the IEEE industrial electronics society. IEEE; 2016, p. 7046–51. http://dx.doi.org/10.1109/IECON.2016.7793413.

[55] Sutskever I, Vinyals O, Le QV. Sequence to sequence learning with neural networks. Adv Neural Inf Process Syst 2014;27. URL https://proceedings.neurips.cc/paper/2014/file/a14ac55a4f27472c5d894ec1c3c743d2-Paper.pdf.

[56] Cho K, van Merriënboer B, Bahdanau D, Bengio Y. On the properties of neural machine translation: Encoder–decoder approaches. In: Proceedings of SSST-8, eighth workshop on syntax, semantics and structure in statistical translation. Doha, Qatar: Association for Computational Linguistics; 2014, p. 103–11. http://dx.doi.org/10.3115/v1/W14-4012.

[57] Sehovac L, Grolinger K. Deep learning for load forecasting: Sequence to sequence recurrent neural networks with attention. IEEE Access 2020;8:36411–26. http://dx.doi.org/10.1109/ACCESS.2020.2975738.

[58] Kim T-Y, Cho S-B. Predicting residential energy consumption using CNN-LSTM neural networks. Energy 2019;182:72–81. http://dx.doi.org/10.1016/j.energy.2019.05.230.

[59] Le T, Vo MT, Vo B, Hwang E, Rho S, Baik SW. Improving electric energy consumption prediction using CNN and Bi-LSTM. Appl Sci 2019;9(20). http://dx.doi.org/10.3390/app9204237.

[60] Shi H, Xu M, Li R. Deep learning for household load forecasting—A novel pooling deep RNN. IEEE Trans Smart Grid 2018;9(5):5271–80. http://dx.doi.org/10.1109/TSG.2017.2686012.

[61] Kong W, Dong ZY, Jia Y, Hill DJ, Xu Y, Zhang Y. Short-term residential load forecasting based on LSTM recurrent neural network. IEEE Trans Smart Grid 2019;10(1):841–51. http://dx.doi.org/10.1109/TSG.2017.2753802.

[62] Li C, Ding Z, Zhao D, Yi J, Zhang G. Building energy consumption prediction: An extreme deep learning approach. Energies 2017;10(10). http://dx.doi.org/10.3390/en10101525.

[63] Yan K, Wang X, Du Y, Jin N, Huang H, Zhou H. Multi-step short-term power consumption forecasting with a hybrid deep learning strategy. Energies 2018;11(11). http://dx.doi.org/10.3390/en11113089.

[64] Kim J-Y, Cho S-B. Electric energy consumption prediction by deep learning with state explainable autoencoder. Energies 2019;12(4). http://dx.doi.org/10.3390/en12040739.

[65] Briggs C, Fan Z, András P. Federated learning for short-term residential energy demand forecasting. 2021, ArXiv, arXiv:2105.13325.

[66] Zhao Y-M, Xiao W, Shuai L, Luo J, Yao S, Zhang M. A differential privacy-enhanced federated learning method for short-term household load forecasting in smart grid. In: 2021 7th international conference on computer and communications. 2021, p. 1399–404. http://dx.doi.org/10.1109/ICCC54389.2021.9674514.

[67] Bennett CJ. Regulating privacy. Cornell University Press; 2018, http://dx.doi.org/10.7591/9781501722134.

[68] Li Q, Wen Z, Wu Z, Hu S, Wang N, Li Y, et al. A survey on federated learning systems: Vision, hype and reality for data privacy and protection. IEEE Trans Knowl Data Eng 2021;1. http://dx.doi.org/10.1109/TKDE.2021.3124599.

[69] Pressmair G, Kapassa E, Casado-Mansilla D, Borges CE, Themistocleous M. Overcoming barriers for the adoption of local energy and flexibility markets: A user-centric and hybrid model. J Cleaner Prod 2021;317:128323. http://dx.doi.org/10.1016/j.jclepro.2021.128323.

[70] Dwork C. Differential privacy. In: Bugliesi M, Preneel B, Sassone V, Wegener I, editors. Automata, languages and programming. Berlin, Heidelberg: Springer Berlin Heidelberg; 2006, p. 1–12. http://dx.doi.org/10.1007/11787006_1.

[71] Dwork C, Roth A. The algorithmic foundations of differential privacy. Found Trends Theor Comput Sci 2014;9(3–4):211–407. http://dx.doi.org/10.1561/0400000042.

[72] Wood A, Altman M, Bembenek A, Bun M, Gaboardi M, Honaker J, et al. Differential privacy: A primer for a non-technical audience. Vanderbilt J Entertain Technol Law 2018;21(1):209–75, URL http://www.jetlaw.org/journal-archives/volume-21/volume-21-issue-1/differential-privacy-a-primer-for-a-non-technical-audience/.

[73] Jayaraman B, Evans D. Evaluating differentially private machine learning in practice. In: 28th $\{USENIX\}$ security symposium ($\{USENIX\}$ security 19). 2019, p. 1895–912, URL https://www.usenix.org/conference/usenixsecurity19/presentation/jayaraman.

[74] Bonawitz K, Ivanov V, Kreuter B, Marcedone A, McMahan HB, Patel S, et al. Practical secure aggregation for privacy-preserving machine learning. In: Proceedings of the 2017 ACM SIGSAC conference on computer and communications security. New York, NY, USA: Association for Computing Machinery; 2017, p. 1175–91. http://dx.doi.org/10.1145/3133956.3133982.

[75] Shamir A. How to share a secret. Commun ACM 1979;22(11):612–3. http://dx.doi.org/10.1145/359168.359176.

[76] Eibl G, Engel D. Differential privacy for real smart metering data. Comput Sci Res Dev 2017;32(1–2):173–82. http://dx.doi.org/10.1007/s00450-016-0310-y.

[77] Zhao J, Jung T, Wang Y, Li X. Achieving differential privacy of data disclosure in the smart grid. In: IEEE INFOCOM 2014 - IEEE conference on computer communications. 2014, p. 504–12. http://dx.doi.org/10.1109/INFOCOM.2014.6847974.

[78] Varrette S, Bouvry P, Cartiaux H, Georgatos F. Management of an academic HPC cluster: The UL experience. In: Proc. of the 2014 intl. conf. on high performance computing & simulation. Bologna, Italy: IEEE; 2014, p. 959–67. http://dx.doi.org/10.1109/HPCSim.2014.6903792.

[79] Chollet F, et al. Keras. 2015, URL https://keras.io.

[80] D. J-M. Smart meter data from London area. 2019, URL https://www.kaggle.com/jeanmidev/smart-meters-in-london.

[81] CACI. The acorn user guide. Tech. rep., CACI; 2014, URL https://acorn.caci.co.uk/downloads/Acorn-User-guide.pdf.

[82] Li T, Sahu AK, Talwalkar A, Smith V. Federated learning: Challenges, methods, and future directions. IEEE Signal Process Mag 2020;37(3):50–60. http://dx.doi.org/10.1109/msp.2020.2975749.

[83] Yang Q, Liu Y, Cheng Y, Kang Y, Chen T, Yu H. Federated learning. Synth Lect Artif Intell Mach Learn 2019;13(3):1–207. http://dx.doi.org/10.2200/S00960ED2V01Y201910AIM043.

[84] McMahan HB, Ramage D, Talwar K, Zhang L. Learning differentially private recurrent language models. 2018, ArXiv, arXiv:1710.06963.

[85] Lu Y, Huang X, Dai Y, Maharjan S, Zhang Y. Blockchain and federated learning for privacy-preserved data sharing in industrial IoT. IEEE Trans Ind Inf 2019;16(6):4177–86. http://dx.doi.org/10.1109/TII.2019.2942190.

[86] Andrew G, Thakkar O, McMahan B, Ramaswamy S. Differentially private learning with adaptive clipping. Adv Neural Inf Process Syst 2021;34. URL https://proceedings.neurips.cc/paper/2021/file/91cff01af640a24e7f9f7a5ab407889f-Paper.pdf.

[87] Abadi M, Chu A, Goodfellow I, McMahan HB, Mironov I, Talwar K, et al. Deep learning with differential privacy. In: Proceedings of the 2016 ACM SIGSAC conference on computer and communications security. 2016, p. 308–18. http://dx.doi.org/10.1145/2976749.2978318.

[88] Mironov I. Rényi differential privacy. In: 2017 IEEE 30th computer security foundations symposium. IEEE; 2017, http://dx.doi.org/10.1109/csf.2017.11.

[89] Glorot X, Bengio Y. Understanding the difficulty of training deep feedforward neural networks. In: Proceedings of the thirteenth international conference on artificial intelligence and statistics. JMLR Workshop and Conference Proceedings; 2010, p. 249–56, URL https://proceedings.mlr.press/v9/glorot10a/glorot10a.pdf.

[90] Lewis CD. Industrial and business forecasting methods: a practical guide to exponential smoothing and curve fitting. Butterworth-Heinemann; 1982.

[91] Lee C-Y, Wu C-E. Short-term electricity price forecasting based on similar day-based neural network. Energies 2020;13(17). http://dx.doi.org/10.3390/en13174408.

[92] Appleyard J, Kocisky T, Blunsom P. Optimizing performance of recurrent neural networks on GPUs. 2016, ArXiv, arXiv:1604.01946.

[93] Hao K. Training a single AI model can emit as much carbon as five cars in their lifetimes. MIT Technol Rev 2019. URL https://www.technologyreview.com/2019/06/06/239031/training-a-single-ai-model-can-emit-as-much-carbon-as-five-cars-in-their-lifetimes/.

[94] Fredrikson M, Jha S, Ristenpart T. Model inversion attacks that exploit confidence information and basic countermeasures. In: Proceedings of the 22nd ACM SIGSAC conference on computer and communications security. 2015, p. 1322–33. http://dx.doi.org/10.1145/2810103.2813677.

A.3.6 Research Paper 6 – *Towards a peer-to-peer residential short-term load forecasting with federated learning*

Towards a peer-to-peer residential short-term load forecasting with federated learning

Joaquin Delgado Fernandez*, Sergio Potenciano Menci*, Ivan Pavic*
*Interdisciplinary Centre for Security, Reliability and Trust (SnT), University of Luxembourg,
Luxembourg, Luxembourg, Email: [sergio.potenciano-menci, joaquin.delgadofernandez, ivan.pavic]@uni.lu

***Abstract*—The inclusion of intermittent and renewable energy sources has increased the importance of demand forecasting in the power systems. Smart meters play a critical role in modern load forecasting due to the high granularity of the measurement data. Federated Learning can enable accurate residential load forecasting in a distributed manner. In this regard, to compensate for the variability of households, clustering them in groups with similar patterns can lead to more accurate forecasts. Usually, clustering requires a central server that has access to the entire dataset, which collides with the decentralized nature of federated learning. In order to complement federated learning, this study proposes a decentralized peer-to-peer strategy that employs agent-based modeling. We evaluate it in comparison to a typical centralized k-means clustering. To create clusters, we compare Euclidian and Dynamic time warping distances. We employ these clusters to build short-term load forecasting models using federated learning. Our results reveal the possibility of using peer-to-peer (P2P) clustering along with simple Euclidean distances and Federated learning (FL) to obtain highly performant load forecasting models in a fully decentralized manner.**

***Index Terms*—Federated Learning, Peer-to-Peer, Clustering, K-means, Agent-Based Modelling, STLF**

I. Introduction

Load forecasting is one of the most crucial aspects of both traditional and modern power systems [1]. The main purpose of load forecasting in power system operational planning is to maintain balance between power supply (generation) and demand (load). The increasing penetration of variable renewable energy sources (VRES), electric vehicles, and prosumers (consumers with VRES) challenges the power system balance. They introduce additional volatility and uncertainty leading to higher imbalances and power system operation costs. To maintain the balance, higher accuracy of short-term load forecasting (STLF) models, along with higher accuracy of VRES forecasting models, is necessary [1]. The STLF models provide forecasts for a time horizon between 1 to 168 hours [1].

Traditional STLF models rely on static standard load profiles and only partially capture the variability of the load. Newer data-driven approaches can provide dynamic models that can better capture the variability of the load [2], [3]. These data-driven approaches rely on techniques such as machine learning (ML) and deep learning (DL). However, they require a large amount of data and high computing power. The roll-out of smart meters with higher measurement granularity, initiated in many countries in the last couple of years, generates the required amount of data for ML and DL. These ML and DL models can forecast load curves (time series) with higher accuracy compared to traditional methods [2]–[4].

