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

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ABSTRACT

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

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

NOMENCLATURE

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

1. INTRODUCTION

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

The growing adoption of renewable energy sources like solar and wind creates fluctuations in power supply, leading to congestion and balancing challenges for the power grid. Additionally, the increased electrification of various sectors, including residential, industrial, and transportation, adds another layer of complexity to the stability of the power grid. In response to these challenges, System operators (SOs) are increasingly leveraging market-

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based strategies such as DR seeking additional flexibility [2]. These strategies not only help balance the variable energy supply but also turn the electrification trend into an advantage. By treating electrified sectors as potential sources of flexibility, DR can align demand with fluctuating supply.

The advent of digital technologies, coupled with the move towards decentralized power systems, adds complexity to an already intricate power grid by increasing the effort required for coordination and operation. Yet, this complexity spawns new business opportunities, from aggregation and forecasting services to real-time monitoring and virtual power plants. As a result, a diverse array of platforms and businesses have emerged to capitalize on these new service opportunities [3].

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

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

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

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

2. RELATED WORK

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

2.1 Industrial demand response

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

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

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

2.2 Energy-related digital platforms

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

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

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

2.3 Design principles for digital platforms

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

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

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

3. RESEARCH APPROACH

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

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

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

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

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

4. ENERGY SYNCHRONIZATION PLATFORM

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

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

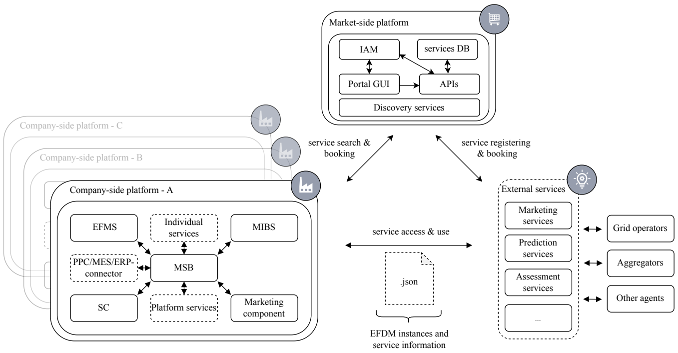

Fig. 1 Simplified architecture of the Energy Synchronization Platform.

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

4.1 *Generic industrial flexibility data model*

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

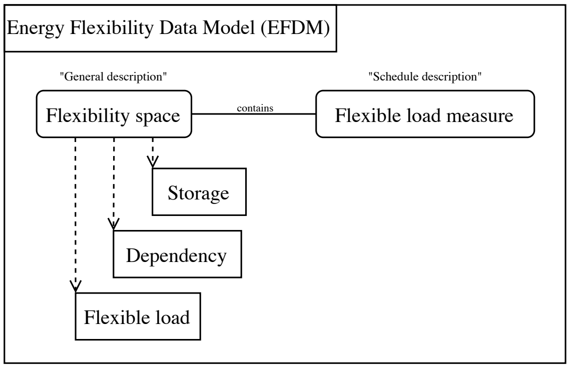

Fig. 2 Logical structure of the EFDM.

The industrial *flexibility space* describes the possibilities (potential) of a flexible industrial energy system to deviate

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

	Dimensions	Characteristics				Ex[1]
General dimensions	Platform operator	Company	Consortium	Aggregator		E
	Access	Web-App	Native-App	Specific interface		NE
	Operational concept	On-Premise	Cloud	Hybrid		NE
	Access requirements	Free Access	Certain criteria to fulfil	Certain devices necessary		NE
	Platform structure	Fixed structure	Modular structure without external interfaces	Modular structure with external interfaces		E
Data-centric dimensions	Platform type	SaaS		Platform as a service (PaaS)		E
	Communication	One-to-Many		Many-to-Many		E
	Data flow	Unidirectional		Bidirectional		E
	Data processing	Transactional	Visual analysis	Data-driven analysis		NE
	Data source	Device		Cloud		NE
Transaction-centric dimensions	Main function	Electricity trading	Energy flexibility trading	Virtual power plant		E
	Trading venue	Stock exchange	Markets for systems ervices	Over-the-counter (OTC)		NE
	Flexibility type	Market flexibility	System flexibility	Grid flexibility		NE
	Market design	Open		Closed		E
	Pricing	Free	Regulated	Free with regulating elements	No pricing	NE

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

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

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

4.2 Company-side platform overview

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

The MSB is the central component for information distribution, facilitating service orchestration. All components and services in the CP connect to the MSB. The MSB supports various industrial and standardized communication and network protocols [25]. Nevertheless, to address the integration challenge raised by experts when using proprietary industrial protocols, such as Siemens S7 for Programmable logic controllers (PLCs), we developed the SC. It acts as a software integration component translating communication and network protocols. However,

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[1] Ex: Exclusivity E: exclusive; NE: non-exclusive.

it requires extensive configuration of the SC to generate and execute EFDM instances. The EFMS functions as a repository for storing EFDM instances and acts as a broker to communicate requested EFDM instances through the MSB. Two core components facilitate the CP's connection with external services registered in the MP. The MIBS enables retrieval of information from market-sided flexibility services, such as weather data, electricity and gas prices, and their forecasts. The marketing component allows the CP to communicate the industrial flexibility potential to external services using EFDM instances and receive activation signals. These signals are translated into EFDM instances and distributed within the CP using the MSB.

