Applied Energy 388 (2025) 125455

Contents lists available at ScienceDirect

Applied Energy

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

The Energy Synchronization Platform concept in the model region Augsburg to enable and streamline automated industrial demand response ☆

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ARTICLE INFO

Keywords:
Automated industrial demand response
Digital energy platform
Energy services
Data model
Reference architecture

ABSTRACT

The industrial sector accounts for a large share of electricity demand and has promising potential for providing demand response services. In parallel, digital platforms have emerged to support industrial demand response. However, these platforms often operate in isolated environments, with customized, single company solutions. This carries the risk of being subject to potential vendor lock-in and challenges related of restricted interoperability due to a lack of agnostic information exchanges. Additionally, many platforms focus on specific flexibility assets or market services, which limits the ability of industrial companies to fully explore their demand response potential. To address these challenges, we propose the Energy Synchronization Platform concept, which features three main innovations. First, its multi-sided architecture enables any industrial company to connect to demand-response-oriented service providers, thus creating value for various stakeholders. Second, it employs a standardized data model to facilitate interoperable and agnostic information exchange, thus reducing vendor lock-in and enhancing cross-platform compatibility (i.e., enabling connections to other platforms and any machine). Third, its modular, service-oriented design supports the integration of diverse market-related services, such as flexibility scheduling, optimization, and grid flexibility. Moreover, we present insights from evaluations of conceptual test operations across different settings, in both laboratories and industrial companies located in a model region in Germany. We discuss factors that influence the deployment of the Energy Synchronization Platform and the potential impacts of its deployment on company operations. The results of this analysis can support practitioners and researchers in developing, improving, or replicating the Energy Synchronization Platform.

1. Introduction

The rapid transformation in the energy sector - particularly the power system - is being driven by three main trends: (1) the expansion of renewable energy and electrification; (2) advancements in digital technologies; and (3) a shift toward decentralized power systems. These trends introduce new complexities (such as potential congestion and balancing challenges for power grid operators) which necessitate increased flexibility [1]. On the demand side, consumers can face considerable price variations [2]. However, alongside these challenges, these trends also present significant opportunities [3]. One is to leverage high-energy-use sectors as potential sources of demand flexibility through demand response (DR) programs within market-based strategies [4].

Within this context, the industrial sector's significant levels of energy demand means this sector can play a critical role in the rapidly evolving power system. For example, in 2022, the European Union's

☆ The short version of the paper was presented at ICAE2023, Doha, Qatar, Dec 3–5, 2023. This paper is a substantial extension of the short version of the conference paper.

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https://doi.org/10.1016/j.apenergy.2025.125455
Received 30 April 2024; Received in revised form 31 October 2024; Accepted 25 January 2025
Available online 6 March 2025

and Germany's industrial sectors accounted for about a quarter of total final energy use [5,6]. Additionally, industry had the highest share of total final electricity consumption in Germany and Europe in 2022, reaching 43% and 36%, respectively [7,8]. This underlines the extent to which industrial consumers offer the greatest potential for providing demand-side flexibility in most industrialized countries [9]. Compared to alternative options for demand-side flexibility provision (such as managing the electrical loads of electric vehicles or heat pumps) industrial energy flexibility has the advantage of not requiring changed behavior from end-users [10]. Furthermore, existing metering infrastructure [10], in combination with continuous monitoring and optimization of production processes, offers greater control than in other sectors. The energy flexibility potential of the German industrial sector indicates a potential increase in load of 9 GW and a reduction in load of 10.7 GW [11]. This makes the industrial sector the prime candidate for DR programs, which can provide much-needed flexibility to system operators (SOs) and other market players (such as aggregators).

Despite this huge potential, industry encounters various challenges when they seek to provide industrial DR [12,13] including economic, regulatory, technological, organizational, behavioral, informational, and competence-related barriers [13]. Meanwhile, the advent of digital technologies and the move toward decentralized power systems add complexity to an already intricate power grid. It increases the effort required to coordinate and operate the system. Yet, this complexity spawns new business opportunities, from aggregation and forecasting services to real-time monitoring and virtual power plants. As a result, various platforms and businesses have emerged to capitalize on these new opportunities to supply services [14]. Some of these platforms have emerged with the goal of facilitating DR programs [15]. However, designing and implementing industrial DR platforms is a challenging task.

These platforms often require substantial technical investment and coordination. They tend to focus on the provision of specific flexibility services (such as ancillary services or load management), operate in silos, and provide customized solutions. There are several potential negative consequences of this approach. Information fragmentation [16,17] can result from this development of a diverse range of platforms. Users of existing solutions are also prone to the risk of vendor lock-in (i.e., difficulties with changing service providers) and interoperability problems (i.e., data format compatibility issues with data formats). They are limited to individual flexibility assets, industrial companies or market-related services [18]. The prevalence of platform specialization is particularly evident in, but not exclusive to, Germany [19]. At the same time, the country is strongly engaged in the drive for Industry 4.0 digitalization [20].

Hence, given that industrial flexibility faces the challenge of isolated solutions with fragmented information across multiple platforms [16,17], vendor lock-in [21], and interoperability issues [12,22,23], it is necessary to work on its mitigation [13] and enable all industrial companies to participate in DR programs.