Classic ML models, such as autoregressive integrated moving averages (ARIMA) or exponential smoothing, have limiting assumptions, such as linearity. With increasing data granularity, these limitations get accentuated. Modern forecasting techniques, such as DL models, can correctly capture these nonlinear and latent patterns in the data, leading to increases in the accuracy of STLF forecasts. DL models use a wide range of techniques, such as long short-term memory (LSTM), Convolutional neural network (CNN), or even hybrid models that combine multiple neural network architectures. Examples of hybrid models are attention-based methods [5], autoencoders [6], and deep autoencoders [7].

Data expansion and changes in the power system create higher variability among households, and consequently, these variations appear in their load profiles. In this regard, the academic literature has opted to cluster household profiles to increase forecasting accuracy [8]. Household clusters contain load profiles with similar characteristics. By doing so, the reduced intrinsic variability of the clusters eases the learning of the models [9]. In turn, fitting the model to a particular dataset and then generalizing it to other clusters would result in high bias and low variance.

In recent years, due to existing data but limited smart meter data access, FL has gained traction as a new framework for STLF as it can overcome these limitations [10], [11]. FL is a decentralized ML multi-party computation technique that can iteratively and collaboratively train any artificial intelligence (AI) model [12]. It provides an alternative to centralized models, as it does not require storing data in a central server (silo) nor exchanges of its peers' (clients') raw data (i.e., smart meter).

STLF can benefit from FL as it reduces the limitations of data availability since peers do not need to share raw data, but rather model parameters [10], [11], [13], [14]. Peer's data present high variability because of their decentralized

We would like to acknowledge the support of the European Union (EU) within its Horizon 2020 programme, project MDOT (Medical Device Obligations Taskforce), Grant agreement 814654. Additionally, this project was supported by the Kopernikus-project "SynErgie" of the German Federal Ministry of Education and Research (BMBF), by PayPal and the Luxembourg National Research Fund FNR (P17/IS/13342933/PayPal-FNR/Chair in DFS/Gilbert Fridgen) as well as by the Luxembourg National Research Fund (FNR) – FiReSpARX Project, ref. 14783405.

nature and distinct load consumption patterns. One solution to reduce this variability is to cluster the households based on their load profiles. However, clustering of load profiles usually requires global access to the data [15], i.e. it has centralized structure. This global access opposes to decentralized nature of FL. Consequently, the combination of clustering techniques and FL suffers from incompatibility [10], [11], [13], [14].

In this study, we propose a decentralized P2P clustering model that allows individual households to collaborate to produce STLF models using FL. We compared our decentralized P2P clustering model to a centralized model commonly used for this purpose. We also included different time series specific distance metrics employed in clustering techniques to generate suitable clusters.

In summary, we propose and evaluate a fully decentralized clustering approach for FL to obtain highly accurate forecasting models.

The remainder of this paper is structured as follows. Section II provides an overview of different clustering techniques, its distance metrics, and a deeper view of FL. Section III presents the clustering logic of the central and peer-to-peer models for later comparison (benchmark). In addition, it provides the FL training process details. Section IV provides an overview of the evaluation process, covering the evaluation metrics dataset, simulation environment, and procedure. Section V compares the results and provides a discussion. Finally, Section VI provides a conclusion.

II. BACKGROUND

In this section, we provide information on different centralized and decentralized clustering techniques, the distance metrics these techniques use, and how FL operates to produce forecasting models.

A. Clustering techniques

Clustering algorithms group data into so-called clusters in which elements of the same cluster share similar properties [15]. These clustering algorithms can be centralized or decentralized, depending on where data storage and computation occur, and can use supervised or unsupervised learning techniques [16].

On the one hand, centralized clustering algorithms require central silos to store all the data and a central server to run the clustering algorithm. Most of the academic literature focuses on centralized clustering algorithms [15].

On the other hand, the extension of decentralized clustering is limited. Most of the examples refer to decentralized algorithms evaluated in Agent Based Modeling (ABM) simulations [17]. In that way, the clustering algorithms are *ad-hoc* solutions for the particular problem they are solving [18]. In ABM, each agent will control a single part of the data set (an agent can be understood as a household), and thus the agents will individually decide on their own. In our case, the agents decide to create or dissolve clusters according to a given similarity metric. Agents can create clusters without needing a central server or silo, enabling a fully decentralized P2P environment and thus moving towards P2P economy [19].

Some methods combine centralized and decentralized characteristics. These methods focus on the decentralization of classic centralized algorithms. For example, Federated k-means [20] can train k-means clustering where distinct clients have shares of the dataset. In Federated k-means the training occurs in rounds where the centroids' moves are averaged every round. In addition, to have meaningful movements, each participant must have a large enough portion of the dataset to replicate the training on the entire data set. This limits the overall scope of the method and requires new fully decentralised methods for FL.

B. Distance Techniques

Regardless of the clustering technique, all the clustering algorithms rely on a similarity metric. This similarity can measure statistical correlation between vectors (see metrics such as Pearson's correlation or Spearman's rank correlation) or measure the separation between vectors (distance metrics). Similarity metrics allow the clustering algorithm to estimate whether or not two entries should be in the same cluster.

For this paper, we considered the two leading distance metric approaches to measure the closeness between time series (i.e., household load profiles). These distance metrics are Euclidean and Dynamic time warping (DTW).

a) Euclidean: A standard metric for comparing two vectors is the Euclidean distance. It requires a point-to-point mapping between comparable observations between two time series. However, in the case of slight misalignment along the time axis (generally the x axis), the distance metric between the two time series becomes significantly affected. Such misalignment can occur due to instrument measurement errors and time delays.

b) DTW: Under temporal constraints, standard distance measurements, such as Euclidean distances, fail to estimate the similarity of time series. For instance, multiple misalignments and links could simultaneously appear in different phases during the progression of a temporal series.

One solution to time alignment issues that might occur when time series are in phase or at different paces is DTW. Given two sequences X of length n and Y of length m, their DTW distance $D(X, Y)$ is defined as follows:

$$dtw(i,j) = \begin{cases} \infty & \text{if } i = 0 \text{ or } j = 0 \\ 0 & \text{if } i = j = 0 \\ \|X_i, Y_j\| + \min \begin{cases} dtw(i-1,j) \\ dtw(i,j-1) \\ dtw(i-1,j-1) \end{cases} & \begin{matrix} \forall i \in X,\ \forall j \in Y \\ dtw(i,j) \end{matrix} \end{cases} \tag{1}$$

DTW has been widely used to find similarities between time series. However, as seen in Equation (1), DTW is a recursive function over the lengths of the two time-series and hence computationally expensive. The computational burden could be bounded to a quasi-quadratic form of $O(n \cdot m)$ where n and m are the lengths of the time series. Although it is a high-complexity computation compared to euclidean methods, it performs well [21].

For example, Figure 1 illustrates the visual difference between the DTW and Euclidean distances for the same two household load profiles over 48 hours. DTW finds alignments across the spikes around t = 15 to t = 20, while the Euclidean cannot, as seen in t=42 where the spike in the green profile is measured against a valley in the blue profile.

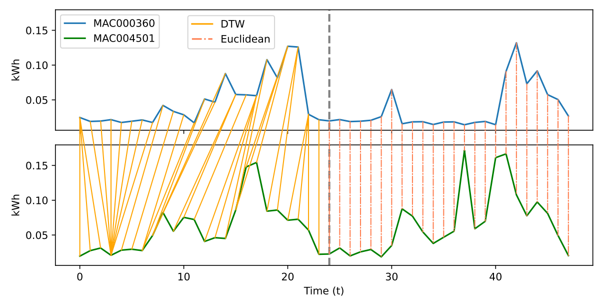


Fig. 1: Comparison of DTW (left) and Euclidian (right) distance over 48h for two residential load profiles.

C. Federated Learning

FL was introduced in 2016 as a way for entities to train a global model between multiple decentralized clients. Each client uses their local data to train models, without sharing their training data. [12]. This shift allowed models to grow by ingesting large amounts of data without the need to store the data in a centralized silo. In FL, clients do not share raw data but information about models, normally with a server. Thus, the server will process the models from the clients, reaching a consensus without accessing the local data of the clients. More specifically, FL works as follows: initially, the server selects an AI model to train. Later, the server shares the model with a random set of clients; normally, the ratio Q represents the fraction of this subset w.r.t. the total number of clients. A higher Q implies that more clients participate in each round of training and vice versa, where $Q = 1$ involves all clients. Once the clients receive the initial model, they begin training it. Each client uses their local data to train the received AI model.

Clients will share different information with the server depending on the FL algorithm. On the one hand, when using the Federated Stochastic gradient descent (Fed-SGD) algorithm, clients share their gradients of the loss at every batch of training. On the other hand, in Federated Average (Fed-Avg), clients share the weights of the trained model after every training epoch. The former requires more communication rounds between the server and the clients [12]. Consequently, the latter is often used. The role of the server once it receives information from the clients is straightforward. The server averages the information (gradients or model weights) and shares the averages back to the selected clients for a new training round. By doing so in an iterative manner, clients train and learn from other clients' data without accessing their data. The output is a collaborative model capturing the variability of clients' data.

III. Models

A. Decentralized ABM Clustering

We use an ABM approach for our fully decentralized P2P model. For the description of the ABM, we follow the Overview, Design concepts and Details (ODD) protocol [22]. We do not consider the ODD+D extension as we do not include human interaction in the model [22].

The models' primary purpose is to demonstrate how households (i.e., agents) can create clusters in a P2P manner. We define only a simple general pattern to assess the model's usefulness: the number of clusters created. It depends on how many agents there are and their interaction.

Our model includes two kinds of entities: smart meters (agents) and federations (collectives). We provide a list of their state variables and their descriptions in Table I. Within the federation, we refer to f_{ID} as the average distance of the smart meters within a federation, meanwhile f_{EID} refers to the extended average distance of the smart meters within a federation including a new smart meter.

TABLE I: Description of entities ad their variables.

Entities	Variable	Description
Smart meter	sm_{lp}	Assigned unique load profile
	sm_{list}	A list of calculated distances
	sm_{id}	Individual smart meter ID
	p_s	Asking threshold
Federation	f_{ID}	Internal federation average distance metric
	f_{EID}	Extended federation average distance
	f_{size}	number of smart meters in a federation
	f_{id}	Individual federation ID

We do not correlate time steps to seconds, minutes, or ours; we keep it agnostic. Similarly, the grid is not a physical attribute but an abstract plane.

Our ABM follows the following process. First, we select a total number of smart meters for our model. Each smart meter will have its own unique load profile (see Section IV-C).

The process then continues by defining two subsets. Subset Z is a defined random number of smart meters. Each smart meter of Z has an internal subset Z', composed by entities. To limit the computation overhead we limit $\|Z'\| = p_s\|Z\|$. Then in an iterative process, each smart meter of Z computes and saves in sm_{list} the distance between itself and each of the entities in Z'.

In the next step, each smart meter of subset Z will sort its distances and choose the shortest distance. Then it can: A) create a federation if none of the smart meters is in a federation, B) join a federation, or C) move to another federation. The last two cases require a deeper explanation. In the case of B), it refers to the smart meter in Z: sm not belonging to a federation, while the smart meter in Z' is in a federation f or viceversa. sm will only join f if f_{EID} is smaller than f_{ID}. In the case of C), both smart meters are part of federations. A smart meter will only change from one federation to another if its movement positively impacts both federation's metrics (ID and EID). If both are on the same federation, the smart meter performs no action.

The iterative process is repeated for a specified number of rounds. The output of the iterations is an undefined number of federations of different sizes and smart meters which did not join any federation.

To initialize ABM, we only need to choose the total number of smart meters, rounds, and metric distance. In our case, we consider 300 smart meters, 300 rounds, and two possible distance metrics (Euclidian and DTW). Thus, the ABM only requires load profiles as input data. The final output of ABM will be different federations (clusters) as depicted in 2.

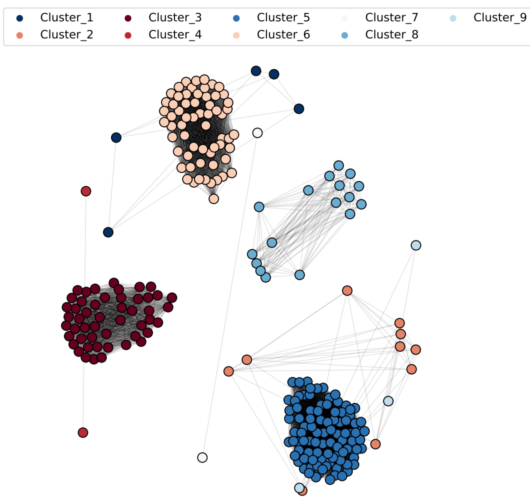


Fig. 2: Clusters after 300 rounds using P2P and DTW.