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

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

4.3 Market-side platform overview

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

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

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

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

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

5. INTERACTIONS IN THE ENERGY SYNCHRONIZATION PLATFORM

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

5.1 Registering a service: External service - MP interaction

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

5.2 Finding a service: CP - MP interaction

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

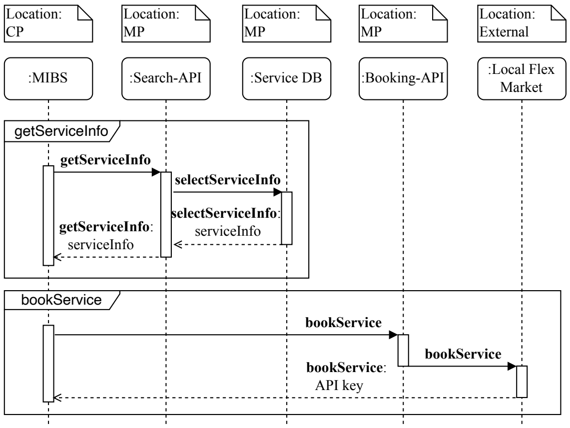

Fig. 3 Simplified service search and booking sequence diagram in the ESP.

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

In our example, once the industrial company decides on a service it wishes to book — in this case, the LFM service to market its industrial flexibility — it takes the following steps as visualized in the simplified process in Figure 3, under the *bookService* frame. It is important to reiterate that the LFM service is not operated by the MP itself. Instead, a third-party company runs the service and utilizes the MP as a marketplace to offer it.

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

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

5.4 Using a service: CP - external service interaction

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

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

The process starts within the CP, where the SCs generate EFDM flexibility potential instances. They register them with the EFMS. The industrial company uses a specialized merge service within the CP to optimize its flexibility potential. This service combines the individual EFDM flexibility potential instances, thereby creating an aggregated flexibility potential.

With its flexibility offering consolidated, the industrial company uses a marketing component to interface with the LFM. This component takes the information from the EFDM flexibility potential instances and converts them into offers compatible with the LFM. Then, it forwards them with a specific API key to the LFM.

The DSO, another LFM user, selects the most suitable offer to solve their problem, e.g., a congestion problem. Once the DSO confirms the selection, the LFM sends a flexibility activation signal to the CP targetting the marketing component. This component translates the LFM signal into a corresponding EFDM flexibility load measure

