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

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

Lucio Anneo SØneca (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)

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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, Timotheø, Esti, IvÆn, 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 atrÆs 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 specially 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 Flexibilitätsmarktösungen ermöglicht. Die übrigen fünf Forschungsarbeiten konzentrieren sich auf den Systembetrieb. Zwei Forschungsarbeiten leisten einen Beitrag durch die Analyse spezieller 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 surtas 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, descodi cando 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, Sergio 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	iii
List of Tables	iv
List of Acronyms	v
I Introduction	1
1.1 Motivation	1
1.2 Thesis structure	5
II Research background	6
2.1 Theoretical background	6
2.2 Research approach: Design science research	9
III Local exibility market fundamentals	12
3.1 Concepts	12
3.2 Fit in the current European electricity market	25
3.3 Regulation push	27
3.4 Challenges	29
IV System organization	31
4.1 Design characteristics	32
4.2 Service integration	32
V System operation	34
5.1 Scalability and replicability analysis for smart grid solutions	35
5.2 Forecasting and scheduling tools	39
VI Conclusion	43
6.1 Synthesis	43
6.2 Limitations and outlook	44
VII Recognition of previous and related work	46

TABLE OF CONTENTS

VIII	References	48
A	Appendix	71
A.1	Publication portfolio	71
A.2	Contribution statements	75
A.3	Appended research publications	79
A.3.1	Research Paper 1 –Decoding design aspects of local exibility markets for congestion management with a multi-layered taxonomy.	79
A.3.2	Research Paper 2 –Energy synchronization platform to enable and streamline automated industrial demand response.	103
A.3.3	Research Paper 3 –Scalability and replicability analysis of grid management services in low voltage networks in local exibility markets: an Inter-ex analysis.	114
A.3.4	Research Paper 4 –Functional scalability and replicability analysis for smart grid functions: the InteGrid project approach.	121
A.3.5	Research Paper 5 –Privacy-preserving federated learning for residential short-term load forecasting	161
A.3.6	Research Paper 6 –Towards a peer-to-peer residential short-term load forecasting with federated learning	176
A.3.7	Research Paper 7 –Optimal industrial exibility scheduling based on generic data format	183

| List of Figures

II.1 DSR methodology taken from [41].	10
II.2 Methodology, approach, and method overview of the different publications. . .	11
III.1 Service time constraint based on [69].	16
III.2 Service categorization per actor based on universal smart energy framework (USEF) [73].	17
III.3 Simple Smart Grid Architecture Model (SGAM) representation.	21
III.4 Simple organization classification of local flexibility market (LFM) actors based on [85].	22
III.5 Simple organizational classification of established and LFMs.	26

| List of Tables

I.1	Research publications overview relevant to this thesis.	4
II.1	Local exibility market literature de nitions.	9
III.1	Local exibility market literature de nitions adapted from RP1-[25].	13
III.2	Overview of local exibility market solutions implemented in Europe since 2016 based and adapted from RP1-[25].	19

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 exibility 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

LIST OF ACRONYMS

- FL federated learning. Page 41, 45
- FSP exibility service provider. Page 37, 38
- GDPR general data protection regulation. Page 30
- HEMS home energy management systems. Page 38
- ICT information and communication technology. Page 3, 8, 20, 21, 36, 45
- IoT Internet Of Things. Page 18
- IS Information Systems. Page 9, 31
- LFM local exibility market. Page iii, 2, 3, 5, 6, 8, 9, 12–35, 37, 38, 40, 42–45
- LSTM long short-term memory. Page 41
- LV low voltage. Page 37, 38
- ML machine learning. Page 40, 41, 45
- MP market platform. Page 33
- MPOPF multi-period optimal power ow. Page 38
- MV medium voltage. Page 38
- NIST National Institute of Standards and Technology. Page 7
- OLTC on load tap changer. Page 14, 38
- OPF optimal power ow. Page 36
- P2P peer-to-peer. Page 26
- PF power ow. Page 36
- PV photovoltaic. Page 15, 37, 39
- RES renewable energy resources. Page 1, 5, 28, 29, 34, 38

LIST OF ACRONYMS

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 effective 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	Rol ²
RP1	Decoding design characteristics of local exibility 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 exibility 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 exibility 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 a 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 cycle" 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 technolog-

ical 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 Kstler, 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 organization¹. 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 exibility 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 exibility market literature de nitions.