B. Centralized k-means clustering

K-means is the main representative of centralized clustering. It has been the go-to solution for clustering due to its usefulness and adaptability. K-means is an unsupervised algorithm which randomly initializes a given number of centroids. These Centroids are the center of a cluster. In every round, the centroids iteratively move towards the center of mass of each cluster until no more moves are required. One way to optimize the number of clusters is to use Silhouettes [23]. It optimizes the tightness and separation of each point in the cluster to find the optimal value. Another way is to use the Elbow method [24]. It offers a visual representation of the best number of clusters comparing the difference in the sum of square errors (SSE) within each cluster.

C. Federated Learning

FL requires a baseline learning model. This model could range from simple linear models to AI architectures. We follow the architectural design of [11] and the Artificial Neuronal Network architecture [6] to be the baseline of our model. Their model is an encoder-decoder architecture with 12 neurons in the latent space. We collect the hyperparameters of the FL model in Table II. In particular, we define Q as a function of the cluster size to limit the computational burden of large clusters. In our case, we define a maximum of 15 clients per round and produce 1-hour-ahead forecasts.

TABLE II: Hyperparameters for FL models.

Parameter	Value
Number of internal rounds before averaging	5
Artificial Neuronal Network architecture	Marino et al. [6]
Clients within a cluster (w)	38
Ratio of clients involved per round (Q)	$Q = \begin{cases} 1.0 & w < 15 \\ \text{w/15} & w \geq 15 \end{cases}$
Optimizer	Adam
Optimizer learning rate (L_r)	10^{-3}
Batch size	128
Number of communication rounds	100

IV. Evaluation

A. Evaluation metrics

Evaluation metrics offer indicators of the models performance and enable fair comparison. Each of the metrics depicts different characteristics of the models and their ability to predict them. On the one hand, absolute metrics such as MAE or MAPE are known to be robust with respect to outliers. On the other hand, quadratic metrics (MSE and RMSE) penalize large prediction errors, as they measure the standard deviation of residuals.

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2 \tag{2}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - x_i| \tag{3}$$

$$MAPE = \frac{100}{n}\sum_{t=1}^{n}\left|\frac{x_i - y_i}{x_i}\right| \tag{4}$$

$$RMSE = \sqrt{\left(\frac{1}{n}\right)\sum_{i=1}^{n}(y_i - x_i)^2} \tag{5}$$

B. Simulation environment

We performed the simulations in the IRIS Cluster of the high-performance computer (HPC) facilities of the University of Luxembourg [25]. The simulations for the clustering ran in an specific node with 1Tb of RAM while the FL model trained on two NVIDIA Tesla V100 with 16Gb or 32Gb depending on the allocation. We programmed the ABM and acFL model in Python using Tensorflow-Federated [26] and MESA framework [27] respectively. The DL models were written in Keras [28] and the time series k-means was built using DTAIDistance [29].

C. Dataset

For our simulations, we used a dataset collected during the Low Carbon London project within the UK Power Networks conducted between November 2011 and February 2014 in the London area [30]. It contains the electrical consumption (kWh) of 5567 households in a half-hour resolution and socioeconomic aggregations of loads using Acorns [31]. We treated our dataset to be ready for the simulations in the following manner. First, we downscaled the values from half-hour resolution to an hour resolution. This implies a reduction in the computational needs of the models. Second, we drop all the null and outlier values. Third, we rescaled the load profiles to a known range (0 to 1) using Min-Max scaler to further increase the model convergence. Forth, to limit the simulations, we restricted our dataset to an individual Accorn. In our case, we selected Accorn H. This results in 372 profiles. To ensure the validity of our simulations, we split the dataset into training and test set. Initially, we divided our households into two sets. In the first one, we randomly selected 300 households representing the training dataset. In the second one, the remaining 72 we used them to evaluate the performance. Regardless of the previous split, we split each particular household again in training and testing. This split affects the training and test of the FL models; by splitting the data we prevent the model to overfit known patterns and thus evaluate its ability to generalize under new conditions. The training set contains information from January 1st 2013 until December of the same year, while the test set contains data from January 2014 to March 2014.

D. Simulation Procedure

To evaluate the performance of both clustering techniques, we established a pipeline as depicted in Figure 3. In step one, we divided the dataset into a training split (300 households) and a test split (76 households). In step two, we perform the clustering. We cluster our data using both P2P and k-means and for each of the clustering techniques, we run one simulation per distance metric (Euclidian and DTW). We optimized the number of k-means clusters using the elbow method. The results of step two are the clusters. These are the input for the third step. In step three, we trained the FL models based on the clusters and the households inside. The result of this step was as many FL models as clusters found in the previous step. In step four, we estimated the most optimal cluster for each of the households in the test split. From this estimation, we subsequently evaluated the forecasting performance of each FL model.

In summary, our pipeline generated a list of estimations per clustering algorithm and per distance that enabled us to evaluate and compare the performance of the two approaches (fully decentralized and centralized).

V. Results

We analyze our results from two points of view. The first is the absolute performance of the FL models based on the chosen metrics (IV-A). The second is the computation time of the cluster, calculated in minutes.

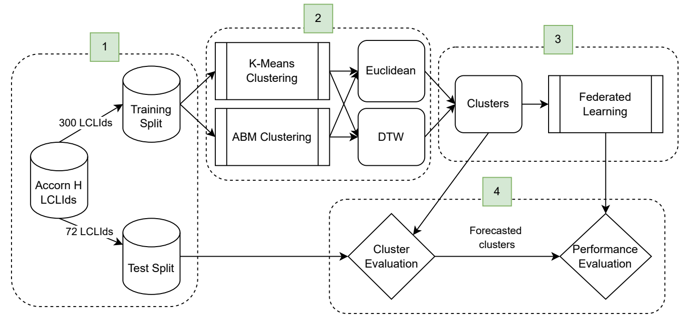


Fig. 3: Simulation pipeline.

We collect in Table III the performance of the P2P and k-means clustering results. On average, k-means perform better than P2P. However, the performance difference is insignificant since it is only 0.51 percentage points (pp), and it could be due to the stochastic nature of the models. On the same page, the difference between DTW and Euclidean distances is limited. Their disparities are 0.13 pp, towards Euclidean distances. These results showcase two readable outcomes. First, our P2P clustering approach leads to results similar to those of a central k-means clustering algorithm, facilitating further fully decentralized forecasting approaches. Second, Euclidian and DTW offer similar results. Their similarity might be a consequence of the small shifts in the load profiles of each smart meter present. These small shifts lead to similar measurements across distances and, thus, similar performance.

Concerning the computation time (see Table III under T[min]), it diverges dramatically between Euclidean and DTW. Euclidean is on the linear order of $O(Max(N, M))$, while DTW is on the quadratic order of $O(N \cdot M)$, being N and M the lengths of the two input sequences. Our results suggest between 4.5 to 9 times slower to compute the clustering when using the DTW distance metric. This is particularly prominent in our P2P case where the distance computations occur at a much higher rate, thus slowing the convergence of the algorithm by almost double. Our findings imply that applying DTW over Euclidean is not justified for clustering consumer load profiles with similar load profiles (small shifts) given in our case by the ACORN classification.

TABLE III: FL performance results of P2P or k-means clustering using Euclidian or DTW.

			MAE	MSE	RMSE	MAPE	T[min]
P2P	Euclidean	μ	0.0055	0.0002	0.0122	13.1284	20
		σ	0.0048	0.0005	0.0090	5.7536	-
	DTW	μ	0.0047	0.0002	0.0116	12.3761	180
		σ	0.0044	0.0005	0.0084	6.3897	-
K-means	Euclidean	μ	0.0036	0.0001	0.0102	10.8050	2
		σ	0.0019	0.0002	0.0055	5.4495	-
	DTW	μ	0.0041	0.0002	0.0105	11.8331	90
		σ	0.0029	0.0003	0.0063	5.6228	-

VI. Conclusions

Traditionally, the high variability of consumer loads has been tackled by clustering them into similar groups. FL is commonly used with centralized clustering approaches, and even though highly effective, this combination suffers from incompatibilities. This paper proposes P2P decentralized clustering technique to solve these incompatibles. We evaluated a new P2P decentralized clustering technique using ABM and compared it to a k-means approach, a traditional centralized clustering technique. Furthermore, we evaluated two distance metrics for clustering: Euclidian and DTW. Eventually, we trained FL models to predict one-hour-ahead load and analyzed the performance of the forecasts together with the total computation time.

Our decentralized P2P clustering approach produces similar clusters to centralized k-means, even with different distance metrics. The FL models trained for each clustering approach perform similarly. Consequently, the decentralized P2P clustering approach enables fully decentralized FL forecasting models.

Our analysis also suggests that classic Euclidean distances perform similarly to more complicated and slower methods like DTW. Without additional computational burden, Euclidean distances are enough to produce adequate clusters for FL.

Acknowledgements

The experiments presented in this paper were carried out using the HPC facilities of the University of Luxembourg [25]– see hpc.uni.lu

References

[1] A. Muñoz, E. F. Sánchez-Úbeda, A. Cruz, and J. Marín, *Short-term Forecasting in Power Systems: A Guided Tour*. Berlin, Heidelberg: Springer Berlin Heidelberg, (2010), pp. 129–160. [Online]. Available: https://doi.org/10.1007/978-3-642-12686-4_5

[2] A. B. Nassif, B. Soudan, M. Azzeh, I. Attilli, and O. AlMulla, "Artificial intelligence and statistical techniques in short-term load forecasting: A review," *ArXiv*, vol. abs/2201.00437, 2021.

[3] H. Hippert, C. Pedreira, and R. Souza, "Neural networks for short-term load forecasting: a review and evaluation," *IEEE Transactions on Power Systems*, vol. 16, no. 1, pp. 44–55, 2001.

[4] I. K. Nti, M. Teimeh, O. Nyarko-Boateng, and A. F. Adekoya, "Electricity load forecasting: a systematic review," *Journal of Electrical Systems and Information Technology*, vol. 7, no. 1, p. 13, 2020. [Online]. Available: https://doi.org/10.1186/s43067-020-00021-8

[5] L. Sehovac and K. Grolinger, "Deep learning for load forecasting: Sequence to sequence recurrent neural networks with attention," *IEEE Access*, vol. 8, pp. 36 411–36 426, 2020.

[6] D. L. Marino, K. Amarasinghe, and M. Manic, "Building energy load forecasting using deep neural networks," in *IECON 2016-42nd Annual Conference of the IEEE Industrial Electronics Society*. IEEE, 2016, pp. 7046–7051.

[7] W. Kong, Z. Y. Dong, Y. Jia, D. J. Hill, Y. Xu, and Y. Zhang, "Short-term residential load forecasting based on lstm recurrent neural network," *IEEE Transactions on Smart Grid*, vol. 10, no. 1, pp. 841–851, 2017.

[8] F. McLoughlin, A. Duffy, and M. Conlon, "A clustering approach to domestic electricity load profile characterisation using smart metering data," *Applied energy*, vol. 141, pp. 190–199, 2015.

[9] D. Syed, H. Abu-Rub, A. Ghrayeb, S. S. Refaat, M. Houchati, O. Bouhali, and S. Bañales, "Deep learning-based short-term load forecasting approach in smart grid with clustering and consumption pattern recognition," *IEEE Access*, vol. 9, pp. 54 992–55 008, 2021.

[10] M. Savi and F. Olivadese, "Short-term energy consumption forecasting at the edge: A federated learning approach," *IEEE Access*, vol. 9, pp. 95 949–95 969, 2021.

[11] J. D. Fernández, S. P. Menci, C. M. Lee, A. Rieger, and G. Fridgen, "Privacy-preserving federated learning for residential short-term load forecasting," *Applied Energy*, vol. 326, p. 119915, 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0306261922011722

[12] B. McMahan, E. Moore, D. Ramage, S. Hampson, and B. A. y Arcas, "Communication-efficient learning of deep networks from decentralized data," in *Artificial intelligence and statistics*. PMLR, 2017, pp. 1273–1282.

[13] F. Han, T. Pu, M. Li, and G. Taylor, "Short-term forecasting of individual residential load based on deep learning and k-means clustering," *CSEE Journal of Power and Energy Systems*, vol. 7, no. 2, pp. 261–269, 2020.

[14] Y. He, F. Luo, G. Ranzi, and W. Kong, "Short-term residential load forecasting based on federated learning and load clustering," *2021 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm)*, pp. 77–82, 2021.