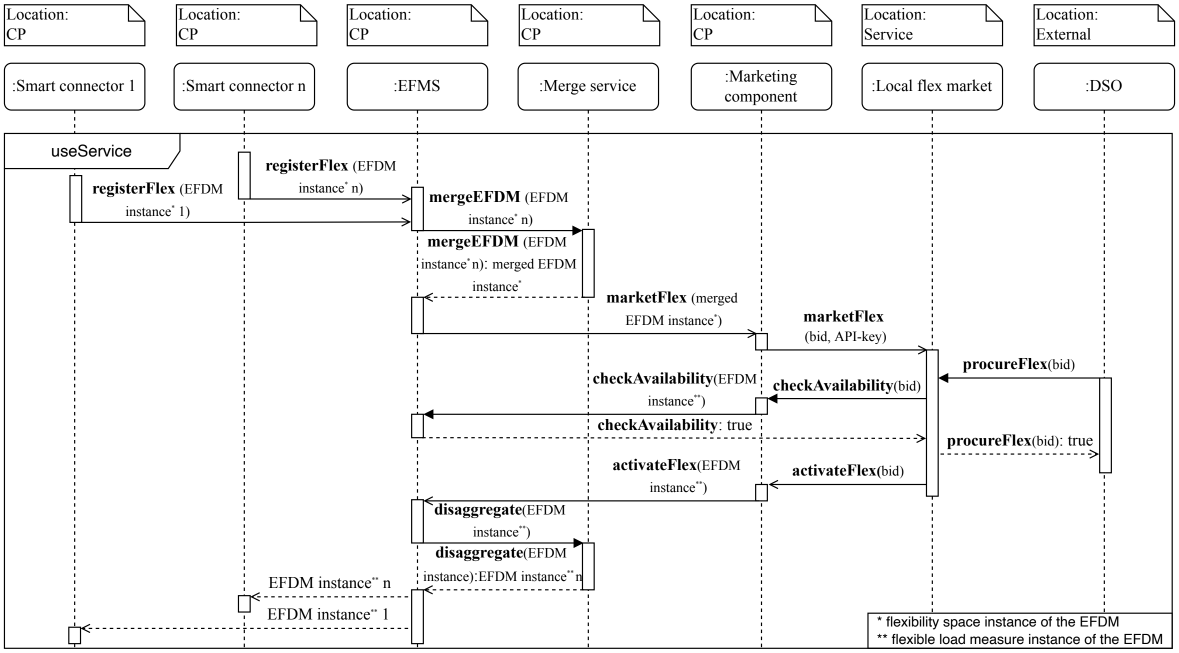

Fig. 4 Simplified industrial flexibility marketing sequence diagram in the ESP.

instance, which is registered in the EFMS for further action.

Finally, the merge service within the CP receives this new EFDM flexibility load measure instance. It disaggregates the measure into individual components and registers them back in the EFMS. The EFMS, in turn, forwards these disaggregated measures to the relevant SCs, enabling them to implement the control actions required to activate the marketed flexibility requested from the DSO.

6. BENEFITS AND CHALLENGES OF THE ENERGY SYNCHRONIZATION PLATFORM

We implemented the ESP as a small-scale demonstrator to test and gather feedback on the CP and MP design choices and functionalities. Three industrial companies across the Augsburg county in Germany participated. One used the LFM service for explicit DR, while another leveraged an aggregator service for similar purposes. In contrast, the remaining used an industrial flexibility market optimization tool service for implicit DR. This section provides a comprehensive analysis of the advantages and challenges that have emerged from the results of the small-scale demonstrator.

6.1 Benefits of the open architecture

To achieve the ESP's goal of automated and interoperable industrial energy management, we adopted an open architecture aligned with the four design requirement categories of Fischer et al. [23] (see Section 2).

The MP's design is inherently flexible, supporting integrating existing and future services. During the demonstration phase, one of the services registered was already pre-existing and used by industrial companies. This openness to integrate even existing services encourages service innovation and market competition, benefiting users by elevating service quality, value, and diversity [31, 32].

The CP's design is equally adaptable, compatible with various industry standards and interfaces, and even accommodates proprietary software not initially designed for energy flexibility. This versatility makes for cost-efficient automated energy management and lowers the barriers for companies to adopt the ESP.

Additionally, our standardized interface between the CP, MP, and external services eliminates the need for company-specific interfaces with service providers, thus preventing long-term vendor lock-in. Given that the cost of re-implementing interfaces is a known issue among participating companies, this feature was particularly well-received during the demonstration phase.

6.2 Benefits following platform adoption

Industrial companies actively engaging with the ESP and its various components and services have reported additional benefits. For instance, by utilizing the EFDM to identify their flexibility potential, these companies gained an in-depth understanding of the interconnectedness of their industrial processes, infrastructure, and energy use. This newfound transparency offers multifaceted advantages:

First, it enables process optimization, peak shaving, precise production cost calculation, and facilitates flexibility marketing as Rösch et al. [31] reports. Second, it aids in sustainable manufacturing. Companies can adjust their energy consumption to align with the availability of renewable energy, thereby reducing CO_2 emissions. Moreover, they can manage fluctuating electricity prices for optimal cost efficiency using the service created by Bahmani et al. [28].

6.3 Challenges in the operation

While the ESP offers various advantages, it is not without challenges, as identified during the demonstration phase.

First, the participating industrial companies noted the investment of time and resources needed to integrate the ESP into their operations, which includes adapting their equipment and gaining proficiency in the new system. Second, the long-term operation of the CP will necessitate ongoing maintenance. Operators must allocate time and resources to update software components, ensuring they remain compatible with evolving industrial standards and interfaces. Lastly, the MP design also presents its own set of challenges. Changes in regulatory frameworks or the entrance of new stakeholders in DR could necessitate updates to management structures or data security protocols.

7. CONCLUSION & OUTLOOK

Industrial flexibility holds significant potential in the evolving energy landscape as a DR resource. However, it faces hurdles such as specialized service requirements, technical limitations, and the need for standardized data models for flexibility information sharing. Addressing these issues, we propose the ESP. This concept comprises two interconnected digital platforms: the CP and the MP, supplemented by the EFDM as a standard data model to articulate industrial flexibility. Our paper delineates the functionalities of each platform and offers an example to illustrate their combined interactions. We also provide insights on the benefits and challenges of a small-scale, practical implementation.

The ESP stands out from existing solutions through its open, service-oriented, and modular architecture, which enables a seamless flow of information from industrial machines to energy market stakeholders. Thus, to further contribute, future steps will focus on testing a broader implementation of the ESP with several CPs and external services available at the MP with an analysis of specific user interactions and performance.

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