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 quantitative approaches using distant methods, as depicted in Figure **II.2**.

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

III | Local exibility 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, exibility, 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 socio-political 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 devel-

opments, including, for instance, inadvertently stimulating 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 requires 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 ap-

plied 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 parties (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, LFM 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	X	Own platform
Cornwall LEM	2016-2020	UK	X	Own platform
InterFlex: FR-UC3, NL demo	2017-2019	FR-NL	X	Own platform
Enera: Northwest of Germany use case	2017-2020	DE	X	Own platform
EU-SysFlex: Portuguese demo PT-FxH-RP	2017-2020	PT	X	Own platform
EU-SysFlex: FI demo	2017-2021	FI	X	Own platform
EU-SysFlex: Italian demo IT-AP	2017-2021	IT	X	Own platform
NODES: Mitnetz	2018-2021	DE	X	NODES
CoordiNet: BUC-ES-1b, BUC-SE-1a/1b	2019-2022	ES-SE	X	Own platform
CoordiNet: BUC-GR-2a/2b	2019-2022	GR	X	Own platform
CoordiNet: BUC-GR-1a/1b	2019-2022	GR	X	Own platform
CoordiNet: BUC-ES-4	2019-2022	ES	X	Own platform
NODES: NorFlex	2019-2022	NO	X	NODES
EUniversal: BUC-PT1	2020-2023	PT	X	NODES
OneNet: WECL-ES-01/02, EACL-HU-02, EACL-SL-01	2020-2023	ES-HU-SL	X	Own platform
OneNet: EACL-HU-01, EACL-SL-02	2020-2023	HU-SL	X	Own platform
OneNet: EACL-CZ-01/02/03	2020-2023	CZ	X	Own platform
OneNet: SOCL-CY-01/02, EACL-PL-01/02/03/04	2020-2023	CY-PL	X	Own platform
EUniversal: BUC-PT2	2020-2023	PT	X	Own platform
EUniversal: BUC-DE-AP/RP, BUC-PL-AP/RP, BUC-PT3/4	2020-2023	DE-PL-PT	X	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	X	Flexible Power
NODES: Smart Senja	In operation	DE-NO	X	NODES
NODES: SthlmFlex	In operation	SE	X	NODES
Piclo: UK Power Networks, Electricity Northwest	In operation	UK	X	Piclo
GOPACS	In operation	NL	X	GOPACS
Enedis: local flexibility platform	In operation	FR	X	Own platform
OMIE: IREMEL and DRES2Market	In development	ES	X	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 unavailability [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 function³. 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 old 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 Visual 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. Zeiselmaier 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. Sim-

ilarly, 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 exist, 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 LFM 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 LFM.

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 res-

idential 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) accel-

eration 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 communication design choices. The overarching platform concept aims to streamline interactions among multiple actors like demand, **LFM** platforms, and other users such as exhibitory 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 Sec-

tion 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 **SRA**s 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 **SRA**s 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 **SRA**s 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 grid-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 exibility 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 exibility 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 ve 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 exibility 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 **VPP** 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 systems (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 conceived, 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, especially on **STLF** models, to discern the state-of-the-art (SOTA) and choose a base-

line 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 multi-party 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. candidate 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]).

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

sponse (Accepted for publication)". In: 15th International Conference on Applied Energy (ICAIE 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 exibility markets: an inter ex analysis". In: 2021 IEEE Madrid PowerTech2021, 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: Energies14.18 (2021) ISSN: 1996-1073 DOI: 10.3390/en14185685 URL: <https://www.mdpi.com/1996-1073/14/18/5685>. Scopus percentile: 83^d. 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 energy326 (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: 99^h. 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 PowerTech2023, 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 exibility scheduling based on generic data format". In: Energy informatics5.1 (2022), p. 26 ISSN: 2520-8942 DOI: 10.1186/s42162-022-00198-4 URL: <https://doi.org/10.1186/s42162-022-00198>