[15] A. Saxena, M. Prasad, A. Gupta, N. Bharill, O. P. Patel, A. Tiwari *et al.*, "A review of clustering techniques and developments," *Neurocomputing*, vol. 267, pp. 664–681, 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0925231217311815

[16] R. Ahuja, A. Chug, S. Gupta, P. Ahuja, and S. Kohli, *Classification and Clustering Algorithms of Machine Learning with their Applications*. Cham: Springer International Publishing, 2020, pp. 225–248. [Online]. Available: https://doi.org/10.1007/978-3-030-28553-1_11

[17] R. Xu and D. C. Wunsch, "Survey of clustering algorithms," *IEEE Transactions on Neural Networks*, vol. 16, pp. 645–678, 2005.

[18] E. Ogston, B. Overeinder, M. van Steen, and F. Brazier, "A method for decentralized clustering in large multi-agent systems," in *Proceedings of the Second International Joint Conference on Autonomous Agents and Multiagent Systems*, ser. AAMAS '03. New York, NY, USA: Association for Computing Machinery, 2003, p. 789–796. [Online]. Available: https://doi.org/10.1145/860575.860702

[19] F. M. T. Brazier, H. la Poutré, A. R. Abhyankar, K. Saxena, S. N. Singh, and K. Tomar, "A review of multi agent based decentralised energy management issues," *2015 International Conference on Energy Economics and Environment (ICEEE)*, pp. 1–5, 2015.

[20] A. Soliman, S. Girdzijauskas, M.-R. Bouguelia, S. Pashami, and S. Nowaczyk, "Decentralized and adaptive k-means clustering for non-iid data using hyperloglog counters," in *Pacific-Asia Conference on Knowledge Discovery and Data Mining*. Springer, 2020, pp. 343–355.

[21] M. Gao, S. Pan, S. Chen, Y. Li, N. Pan, D. Pan, and X. Shen, "Identification method of electrical load for electrical appliances based on k-means ++ and gcn," *IEEE Access*, vol. 9, pp. 27 026–27 037, 2021.

[22] V. Grimm, S. F. Railsback, C. E. Vincenot, U. Berger, C. Gallagher, D. L. DeAngelis *et al.*, "The odd protocol for describing agent-based and other simulation models: A second update to improve clarity, replication, and structural realism," *Journal of Artificial Societies and Social Simulation*, vol. 23, no. 2, 2020.

[23] P. J. Rousseeuw, "Silhouettes: A graphical aid to the interpretation and validation of cluster analysis," *Journal of Computational and Applied Mathematics*, vol. 20, pp. 53–65, 1987. [Online]. Available: https://www.sciencedirect.com/science/article/pii/0377042787901257

[24] R. L. Thorndike, "Who belongs in the family," in *Psychometrika*. Citeseer, 1953.

[25] S. Varrette, P. Bouvry, H. Cartiaux, and F. Georgatos, "Management of an academic hpc cluster: The ul experience," in *Proc. of the 2014 Intl. Conf. on High Performance Computing & Simulation (HPCS 2014)*. Bologna, Italy: IEEE, July 2014, pp. 959–967.

[26] T. F. Authors, "Tensorflow federated," https://github.com/tensorflow/federated, 2018.

[27] J. Kazil, D. Masad, and A. Crooks, "Utilizing python for agent-based modeling: The mesa framework," in *Social, Cultural, and Behavioral Modeling*, R. Thomson, H. Bisgin, C. Dancy, A. Hyder, and M. Hussain, Eds. Cham: Springer International Publishing, 2020, pp. 308–317.

[28] F. Chollet *et al.*, "Keras," https://keras.io, 2015.

[29] W. Meert, K. Hendrickx, T. Van Craenendonck, and P. Robberechts, "Dtaidistance," Aug. 2020. [Online]. Available: https://doi.org/10.5281/zenodo.7158824

[30] J.-M. D., "Smart meter data from london area," 2019. [Online]. Available: https://www.kaggle.com/jeanmidev/smart-meters-in-london

[31] CACI, "The acorn user guide," CACI, Tech. Rep., 2014.

A.3.7 Research Paper 7 – *Optimal industrial flexibility scheduling based on generic data format*

Bahmani *et al. Energy Informatics* 2022, **5**(Suppl 1):26
https://doi.org/10.1186/s42162-022-00198-4

Energy Informatics

RESEARCH

Open Access

Optimal industrial flexibility scheduling based on generic data format

Ramin Bahmani*, Christine van Stiphoudt, Sergio Potenciano Menci, Michael SchÖpf and Gilbert Fridgen

From The 11th DACH+ Conference on Energy Informatics 2022 Freiburg, Germany. 15-16 September 2022

*Correspondence:
ramin.bahmani@uni.lu

SnT, Interdisciplinary Center for Security, Reliability and Trust, University of Luxembourg, 29 Av. John F. Kennedy, 1855 Luxembourg City, Luxembourg

Abstract

The energy transition into a modern power system requires energy flexibility. Demand Response (DR) is one promising option for providing this flexibility. With the highest share of final energy consumption, the industry has the potential to offer DR and contribute to the energy transition by adjusting its energy demand. This paper proposes a mathematical optimization model that uses a generic data model for flexibility description. The optimization model supports industrial companies to select when (i.e., at which time), where (i.e., in which market), and how (i.e., the schedule) they should market their flexibility potential to optimize profit. We evaluate the optimization model under several synthetic use cases developed upon the learnings over several workshops and bilateral discussions with industrial partners from the paper and aluminum industry. The results of the optimization model evaluation suggest the model can fulfill its purpose under different use cases even with complex use cases such as various loads and storages. However, the optimization model computation time grows as the complexity of use cases grows.

Keywords: Industrial flexibility optimization, Mixed-integer linear programming, Generic flexibility description, Load dependency

Introduction

Traditional power systems are centralized since the electric flow is unidirectional, from bulk power plants to consumers. However, the transition into a modern power system enabled by Information and communication technology (ICT) and enacted policies to combat global warming increase Renewable Energy Sources (RES), distributed in many cases. These RES depend on weather conditions for their optimal operation and thus increase the challenge of sustaining power system stability. To meet this challenge, the energy system needs energy flexibility. Union of the Electricity Industry—EURELECTRIC aisbl (2014) defines the term flexibility as the *"[...] modification of generation injection and/or consumption patterns in reaction to an external signal (price signal or activation) to provide a service within the energy system"*. Energy flexibility provision thus can have many different sources. Whereas options such as the enhancement of transmission lines or the building of new electrical storages or power plants are cost-intensive to implement (Palensky and Dietrich 2011; Heffron et al. 2020) (i.e., high investment costs), the adjustment of electricity demand has the advantage that the energy flexibility providing assets already exist (Heffron et al. 2020). The so-called DR, as one part of Demand Side Management (DSM), describes short-term changes at the electricity consumption side (Palensky and Dietrich 2011).

In Germany, the industrial sector has the highest share of final electricity consumption at 41% (Energiebilanzen 2021). Thus, it offers a high potential to impact a change of demand using DR. However, the identification and application of industrial energy flexibility are challenging tasks. Industrial companies have complex and a variety of industrial processes where industrial energy flexibility is not a core business for most of them. Hence, most industrial companies use tailored decision support systems to help them determine their optimal adjustment of electricity demand in terms of time and characteristics that require customized scheduling models. Thus, these tailored solutions pose a threefold challenge. First, they might require a relatively high investment, especially hurdling small and medium-sized companies (Bauernhansl et al. 2019). Second, they tend to lack interoperability features, notably in using a single, specific model to describe their energy flexibilities (Bauernhansl et al. 2019). This specific model instantly creates vendor lock-in problems (unable to switch between service providers easily) (Potenciano Menci et al. 2021; van Stiphoudt et al. 2021). Third, tailored models and existing literature tend to be use-case-specific, resulting in case-dependent models (Helin et al. 2017; Zhou et al. 2017; Xu et al. 2020) and the consideration of single processes (Howard et al. 2021). Therefore, industrial companies find several barriers to realizing their energy flexibility potential. To address these challenges, there is a need for a holistic, interoperable, and generic use-case-independent model, which industrial companies can use to support their decision of where (i.e., which market) and when (i.e., which times) they can market their industrial energy flexibility.

We propose an optimization model for calculating an optimal adjustment of electricity demand for industries that is generic, holistic, and interoperable for a given horizon. We achieve generality by building upon a generic data model that describes energy flexibility, introduced by Schott et al. (2019). This generic data model allows us to decouple model generation (flexibility description) and optimization, letting industrial companies specify their level of detail in their model's description. In addition, it enables us to consider in the optimization model the inclusion of connected systems, including a wide range of storage types (e.g., energy, heat, compressed air, electric) and dependencies between different processes and/or machines. We consider the model holistic because it allows industrial companies to run the optimization for various scenarios considering different optimization horizons, energy markets, or flexibility descriptions to compare potential benefits. Thus, it can assist industrial companies in selecting where and when to market their flexibility using the optimal schedule. By using defined and generic inputs and outputs to describe flexibilities, the model becomes interoperable: Companies that describe their energy flexibilities with the data model introduced in Schott et al. (2019) can apply this optimization model. Furthermore, industrial companies could combine the optimization model we propose with other solutions which already use the same generic data model (Lindner et al. 2022; Bank 2021).

The paper is structured as follows. The "Related Work" section provides a brief overview of related work in energy flexibility optimization and scheduling. The "Model" section introduces the optimization and scheduling model formulation based on a mixed-integer linear programming approach. The "Use cases and results" section focuses on implementing the model under different use cases to evaluate its output. The "Discussion" section focuses on the discussion about the features of the proposed model based on the simulation results from the previous section. Finally, the "Conclusions" section summarizes the results but also acknowledges the limitations of the proposed model in addition to the research outlook.

Related work

Energy flexibility optimization focused on demand (household, industrial, etc.) or in combination with supply is a widely investigated topic within literature. In this context, DR applied to industrial energy flexibility refers to the deviation in the consumption patterns of an industrial consumer to take part in energy flexibility markets (any market trading power and capacity) (Fridgen et al. 2017; Commission et al. 2022; Shoreh et al. 2016). In this regard, a production plant can shift its production plan to make a monetary profit by taking part in current electricity markets (e.g., wholesale) and in new potential markets (e.g., local flexibility markets) with its energy flexibility (Bauernhansl et al. 2019).

Industrial companies mostly optimize their industrial processes focusing on efficiency regarding other production inputs than energy, which often prevents their industrial processes from being energy flexible. Additionally, industrial processes have different characteristics, limiting the availability of complete generic models (i.e., any model that can accept any process) (Schott et al. 2019).

One characteristic of industrial processes and their energy flexibility is the connection between industrial processes and/or machines (Shoreh et al. 2016). Each link creates a dependency. There is a need to consider these dependencies between processes and/or machines to create generic models for industrial energy flexibility. Nevertheless, for simplification purposes, many authors do not consider dependencies in their models and thus limit their models' general application. For instance, in Angizeh et al. (2019), authors propose an energy flexibility scheduling method for industrial consumers considering on-site generation. However, they do not consider the dependency between loads. Likewise, the models proposed in Shrouf et al. (2014) and Varelmann et al. (2022) focus on optimizing the production scheduling and participating in different markets considering a single industrial machine, respectively. Therefore, they contribute to considering aspects such as different power states, load shifting, and participating in different markets but do not consider the dependencies within the industrial process.

Other authors employ material flow models to tackle such dependency problems in their optimization. Material flow models are one possible way to model dependencies. For example, using a material flow model, authors in Mitra et al. (2012) investigate an optimal production planning method for energy-intensive industrial plants (e.g., air separation plant and cement plant). Similarly, authors in Wanapinit et al. (2021)

present a modular energy flexibility model for industrial end-users using a material flow model. Their model covers energy flexibility features such as ramp rates and time limits for energy flexibility activation. Authors in Ashok and Banerjee (2001) proposed a method to minimize the electricity costs considering the process, storage, and manufacturing constraints. In Ruohonen et al. (2011), the authors present a model for cost-effective scheduling of paper pulp mill. The authors in Ramin et al. (2018) investigate the DSM of industrial processes considering production constraints. Authors in Khatri et al. (2021) propose a coupled generic modeling library and optimal control to react and control based on fixed or variable price signals. Their generic modeling library enables industrial companies to model down to individual machines and how to control them. Their optimization provides a schedule allowing the control model to act accordingly. Similarly, authors in Castro et al. (2009) proposed a resource-task-network approach to schedule continuous production plants based on electricity price. Nevertheless, their optimizations in many cases using material flow models could hurdle the generality of their model. This is because material flow modeling needs a detailed description of each industry. Thus, it might result in case-specific models.

Further improvement of generic industrial energy flexibility modeling has to do with the inherent features of the industrial energy flexibility such as ramping of the machines, energy storage modeling, and limited run-time of the machines, which the authors in Moon and Park (2014) and Barth et al. (2018) considered in their proposed model.

Moreover, there are contributions in the optimization domain that employ heuristic approaches (Gong et al. 2019). Heuristics' ability to calculate fast solutions has increased their application mostly in large-scale problems (Küster et al. 2021). Although heuristics might be a fast solution, they cannot guarantee the global (optimal) solution and might result in a locally optimal solution.

Nevertheless, demand modeling requires data transfer regardless of the feature selection and optimization model. To enable the data transfer between various sectors and provide standardization, having a data model is highly important but imposes a challenge. For instance, authors in Huber (2018) briefly explored the necessary parameters to describe a flexible data model for DSM. More extensively, authors in Schott et al. (2019) propose a generic data model which can describe various energy flexibility aspects, improve the information exchange, and enhance energy flexibility automation. This generic data model enables cross-sectoral usage (i.e., residential and industrial), facilitating targeted cross-sectoral optimizations. They challenged their proposed data model against the feature-checklist developed by Barth et al. (2018) and were able to include all features in the proposed data model. Authors in Lindner et al. (2022) for instance, leverage the potential of the generic data model to propose a possible merging service that could combine various descriptions into one. Authors in Bank (2021) propose a conceptual step step-wise approach to integrating the generic data model for production planning.

In summary, many authors solve their optimizations in a simplified yet efficient and fast manner, considering specific use cases. Within these specific use cases, many authors select a limited number of relevant features for their models to solve their optimization problems and thus, develop tailored solutions. These specific use cases face a threefold problem (Bauernhansl et al. 2019). First, they limit the holism of their model due to their selection of relevant features for simplification and fast optimization solutions. Second, their models tend to lack interoperability across different demand types. Since their models usually only focus on one demand-type, it delimits the feature selection and optimization method. Third, they hurdle their model's replicability since it is a tailored solution across the same industry. This tailored model would require, in some cases, extensive modifications to adjust to other boundary conditions. Therefore, many demand models, even those focused on industrial demand flexibility, face holistic, interoperable, and replicable (transferable) limitations. According to Helin et al. (2017), such attributes are necessary for industrial flexibility modeling.

Model

The proposed optimization model (artifact) takes three different inputs and produces two different outputs, depicted in Fig. 1. The optimization uses a generic data model, the Energy Flexibility Data Model (EFDM) from van Stiphoudt et al. (2021); Schott et al. (2019). The EFDM is the core for describing (1) the flexibility potential and (2) the specific power profile the flexible loads have to follow, known as flexible load measure. Therefore, the EFDM offers companies an entire framework in JavaScript Object Notation (JSON) to work with flexibilities descriptions (Schott et al. 2019). We considered the guidelines proposed in Hevner et al. (2004) to design the optimization model. Moreover, we followed the iterative methodology for developing and evaluating the model proposed by Peffers et al. (2007). However, we only describe in this manuscript the final optimization model and not the multiple iterations needed for the model development. Hereafter, each subsection covers the inputs the optimization model uses, the mathematical description of the optimization model, and the optimization output. We coded the model in Python using the Gurobi solver (Gurobi Optimization 2022) and tested it on a computer with a Core i7 CPU @ 2.6 GHz processor and 32 GB RAM.

Inputs

Energy market prices

The first input to our optimization model is the energy market prices (i.e., electricity markets). Notably, the optimization can use the power exchange prices (i.e., European Power Exchange (EPEX)) from the spot market contained in the wholesale market as well as price forecasts expressed as time series. It supports data intake from the day-ahead and intraday (auction and continuous) since it allows for different time resolutions

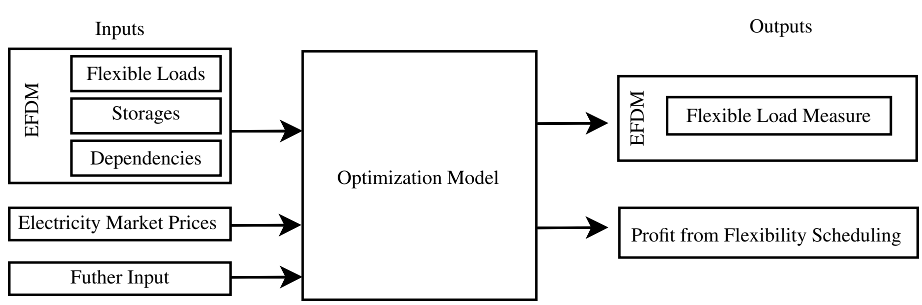


Fig. 1 Input and outputs of the optimization model

Table 1 Key figures of the EFDM as used by the optimization model

Key	Value (type)	Description
Validity	Integer ≥ 0	The interval where using the flexible load is allowed for flexibility purposes
Power states	Continuous ≥ 0	The deviation offlexible load from the normal operating point. The deviation ispositive in the load increase type,and it is negative in the loaddecrease type
Holding duration	Integer ≥ 0	The time length that flexible loads operate per usage
Usage numbers	Integer ≥ 0	The allowed number of usages in the optimization period
Modulation number	Integer ≥ 0	The number of permitted changes in the power state value per usage (without counting the power state change related to activation and deactivation)
Activation gradient	Continuous ≥ 0	The power change rate during the activation
Deactivation gradient	Continuous ≥ 0	The power change rate during the deactivation
Regeneration duration	Integer ≥ 0	The time limitation to activate a load after deactivation
Costs	Continuous ≥ 0	The cost of using flexible load, excluding the electric costs

Table 2 Storage key figures of the EFDM as used by the optimization model

Key	Value (type)	Description
Maximum capacity	Continuous ≥ 0	Maximum capacity of the storage
Initial energy content, including the timestamp	Continuous ≥ 0	Value of energy content stored at specified timestamp
Target energy content, including the timestamp	Continuous ≥ 0	Value of energy content that storage should reach at a specified timestamp
Energy loss	Continuous ≥ 0	Lost energy from storage because of exchange with the environment
Suppliers	String	Flexible loads that are filling the storage. Suppliers and stored value in the storages are linked using conversion efficiency
Drain	String	Loads that storage must serve in the specified time interval

(i.e., 15-min and 1-h values). The data input enables the analysis of price volatility in the electricity markets and the identification of the best possible marketing time, which may include times with negative prices.

EFDM: flexible loads, storages and dependencies

The second input of the optimization model is the flexibility description. Industrial companies can and are responsible to describe their flexibility using the EFDM developed in Schott et al. (2019) through its three main categories with any any level of detail they chose. These categories are the *flexible loads*, *storages*, and *dependencies*.

The *flexible load* category is the main flexibility description. It contains several key figures for the description, provided in Table 1.

Industrial companies might use a wide range of *storage* systems in their processes, such as heat, cold, compressed air, and electrical energy storage (EES). They can describe these *storages* using the *storage* category within the EFDM, utilizing several key figures, as described in Table 2.

Industrial companies can have complex processes. Their industrial processes involve machines that depend on one another. To capture industrial processes' complexity, industrial companies can describe these dependencies in the EFDM using the category *dependencies* between flexible loads. However, using the EFDM as inputs to describe the flexibility restricts the use of a material flow for our model. The EFDM can cover a dependency between two flexible loads. Dependencies internally in the EFDM have different types. This constitutes the necessity of activation/deactivation of one flexible load before/after another. There can be a dependency between the activation/deactivation time of *Load1* and *Load2*, as we depict in Fig. 2 in two examples. On the left, *Load1* imposes the activation of *Load2* after activation of *Load1*. It additionally provides lower and upper dependency boundaries. Using lower and upper boundaries and not one specific time for the dependencies can extend the flexibility options and result in more chances to capture all possible flexibilities. On the right, the deactivation of *Load1* requires the activation of *Load2* after and within the allowed boundaries.

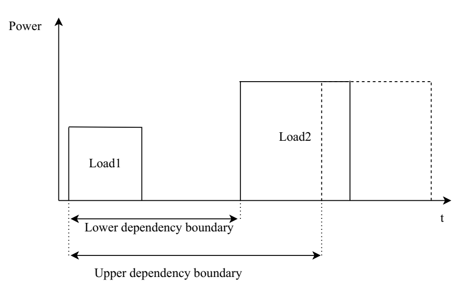
Further input

The third input to our optimization model includes additional information required for the optimization. The first additional input required is an optimization period. In addition to the validity time of the flexible loads passed with the EFDM, the optimization model requires an optimization period for which the optimization should perform the calculation. The second additional input is a selection of the electricity markets that the optimization model should consider. If no further input is selected, the optimization model considers all electricity markets for which electricity prices are available in the Electricity Market Prices input. The third additional input is the physical limitation of the grid connection point. The consideration restricts the power exchange to fulfill this grid constraint.

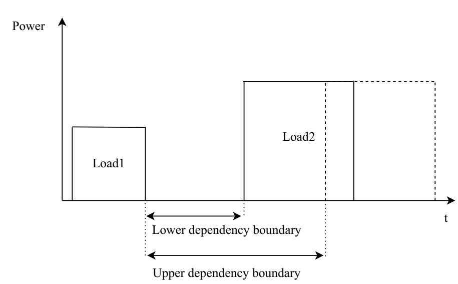
Mathematical model

Objective function

The core of the mathematical model is the objective function, which aims to maximize the profit by exploiting the market price differences and marketing industrial flexibility by either increasing or decreasing loads (i.e., modifying their power state). Equation (1) provides the objective function. L_{Neg}, L_{Pos}, L, and T are sets for load decrease flexibilities, load increase flexibilities, all the loads (union of L_{Neg} and L_{Pos}), and optimization horizon. The first term in the objective function (in the left) represents the profit obtained by decreasing the flexible loads. The second term (in the middle) represents the influence of increasing



(a) Dependency type start-start



(b) Dependency type end-start

Fig. 2 Dependencies between different loads the flexible loads. The third term (in the right) represents the costs associated with using the flexibilities (ac_l). In this objective function, $p_{l,t}$ is the variable expressing the magnitude of the power deviation, and $y_{l,t}$ is the binary variable which is equal to 1 in case flexible load l is activated at time t and is 0 otherwise. The parameters λ_t and ac_l express the electricity price at time t and the activation cost of flexible load l for flexibility purposes, respectively. Therefore, the objective function is as follows:

$$\max\left(\underbrace{\sum_{l\in L_{Neg}}\sum_{t\in T} p_{l,t}\lambda_t}_{load\ decrease\ profit} - \underbrace{\sum_{l\in L_{Pos}}\sum_{t\in T} p_{l,t}\lambda_t}_{load\ increase\ profit} - \underbrace{\sum_{l\in L}\sum_{t\in T} y_{l,t}\, ac_l}_{load\ activation\ cost}\right). \tag{1}$$

Power state constraints

The power state constraint forces the optimization to operate under a lower and an upper power deviation ($p_{l,t}$) is as follows:

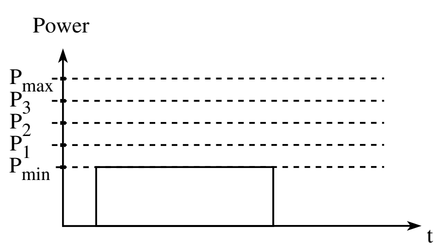
$$p_{l,min}I_{l,t} \le p_{l,t} \le p_{l,max}I_{l,t} \qquad \forall\, l \in L,\ t \in T \tag{2}$$

where $I_{l,t}$ is the current status binary variable of the flexible load l. In case the flexible load l is active at time t, the binary variable $I_{l,t}$ is 1 and $I_{l,t}$ is 0 otherwise.

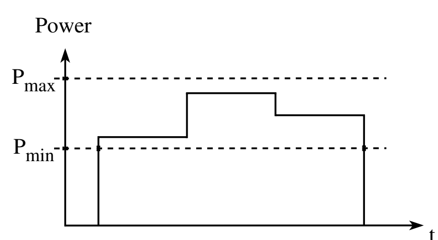
Nevertheless, some flexible loads might require to only operate at specific power states. In such an event requiring discrete power states, Eqs. (3) and (4) are necessary. The term $states_l$ equals the number of permissible power states of load l between $p_{l,min}$ and $p_{l,max}$. $Int_{l,t}$ is the integer variable controlling the power state value in case the power state is discrete, and $p_{l,min}$ and $p_{l,max}$ are minimum and maximum power deviation of flexible load l. Figure 3a provides an example of one flexible load l with 5 possible power states. Therefore, we have:

$$p_{l,t} = p_{l,min}I_{l,t} + \frac{p_{l,max} - p_{l,min}}{states_l + 1}\, Int_{l,t} \qquad \forall\, l \in L,\ t \in T \tag{3}$$

$$0 \le Int_{l,t} \le (states_l + 1)\, I_{l,t} \qquad \forall\, l \in L,\ t \in T. \tag{4}$$



(a) Representation of 5 discrete power states of a flexible load.