Appendix

-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. Gutsch, and U. Krisper. “Tso-dso interaction in 2030/2040: scalability of the traf c light system concept in the project integrid”. In: *E & i elektrotechnik und informationstechnik* 38.8 (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 exibility markets)”. In: *Energy informatics* 5 (2022)
- S. Potenciano Menci, R. Schwalbe, C. Corner, B. Herndler, J. Kahtan, C. Gutsch, and T. Gross. “Functional scalability and replicability analysis framework for dis-

tribution grids”. In: CIREN 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. Energie exibilität in der deutschen Industrie. Band 2: Markt- und Stromsystem, Managementsysteme und Technologien energie exibler Fabriken [Energy exibility in German industry. Volume 2: Market and power systems, management systems and technologies of energy exible 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. Energie exibilitätsdatenmodell der Energiesynchronisationsplattform : Teil der Reihe "Diskussionspapiere V4 - Konzept der Energiesynchronisationsplattform" [Energy exibility data model of the energy synchronization platform: part of the series "concept of the energy synchronization platform. Discussion papers v4".], 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.

Appendix

A.3 Appended research publications

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

Appendix

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

Appendix

A.3.3 Research Paper 3 –Scalability and replicability analysis of grid management services in low voltage networks in local flexibility markets: an Inter ex analysis

Appendix

A.3.4 Research Paper 4 –Functional scalability and replicability
analysis for smart grid functions: the InteGrid project approach

Appendix

A.3.5 Research Paper 5 –Privacy-preserving federated learning for residential short-term load forecasting

Appendix

A.3.6 Research Paper 6 –Towards a peer-to-peer residential short-term load forecasting with federated learning

Appendix

A.3.7 Research Paper 7 –Optimal industrial exhibity scheduling
based on generic data format

Use case I—simple exible loads

is rst use case explores the capabilities of the optimization model when dealing with simple, exible loads. We consider in this use case four di erent loads with neither dependencies among them nor a connection to a storage system. erefore, 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 exible loads and their characteristics included in their EFDM description. e 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 exible loads have the same type, 'decrease.' In other words, the exibility they offer is to decrease their power consumption. For example, load 1 can operate in between two power states (and). ree 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 3 between 18:00 and 24:00. Similarly, almost all loads have no activation costs, except which in this case it costs 13€ every time it gets activated. Each load has a di erent holding duration. For instance, load 2 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 exible 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 exible load 2 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]

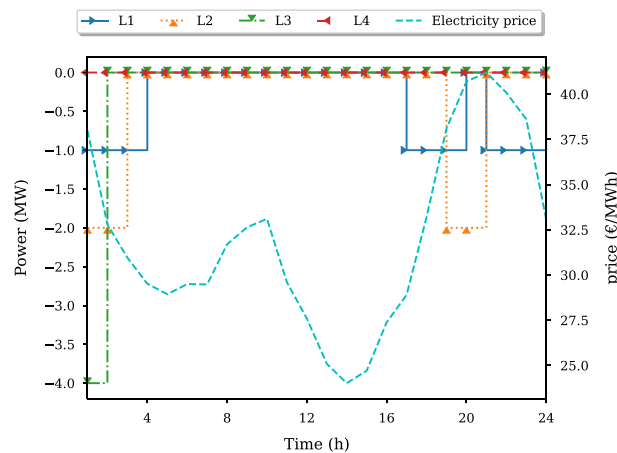


Fig. 4 Optimal scheduling for exible loads in case I

The optimization reduces the power of exible 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 exible 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 exible loads.

Use case II— exible loads with dependencies

This second use case explores the capabilities of the optimization model when dealing with more complex definitions of exible 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 $start-start-after$ dependency and Eq. (19) for the $end-start-after$ dependency.