(b) Case without discrete power states and restriction on modulation number.

Fig. 3 Representation of power states

Some flexible loads might only be able to operate in one unique power state. For these type of flexible loads, we propose two equations as follows:

$$p_{l,t} - p_{l,t-1} \leq p_{l,max}\, y_{l,t} \qquad \forall\, l \in L,\ t \in T \tag{5}$$

$$p_{l,t-1} - p_{l,t} \leq p_{l,max}\, s_{l,t} \qquad \forall\, l \in L,\ t \in T. \tag{6}$$

They impose only one value for the power state during the activation period and model loads with 0 modulation numbers—the number of changes of the power state value during the holding duration. In this regard, only one increase and one decrease in the power are allowed in the flexibility's start-up and shut-down time, resulting in only one power state during the flexibility activation. The binary variable $s_{l,t}$ is equal to 1 if flexible load l shuts down at time t, and it will be 0 otherwise.

For those flexibility loads, which can freely operate under any power state, for example, as Fig. 3b depicts, only require the constraint given by Eq. (2).

Activation and deactivation constraints

Another set of constraints we subject the optimization function to are the activation and deactivation of the flexibilities which additionally cover other aspects. For instance, Eq. (7) provides the holding duration constraint for a given load l between the step limits $IT_{min,l}$ to $IT_{max,l}$ as follows:

$$y_{l,t} \leq \sum_{h=IT_{min,l}}^{IT_{max,l}} s_{l,\,t+h} \qquad \forall\, l \in L,\ t \in T. \tag{7}$$

Moreover, each flexible load can have a regeneration time (DT_l) impeding the reactivation of the flexibility during that time, expressed as the following:

$$\sum_{h=t}^{t+DT_l-1} (1 - I_{l,h}) \geq DT_l s_{l,t}\ \forall\, l \in L,\ t \in T. \tag{8}$$

Furthermore, flexibilities might be constrained to a specific time for their activation representing its validity for operation as follows:

$$I_{l,t} \leq validity_{l,t} \forall\, l \in L,\ t \in T \tag{9}$$

where the $validity_{l,t}$ is a binary parameter equal to 1 if load l is allowed to be in active status and is 0 otherwise. We limit the number of usages a flexible load can have through Eq. (10). In it, $Usage_{l,min}$ and $Usage_{l,max}$ control the minimum and maximum number of times that flexible load l can be used during the optimization horizon respectively. Moreover, we impede the flexible load activation and deactivation at the same time using Eq. (11). Thus, these equations are:

$$Usage_{l,min} \leq \sum_{t\in T} y_{l,t} \leq Usage_{l,max} \forall\, l \in L \tag{10}$$

$$y_{l,t} + s_{l,t} \leq 1 \forall\, l \in L,\ t \in T. \tag{11}$$

The last constraint we consider for the activation and deactivation of flexible loads is to define the relationship between the binary variables and is as follows:

$$y_{l,t} \; - s_{l,t} \; = I_{l,t} - I_{l,t-1} \forall\, l \in L,\, t \in T \tag{12}$$

where $y_{l,t}$, $s_{l,t}$, and $I_{l,t}$ are binary variables used for starting time, ending time, and the status of the flexible load, respectively.

Storage model

We include storages into the optimization model using the following constraints. The first constraint is the energy storage balance given by Eq. (13). In this equation, ST is the set of the storages. It considers the stored energy in the storage at a given time t. Notably, $E_{e,t}$, $p_{e,t,ch}$, and $p_{e,t,dis}$ are variables for stored energy, charging rate, and discharging rate of the storage, respectively. $E_{e,loss}$ indicates the energy loss due to the energy exchange with the environment. Therefore, we have:

$$E_{e,t} = E_{e,t-1} + p_{e,t,ch} - p_{e,t,dis} - E_{e,loss} \qquad \forall\, e \in ST,\, t \in T. \tag{13}$$

Equation (14) represents the storage charging balance. In this equation, $p_{e,t,ch}$ represents the storage charging using the flexible loads connected to storage e, demonstrated as $l \in \gamma_e$. The loads connected to each storage charge them considering the conversion efficiency eff_l. Therefore, we have:

$$p_{e,t,ch} = \sum_{l \in \gamma_e} eff_l \, p_{l,t} \forall\, e \in ST,\, t \in T. \tag{14}$$

The third storage related constraint defines the drain times given by Eq. (15). In order to model the "drain", which is described in the EFDM, $p_{e,t,dis}$ should be equal to fixed parameter $p_{e,t,drain}$ at certain time slots. Moreover, the storage requires at certain times to charge up to the "target energy content" described in the EFDM. To do so, $E_{e,t}$ (energy content) should be equal to predefined values ($E_{e,t,target}$) at that certain time slots, as Eq. (16) collects. In Eqs. (15) and (16) the sets $T_{drain,e}$ and $T_{target,e}$ are the two constraints the optimization aims to satisfy. The former is the time to drain and the latter is the target energy content constraint. Therefore, these equations are:

$$p_{e,t,dis} = p_{e,t,drain} \forall\, e \in ST,\; t \in T_{drain,e} \tag{15}$$

$$E_{e,t} = E_{e,t,target} \forall\, e \in ST,\; t \in T_{target,e} \;. \tag{16}$$

Dependency

The inclusion of dependencies into the optimization model is not a trivial endeavour. Therefore we consider a set of five equations to introduce dependencies into the optimization model. These five equations (17), (18), (19), (20) (21) consider the effect of activating or deactivating one flexible load based on another flexible load creating based on the possible combinations of how they can interact. The following sets of load dependencies used in this model are:

- $D_{start-start-after}$: Activation of one load after activation of another.
- $D_{start-start-before}$: Activation of one load before activation of another.
- $D_{end-start-after}$: Activation of one load after deactivation of another.
- $D_{end-start-before}$: Activation of one load before deactivating another.
- $D_{exclusion}$: Restricts the activation of a load based on the activation of another load.

Pointedly, the first combination is as follows:

$$y_{l_i,t} \leq \sum_{h=a}^{b} y_{l_j,t+h} \ \forall \, l_i \ and \ l_j \in D_{start-start-after} \ \ (i \neq j), \ t \in T \tag{17}$$

where it considers for the time steps from a to b that the optimization should activate the flexible load l_j after the activation of l_i. Differently, the second combination is Eq. (18). It is different from the previous equation as l_j must be now activated before the activation of the load l_i, formulated as follows:

$$y_{l_i,t} \leq \sum_{h=a}^{b} y_{l_j,t-h} \ \forall \, l_i \ and \ l_j \in D_{start-start-before} \ \ (i \neq j), \ t \in T. \tag{18}$$

Another combination is to activate the load (l_j) after or before the deactivation of another load (l_i), represented as follows:

$$s_{l_i,t} \leq \sum_{h=a}^{b} y_{l_j,t+h} \ \forall \, l_i \ and \ l_j \in D_{end-start-after} \ \ (i \neq j), \ t \in T \tag{19}$$

$$s_{l_i,t} \leq \sum_{h=a}^{b} y_{l_j,t-h} \ \forall \, l_i \ and \ l_j \in D_{end-start-before} \ \ (i \neq j), \ t \in T. \tag{20}$$

The last combination for a dependency we consider is as follows:

$$\sum_{h=a}^{b} y_{l_j,t+h} \leq (1 - y_{l_i,t})(b - a + 1) \ \ \forall \, l_i \ and \ l_j \in D_{exclusion} \ \ (i \neq j), \ t \in T \tag{21}$$

where a flexible load (l_i) prevents another flexible load's (l_j) activation. Thence, with these 5 equations creating a set of dependencies between two loads the model can consider interdependencies—two or more loads depend on each other and other loads—by creating a chain of loads which interdepend.

Grid constraint

The last constraint for our model can deal with the physical limitation of the grid connection point from industrial flexibilities. Therefore, we consider the physical grid constraint in the model through Eq. (22) to restrict the power exchange with the grid at the grid connection point. In the current version of the EFDM (Schott et al. 2019) the grid constraint is not included. Nevertheless, we consider this addition meaningful and propose to consider this adjustment in a future version of the EFDM. Thus, we have:

$$-P^{max}_{grid,t} \leq \sum_{l \in L_{Pos}} p_{l,t} - \sum_{l \in L_{Neg}} p_{l,t} \leq P^{max}_{grid,t} \forall \ t \in T. \quad (22)$$

Outputs

The optimization model with its objective function (Eq. 1) and the subjected constraints (Eqs. 2–22) calculates the optimal solution and provides two main outputs.

EFDM: flexible load measure

One output of the optimization model is describing a specific flexibility measure. In other words, it provides the optimal schedule for an industrial flexibility. A flexibility measure describes therefore no longer a flexibility potential. A flexibility measure contains a fixed load deviation (fixed power state for the intervals) with fixed periods (holding duration, modulation duration, activation/deactivation duration). The EFDM (Schott et al. 2019) enables in an standard manner to describe the flexibility measure using the so-called “flexible load measure” category, with its defined JSON Schema (van Stiphoudt et al. 2021).

Calculated profit

The second output of the optimization model is the maximized profit that industries could potentially achieve by marketing their flexibility load measures. For the calculation, the optimization in Eq. (1) considers the electricity prices passed as time series from the wholesale spot market (Day-Ahead, Intraday) or forecasted values in a specified validity time, Eq. (9), as well as the activation costs (ac_l) of a flexibility load measure. The calculated profit is the potential total amount given in Euros achievable by executing the calculated flexibility schedule. The optimization model calculates the profit per flexibility schedule.

Use cases and results

To demonstrate the capabilities of the proposed model, we investigate and evaluate the model under three different use cases. In the first use case, we evaluate the model using four simple, flexible loads in a simple context (i.e., without dependencies and storages). In the second use case, we evaluate the model using four flexible loads within an interdependent context (i.e., with dependencies and without storages). In the last use case, the complexity rises, and we evaluate the model using eight flexible loads in an interdependent and connected context, including storages (i.e., with dependencies and storages) to assess the full potential of the proposed model. However, our primary inputs, the EFDM is not a digital twin of a specific process. Still, we built them upon the learnings from several workshops and bilateral discussions with industrial partners from the paper and aluminum industry. We discussed several industrial processes they currently have, their structural features, the technical parameters, and the values they might include when describing their flexibility using the EFDM. However, our model contains synthetic data generated when describing the flexible loads since our industrial partners were unwilling to reveal actual production data and specific processes for publication.

Use case I—simple flexible loads

This first use case explores the capabilities of the optimization model when dealing with simple, flexible loads. We consider in this use case four different loads with neither dependencies among them nor a connection to a storage system. Therefore, the optimization model implements:

- Optimization function: given by Eq. (1).
- Main constraints: subject to Eqs. (2)–(12).

We collect in Table 3 an overview of the four flexible loads and their characteristics included in their EFDM description. The electricity prices considered, input for the optimization (24 h horizon), corresponds to the EPEX Day-ahead auction DE-LU on the 08/08/2020 (Bundesnetzagentur 2022).

All considered flexible loads have the same type, 'decrease.' In other words, the flexibility they offer is to decrease their power consumption. For example, load $L1$ can operate in between two power states (P_{max} and P_{min}). Three out of four loads do not face any restrictions concerning their validity (when the optimization cannot activate them). However, the optimization model can only activate load $L3$ between 18:00 and 24:00. Similarly, almost all loads have no activation costs, except $L4$, which in this case it costs 130 € every time it gets activated. Each load has a different holding duration. For instance, load $L2$ can remain activated for a minimum of 1 h and a maximum of 2 h. Only $L2$ needs a period of 3h between activations regarding their regeneration time. Finally, the optimization can decide not to activate any of the loads. Contrary, if the optimization uses the loads, it is restricted by the usage number. For instance, the optimization can use $L1$ up to three times or $L4$ one time.

We collect the optimization results in Fig. 4. In it, the flexible load $L1$ is a 'decrease' type; it should decrease its power consumption when the prices are high. Indeed, Fig. 4 corroborates this operation as $L1$ decreases its power between 01:00–04:00, 17:00–20:00, and 21:00–24:00, also within the limits of the validity time and the usage number to achieve a higher profit (reduction of power when the electricity price is high).

Similarly, the optimization activates flexible load $L2$ twice, in the beginning, between 01:00 and 03:00, and almost at the end, between 19:00 and 21:00. Although the activation between hours 18 and 24 could result in a higher profit (price is higher than hours 1–3), the 3-h regeneration time prevents it.

Table 3 Load's characteristics considered in use case I

key figure	Units	L1	L2	L3	L4
Load deviation type	–	Decrease	Decrease	Decrease	Decrease
Power state	MW	[0, 1]	[2, 2]	[3, 4]	[0.5,1.5]
Validity restriction	Time	None	None	18–24	None
Activation cost	€	0	0	0	130
Holding duration	h	[1, 3]	[1, 2]	[1, 1]	[2, 2]
Regeneration time	h	0	3	0	0
Usage Number	–	[0, 3]	[0, 2]	[0, 1]	[0, 1]

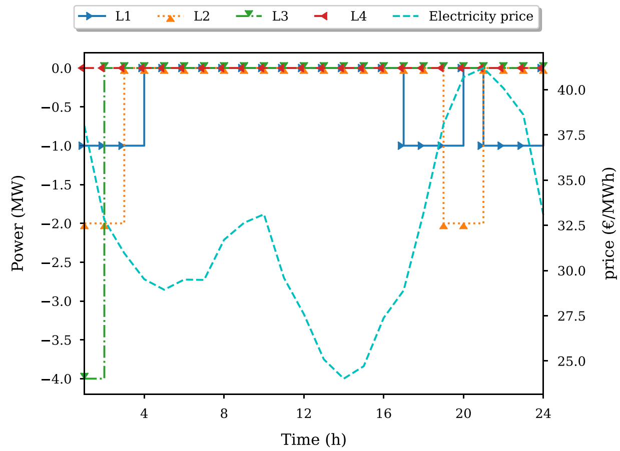


Fig. 4 Optimal scheduling for flexible loads in case I

The optimization reduces the power of flexible load $L3$ by 4 MW only once during the entire optimization horizon. It makes the maximum profit based on the electricity market prices and the validity of this load, restricting its usage between 18:00 and 24:00. This restriction prevents the optimization from decreasing the power consumption when the electricity prices are the highest (19:00–23:00).

Concerning the last flexible load, the optimization does not activate (reduce the power of) $L4$ since it has an activation cost, and it will decrease the total profit.

Finally, the model needed 0.180 s to converge in this use case to optimize these four flexible loads.

Use case II—flexible loads with dependencies

This second use case explores the capabilities of the optimization model when dealing more complex definition of flexible loads, as we consider dependencies between loads. In this use case, we consider a new four different loads without including a connection into a storage system. For this use case, the optimization model considers and implements the following:

- Optimization function: given by Eq. (1).
- Main constraints: subject to Eqs. (2)–(12).
- Dependencies constraints : subject to Eq. (17) for the $D_{start-start-after}$ dependency and Eq. (19) for the $D_{end-start-after}$ dependency.

Similar to the previous use case, we offer in Table 4 an overview of the four flexible loads and their characteristics included in their EFDM description. Additionally, we describe the dependency between loads in Table 5. As in the previous use case, we consider the same date, simulation horizon (24 h), and source for the electricity prices, the EPEX Day-ahead auction in the area of DE-LU on the 08/08/2020 (Bundesnetzagentur 2022).

In this second use case, there is a mix of load types. Three loads ($L2$, $L3$, $L4$) are decrease type, while $L1$ is increase type. In other words, the flexible load $L1$ can increase

Table 4 Load's characteristics considered in use case II

key figure	Units	L1	L2	L3	L4
Load deviation type	–	Increase	Decrease	Decrease	Decrease
Power state	MW	[0.5, 1]	[2, 2]	[3, 4]	[0.5, 1.5]
Validity restrictions	Time	None	None	None	None
Activation costs	€	0	0	0	0
Holding duration	h	[1, 3]	[1, 2]	[1, 1]	[2, 2]
Regeneration time	h	0	0	0	0
Usage Number	–	[0, 3]	[0, 2]	[0, 1]	[0, 2]

Table 5 Characteristics of dependencies in use case II

Trigger load	Dependent load	Dependency type
L2	L1	L1 must start 1–3 h after the activation of L2
L3	L4	L4 must start 2 h after deactivation of L3

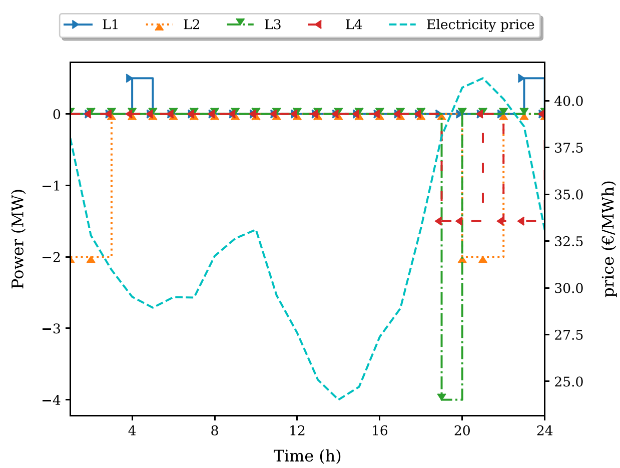


Fig. 5 Optimal scheduling for flexible loads in use case II

its power consumption contrary to the other loads. All loads in this use case have continuous power states, meaning they can only decrease or increase their power consumption by the values collected in Table 4. None of the loads have any activation costs or regeneration time. However, all loads face limitations imposed by the holding duration and the usage number. The former requires $L1$ to remain a minimum of one and a maximum of 3 h in each activation period. The latter limits the optimization to use a maximum of three times $L1$.

We collect the results of the optimization in Fig. 5.

The results provided by the optimization follow the imposed restrictions. On the one hand, the first dependency ($D_{start-start-after}$) in Table 5 forces $L1$ activation between 1 and 3 h after the activation of $L2$. In other case the optimization activates $L2$ between 01:00 and 03:00 while $L1$ between 05:00 and 06:00. However, the $L1$ and $L2$ dependency prevents $L1$ from increasing its power consumption during the lowest electricity price

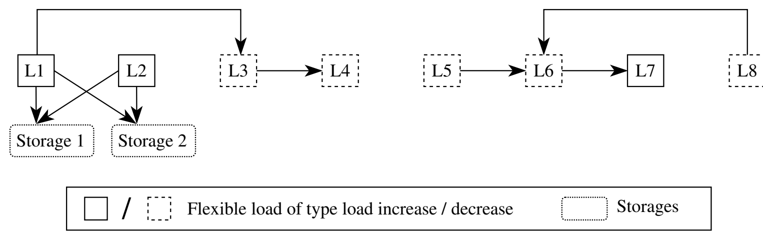


Fig. 6 Relationship between flexible loads and storages in use case III

Table 6 Characteristics of the loads' key figures of use case III based on the description of the EFDM

key figure	Units	L1	L2	L3	L4	L5	L6	L7	L8
Load deviation type	–	Increase	Increase	Decrease	Decrease	Decrease	Decrease	Increase	Decrease
Power state	MW	[1,2]	[2,2]	[1,2]	[0.5,1.5]	[2.2,2.7]	[1.8,3.2]	[1.2,2.2]	[1.3,1.7]
Validity restrictions	Time	None	None	None	None	None	None	None	None
Activation costs	€	0	0	0	0	0	0	0	0
Holding duration	h	[1,3]	[1,2]	[1,3]	[2,3]	[1,2]	[1,1]	[1,1]	[1,2]
Regeneration time	h	0	0	0	0	0	0	0	0
Usage Number	–	[0,5]	[0,4]	[0,2]	[0,3]	[0,1]	[0,2]	[0,2]	[0,3]

period (13:00–15:00). The optimization considers the same logic for the second activation of $L2$ at 20:00 given the constraint of $L2$; the optimization can only activate it twice. On the other hand, the second dependency forces the optimization to use $L4$ after 2 h of deactivating $L3$. The optimization activates $L3$ by decreasing 4 MW the power and decreasing, 2 h later, by 1.5 MW the power consumption of $L3$. However, since $L4$ can have two activations, the optimization between 19:00 and 21:00 decreases by 1.5 MW the power of $L4$. For this use case, the optimization model needed 0.112 s.

Use case III—flexible loads with dependencies and storages

This last use case explores an even more complex case than the previous ones. In this use case, the optimization faces eight flexible loads with several dependencies. Additionally, this use case includes two storages systems. We depict this complex relationship in Fig. 6.

For this complex use case, the optimization implements:

- Optimization function: given by Eq. (1).
- Main constraints: subject to Eqs. (2)–(12).
- Dependencies constraints: subject to Eq. (17) for the $D_{start-start-after}$ dependency and Eq. (19) for the $D_{end-start-after}$ dependency.
- Storage constraints: subject to Eqs. (13)–(16).

As previous use cases, we collect in Table 6 all flexible loads' characteristics contained in the EFDM description. Additionally, we collect in Table 7 the description of the dependencies constraints the loads have, whereas in Table 8 we collect the description of the two storages present in the use case. Both storages have 10 MWh capacity, modeled with 0 energy loss and specified drain time and quantity. Storage 1 should be drained between

Table 7 Characteristics of dependencies in use case III

Trigger load	Dependent load	Dependency type
L1	L3	L3 must start 2 h after the activation of L1
L3	L4	L4 must start 3 h after the deactivation of L3
L5	L6	L6 must start 3 h after the activation of L5
L6	L7	L7 must start 3 h after the activation of L6
L8	L6	L6 must start 3 h after the deactivation of L8

Table 8 Characteristics of storages in use case III

Storage	Max capacity [MWh]	Energy loss [MW/h] $E_{e,loss}$	Drain time [hour] $T_{drain,e}$	Drain quantity [MW] $p_{e,t,drain}$	Connected to
Storage 1	10	0	[19,21]	1	L1, L2
			[36,38]	1.2	
Storage 2	10	0	[15,17]	1.5	L1, L2
			[43,45]	1.1	

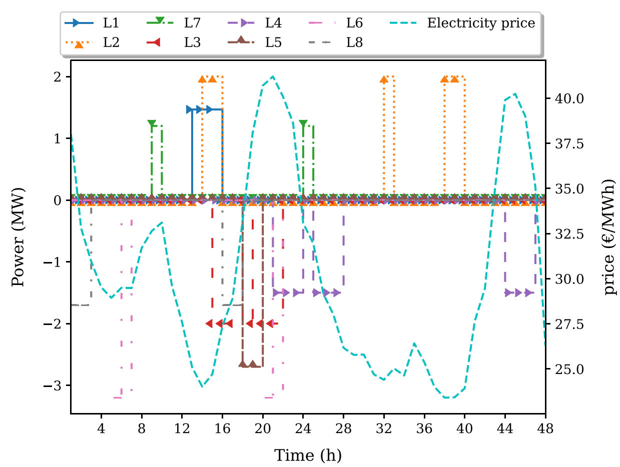


Fig. 7 Optimal scheduling for flexible loads in use case III

hours 19–21 and 36–38 with the power equal to 1 and 1.2 MW, respectively. Likewise, Storage 2 should be drained between hours 15 and 17 with 1.5 MW and during hours 43–45 with the amount of 1.1 MW. Both flexible loads, $L1$ and $L2$ connect to each storage system and have conversion efficiency (eff_l) equal to 1. Following the previous two use cases, the electricity prices input for the optimization considered corresponding to the EPEX Day-ahead auction DE-LU. In this case, the simulation horizon considers 48 h, therefore, the prices are for 08/08/2020, and 09/08/2020 (Bundesnetzagentur 2022).

We depict the optimization results in Figs. 7 and 8. The former presents the optimal load schedule for all loads. The latter presents the scheduling for the storage systems. The loads $L1$ and $L2$ must charge the storage systems to provide the energy demand required by the industrial process during the drain times. Therefore, it uses $L1$ and $L2$

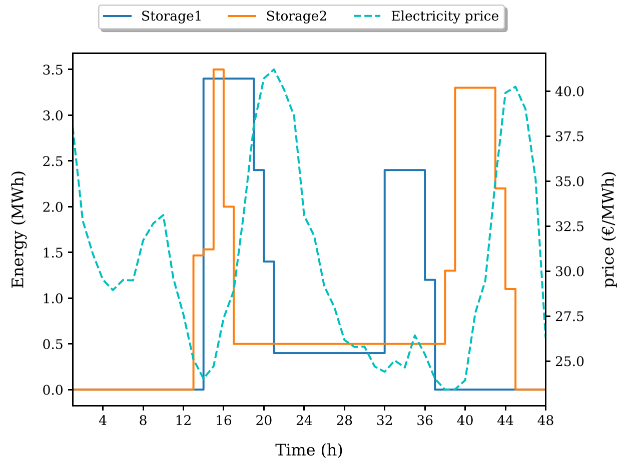


Fig. 8 Optimal scheduling for storages in use case III

several times during the optimization horizon (48 h) in the low-price hours accordingly between hours 12:00–26:00 and 32:00–40:00 (see Fig. 8). From our results (see Fig. 7), we can observe that optimization can deal with difficult constraints. For instance, $L1$, $L2$, and $L7$ increase their power consumption when prices are low without exciding the number of times the optimization can activate them. Nevertheless, these complex constraints provoke the activation of some flexible loads when the electricity price is not at its highest. For instance, the optimization activates $L6$ at hour 06:00, not the highest price hour, because it depends on $L8$.