Similar to the previous use case, we offer in Table 4 an overview of the four exible 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. Free loads (L3, L4) are decrease type, while L1 is increase type. In other words, the exible load L1 can increase

Table 4 Load's characteristics considered in use case II

key_gure	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

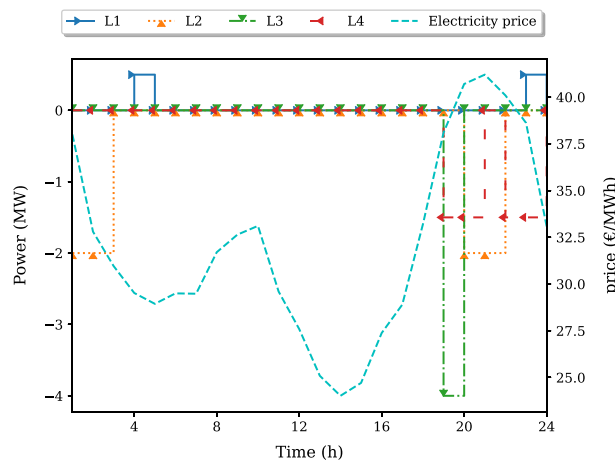


Fig. 5 Optimal scheduling for exible loads in use case II

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 L2 and L1 dependency prevents L1 from increasing its power consumption during the lowest electricity price

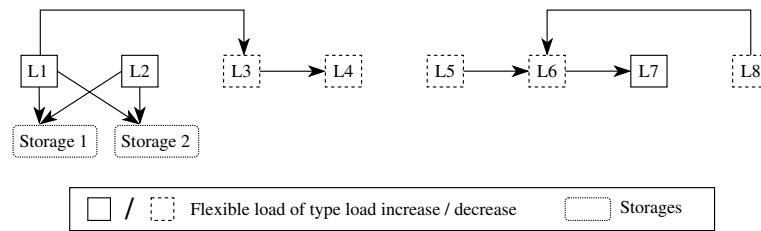


Fig. 6 Relationship between flexible loads and storages in use case III

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 ϕ_2 ; 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, 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 storage 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 $start-start-after$ dependency and Eq. (19) for the $end-start-after$ 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] $\rho_{e,t,drain}$	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	

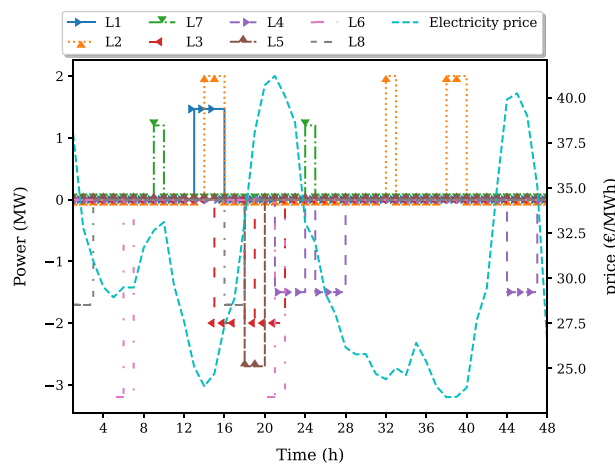


Fig. 7 Optimal scheduling for exible loads in use case III

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 exible loads, L1 and L2 connect to each storage system and have conversion efficiency 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

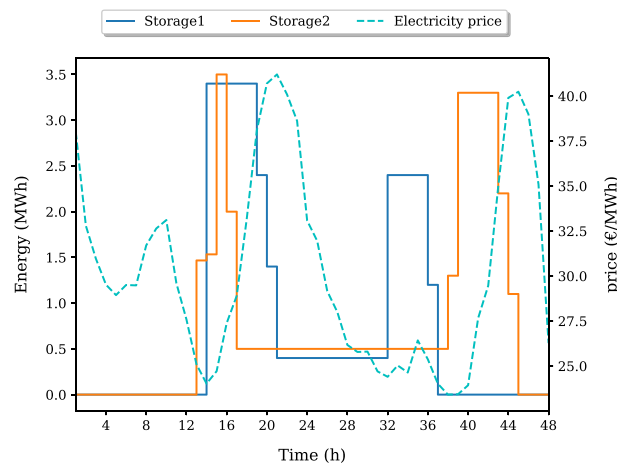


Fig. 8 Optimal scheduling for storages in use case III

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. 8), 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 exceeding 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.

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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.

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Declarations

Competing interests
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