Overall, all these complexities impact the optimization model, which requires a total of 3.3 s to converge.

Discussion

We tested the model in three synthetic use cases developed from discussions with aluminum and paper industries, where we exposed the optimization model against an increasing complexity in the industrial process description. We acknowledge the limitations of our evaluation, especially by not considering an existing industrial process due to the unavailability of data and not comparing our results to the benchmark of an exact process modeling.

Nevertheless, the model we propose performs as intended. We demonstrate the model's capability to offer a solution when facing complex EFDM descriptions. Examples of complex EFDM description are continuous power states, regeneration time, energy and material storage modeling, activation/deactivation ramping, different modulation numbers, holding durations, dependencies between flexible loads, and even connections to storage systems. The model's ability to handle EFDM descriptions has implications.

First, the optimization model does not require information on material flow nor information about the baseline power consumption of the industry, which industrial companies are not usually willing to share due to competitiveness. Thus, industrial companies can describe their processes without disclosing sensitive data and minimizing the necessary information. However, certain information still is required for the description using the EFDM, but not intrusive. On the one hand, the optimization using the EFDM might yield a worse result than the exact modeling of a specific industrial process. However, it might depend on the level of detail expressed in the flexibility description using the EFDM. On the other hand, the model is generic and serves its purpose for any industrial process described using the EFDM. Consequently, the model is replicable. In other words, different companies can use the model for their industrial processes and would require only one model instead of many multiple specific models for each industrial process.

Second, the optimization model can handle different time steps (e.g., 1 h and 15 min) and horizons such as day-ahead and intraday markets, opening a potential marketing opportunity for industrial companies. However, the model might face constraints (i.e., computation time and resources needed) when calculating the optimal solution with many loads, dependencies, and storage systems.

Third, even though this paper concentrated on testing the model for industrial flexibility, the applications of the proposed optimization model can go beyond the industrial sector. For instance, if electric vehicles and residential buildings use the EFDM to describe their flexibility, they could use the model.

Conclusions

We presented an optimization model to generate an optimal load schedule based on electricity prices and a generic data model for flexibility description, the EFDM. The model provides the schedule also using the EFDM description, simplifying the communication, technical, and economic issues specific use-case-oriented optimization models face. We evaluated the model under several use cases to demonstrate its capabilities when facing simple or complex industrial flexibility descriptions considering electricity prices from a day-ahead market. The model handled all the complexities, although the computation time and complexity grow as the optimization needs to consider more flexible loads and dependencies between loads and storage systems. Therefore, the model might face some limitations against a significant number of variables or when misused (i.e., used for whole industrial process scheduling). Future research could tackle some inefficiencies (computation time) and other limitations we acknowledge (comparison of the results with an exact optimization model). Nevertheless, the proposed optimization model could help industries market their flexibility. The model could enable any demand-user, such as residential or electric vehicle charging management operators, to use the generic optimization model if they describe their flexibility using the EFDM.

Acknowledgements

Supported by PayPal and the Luxembourg National Research Fund FNR (P17/IS/13342933/PayPal-FNR/Chair in DFS/Gilbert Fridgen).

About this supplement

This article has been published as part of Energy Informatics Volume 5 Supplement 1, 2022: Proceedings of the 11th DACH+ Conference on Energy Informatics. The full contents of the supplement are available online at https://energyinformatics.springeropen.com/articles/supplements/volume-5-supplement-1.

Author contributions

All authors contributed to the conception of the research. RB, MS and SPM contributed to the design of the work. RB, CvS and SPM drafted the first version of the paper. MS and GF supervised the research conception, provided feedback and participated in the paper revision. All authors read and approved the final manuscript.

Funding

Financial support from the Kopernikus-Project "SynErgie" by the Federal Ministry of Education and Research of Germany (BMBF) and the project supervision by the project management organization Projektträger Jülich (PtJ).

Availibility of data and materials
Not applicable.

Declarations

Competing interests
The authors declare that they have no competing interests.

Published: 7 September 2022

References

AG Energiebilanzen eV (2021) Auswertungstabellen zur Energiebilanz Deutschland—Daten für die Jahre von 1990 bis 2020". Retrieved March 29, 2022 from (2021)

Angizeh F, Parvania M, Fotuhi-Firuzabad M, Rajabi-Ghahnavieh A (2019) Flexibility scheduling for large customers. IEEE Trans Smart Grid 10(1):371–379

Ashok S, Banerjee R (2001) An optimization mode for industrial load management. IEEE Trans Power Syst 16(4):879–884

Bank L, Wenninger S, Köberlein J, Lindner M, Kaymakci C, Weigold M, Sauer A, Schilp J (2021) Integrating energy flexibility in production planning and control—an energy flexibility data model-based approach. Institutionelles Repositorium der Leibniz Universität Hannover, Hannover

Barth L, Ludwig N, Mengelkamp E, Staudt P (2018) A comprehensive modelling framework for demand side flexibility in smart grids. Comput Sci Res Dev 33(1–2):13–23

Bauernhansl T, Bauer D, Abele E, Ahrens R, Bank L, Brugger M, Colangelo E, Eigenbrod H, Fridgen G, Vazquez FG, Grigorjan A, Jarke M, Keller R, Lodwig R, Pullmann J, Reinhart G, Rösch M, Sauer A, Schel D, Schlereth A, Schott P, Schulz F, Sedlmeir J, Seitz P, Simon P, Weber T (2019) Industrie 4.0 als befähiger für energieflexibilität. In: Sauer A, Abele E, Buhl HU (eds) Energieflexibilität in der Deutschen Industrie: Ergebnisse aus dem Kopernikus-Projekt—Synchronisierte und Energieadaptive Produktionstechnik zur Flexiblen Ausrichtung Von Industrieprozessen Auf Eine Fluktuierende Energieversorgung—SynErgie. Fraunhofer Verlag, Stuttgart

Bundesnetzagentur: (2022) SMARD—Market data. Retrieved March 29, 2022 from (2022). https://www.smard.de/en/

Castro PM, Harjunkoski I, Grossmann IE (2009) New continuous-time scheduling formulation for continuous plants under variable electricity cost. Ind Eng Chem Res 48(14):6701–6714. https://doi.org/10.1021/ie900073k

Commission E, for Energy D-G, Antretter M, Klobasa M, Kühnbach M, Singh M, Knorr K, Schütt J, Boer J, Rolser O, Hernandez Diaz D, Fitzschen F, Garcerán A, Reina R, Stemmer S, Steinbach J, Popovski E (2022) Digitalisation of Energy Flexibility

Fridgen G, Keller R, Thimmel M, Wederhake L (2017) Shifting load through space-the economics of spatial demand side management using distributed data centers. Energy Policy 109:400–413

Gong X, De Pessemier T, Martens L, Joseph W (2019) Energy- and labor-aware flexible job shop scheduling under dynamic electricity pricing: a many-objective optimization investigation. J Clean Prod 209:1078–1094

Gurobi Optimization (2022) Retrieved March 29, 2022 from. https://www.gurobi.com

Heffron R, Körner M-F, Wagner J, Weibelzahl M, Fridgen G (2020) Industrial demand-side flexibility: a key element of a just energy transition and industrial development. Appl Energy 269:115026

Helin K, Käki A, Zakeri B, Lahdelma R, Syri S (2017) Economic potential of industrial demand side management in pulp and paper industry. Energy 141:1681–1694

Hevner AR, March ST, Park J, Ram S (2004) Design science in information systems research. MIS Q 28(1):75–105

Howard D, Ma Z, Jørgensen B (2021) Evaluation of industrial energy flexibility potential: a scoping review, pp. 1074–1079

Huber J, Klempp N, Weinhardt C, Hufendiek K (2018) An interactive online-platform for demand side management. In: e-Energy '18: Proceedings of the Ninth International Conference on Future Energy Systems, pp. 431–433

Khatri R, Schmidt M, Gasper R (2021) Active participation of industrial enterprises in electricity markets—a generic modeling approach. Energy Inf 4(3):20

Küster T, Rayling P, Wiersig R (2021) Pozo Pardo. Multi-objective optimization of energy-efficient production schedules using genetic algorithms. Optim Eng, F.D

Lindner M, Wenninger S, Fridgen G, Weigold M (2022) Aggregating energy flexibility for demand-side management in manufacturing companies—a two-step method. In: Behrens B-A, Brosius A, Drossel W-G, Hintze W, Ihlenfeldt S, Nyhuis P (eds) Production at the Leading Edge of Technology. Springer, Cham, pp 631–638

Mitra S, Grossmann IE, Pinto JM, Arora N (2012) Optimal production planning under time-sensitive electricity prices for continuous power-intensive processes. Comput Chem Eng 38:171–184

Moon J-Y, Park J (2014) Smart production scheduling with time-dependent and machine-dependent electricity cost by considering distributed energy resources and energy storage. Int J Prod Res 52(13):3922–3939

Palensky P, Dietrich D (2011) Demand side management: demand response, intelligent energy systems, and smart loads. IEEE Trans Indus Inf 7(3):381–388

Peffers K, Tuunanen T, Rothenberger MA, Chatterjee S (2007) A design science research methodology for information systems research. J Manag Inf Syst 24(3):45–77

Potenciano Menci S, van Stiphoudt C, Fridgen G, Schilp J, Köberlein J, Bauernhansl T, Sauer A, Grigorjan A, Schel D, Schlereth A, Schulz F, Weigold M, Lindner M, Schimmelpfenning J, Winter C (2021) Referenzarchitektur der Energiesynchronisationsplattform: Teil der Reihe "Diskussionspapiere V4—Konzept der Energiesynchronisationsplattform", s.l. Retrieved March 05, 2022 from (2021). http://publica.fraunhofer.de/dokumente/N-642369.html

Ramin D, Spinelli S, Brusaferri A (2018) Demand-side management via optimal production scheduling in power-intensive industries: the case of metal casting process. Appl Energy 225:622–636
Ruohonen P, Ahtila P (2011) Qualitative analysis of a thermo mechanical pulp and paper mill using advanced composite curves. Energy 36(6):3871–3877
Schott P, Sedlmeir J, Strobel N, Weber T, Fridgen G, Abele E (2019) A generic data model for describing flexibility in power markets. Energies 12(10):1893
Shoreh MH, Siano P, Shafie-khah M, Loia V, Catalão JPS (2016) A survey of industrial applications of demand response. Electric Power Syst Res 141:31–49
Shrouf F, Ordieres-Meré J, García-Sánchez A, Ortega-Mier M (2014) Optimizing the production scheduling of a single machine to minimize total energy consumption costs. J Clean Prod 67:197–207
Union of the Electricity Industry—EURELECTRIC aisbl: Flexibility and Aggregation—Requirements for their interaction in the market. Retrieved March 29, 2022 from (2014)
van Stiphoudt C, Potenciano Menci S, Schöpf M, Fridgen G, Weigold M, Lindner M, Buhl HU, Duda S, Schott P, Weibelzahl M, Wenninger S (2021) Energieflexibilitätsdatenmodell der Energiesynchronisationsplattform: Teil der Reihe "Diskussionspapiere V4—Konzept der Energiesynchronisationsplattform", s.l. Retrieved March 05, 2022 from (2021). https://eref.uni-bayreuth.de/68094/
Varelmann T, Erwes N, Schäfer P, Mitsos A (2022) Simultaneously optimizing bidding strategy in pay-as-bid-markets and production scheduling. Comput Chem Eng 157:107610
Wanapinit N, Thomsen J, Kost C, Weidlich A (2021) An milp model for evaluating the optimal operation and flexibility potential of end-users. Appl Energy 282:116183
Xu X, Abeysekera M, Gutschi C, Qadrdan M, Rittmannsberger K, Markus W, Wu J, Jenkins N (2020) Quantifying flexibility of industrial steam systems for ancillary services: a case study of an integrated pulp and paper mill. IET Energy Syst Integr 2(2):124–132
Zhou D, Zhou K, Zhu L, Zhao J, Xu Z, Shao Z, Chen X (2017) Optimal scheduling of multiple sets of air separation units with frequent load-change operation. Sep Purif Technol 172:178–191

Publisher's Note