A potential solution should not focus on the creation of a single dedicated service specialization for an entire platform/service offering [23]. This option is adopted by many aggregators [24]. Rather, it should promote interoperability to facilitate the exchange of information and service selection [23]. To that end, we propose the following research question: *How can diverse services for the provision of automated industrial DR be integrated in an interoperable and agnostic fashion through a digital integration platform?* In response, we introduce the ESP, to enable and streamline automated industrial DR. We developed and evaluated the ESP within a model region of Germany to examine potential benefits, impacts, challenges, and barriers associated with operating energy-flexible factories in a regional context. Adopting this approach facilitates an evaluation of our design across various locations and industrial sectors, including steel manufacturing, paper production and more. Through these engagements, we have enriched our understanding and refined the concept and design of the ESP. Thus, this manuscript contributes with:

- **Actionable requirements for the design process** of a digital integration platform (i.e., ESP).
- A **conceptual description of a reference architecture**, which can serve as a blueprint for practitioners and researchers who wish to replicate the concept of the ESP or its components.
- An **overview of interactions** among the components of the ESP. These examples illustrate the steps required to use external market-side services focused on the provision of industrial demand response.
- An **information flow evaluation** from the information exchanges between components of the ESP in a model region of Germany, using the example of an industrial company from the region.
- Insights into **influencing factors and impacts of the ESP's conceptual test implementations**. These insights support practitioners and researchers in their work to develop, improve, or replicate the design and concept of the ESP.

The remainder of the paper is structured to explore systematically various aspects of our research. Beginning with Section 2, we delineate our related work by focusing on three key concepts: industrial DR; digital platforms in the energy sector; and the exploration of design principles for digital platforms. Subsequently, Section 3 introduces and elaborates on our research approach. In Section 4, we examine the conceptual architecture of the ESP. In Section 5, we illustrate the ESP's internal interactions, that is, delineating its core functionalities. In Section 6, we present an overview of the model region, complemented by an evaluation of conceptual test operations and one use case description of a specific implementation by an industrial company. In Section 7, we provide a discussion that introduces the knowledge gleaned from our development and testing work conducted over several year. Finally, in Section 8, we synthesize our contributions and outline future steps.

2. Related work

Successful development of our reference architecture, requires us to explore three main domains: (1) industrial DR; (2) digital energy platforms; and (3) platform design principles. We focus on industrial DR given its potential as a source of flexibility. We take a holistic perspective by examining energy-related platforms. By not focusing solely on DR platforms, we can learn from a wider range of platforms and services. Lastly, we consider platform design principles. This is an essential element of our contribution since we are aiming to develop a reference architecture by learning from previous work.

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*" [25]. In other words, customers, including industrial companies, modify their operational plans based on incoming signals, such as the price of electricity or other inputs. Furthermore, the European Union distinguishes between two DR categories [25]. On the one hand, implicit (so-called "price-based") DR refers to customers' reactions to price signals (electricity prices and/or network tariffs) through automated systems or personal action. However, implicit DR is provided as part of the service contract with the customer and does not include participation in electricity markets. On the other hand, explicit (so-called "incentive-driven") DR refers to demand traded on different electricity markets (e.g., wholesale, balancing power, and ancillary services) through aggregator services or single large customers. This latter category of DR provides SOs with a solution to adjust consumers' loads to tackle operational issues [25,26]. However, these two DR categories are not replacements for each other, rather they are interconnected and complementary given their different scopes [25].

Notably, industrial DR can leverage both DR categories, although it needs to fulfill technical and time-scale requirements [12]. Shoreh et al. [12] further clarify that not all industries are suitable for every DR programs, given their different processes, production, and planning characteristics, in addition to the technical requirements for participation. This becomes especially evident when analyzing how industrial DR can be provisioned in practice.

Various approaches exist in the literature regarding classifying, modeling, and assessing industrial DR potential (such as the industrial DR scoring system proposed by Rusche et al. [27]). The German VDI standard 5207 [28] offers a comprehensive and practical summary of potential energy-flexibility measures that can be implemented to provide a DR service. These energy-flexibility measures are categorized according to the three levels of management within a factory [29]: manufacturing level; manufacturing control level; and enterprise control level. The response time of each energy-flexibility measure increases from the manufacturing level to the enterprise control level. At the manufacturing level, DR can be achieved by adjusting process parameters (e.g., pressure); interrupting processes; storing energy (e.g., inherently); operating in a bivalent energy manner; or changing the processing sequence [28]. While DR at the manufacturing level is rather technology-focused, the use of operations management techniques increases at the manufacturing control and enterprise control levels [29]. Examples of energy-flexibility measures at these levels include shifting job start dates, adjusting energy procurement, and adjusting start dates or times of shifts [28]. As part of these adjustment processes when seeking to manage DR, it is required to acknowledge the unique characteristics of each industrial company, including its processes, system dependencies, and energy-related infrastructure challenges.

Furthermore, the successful deployment of industrial DR faces several barriers [12,13]. Leinauer et al. [13] identified and grouped these barriers into economic, regulatory, technological, organizational, behavioral, informational, and competence-related obstacles as summarized and supported by supplementary literature in Table 1.

Independently of the research stream related to general DR barriers, Panetto et al. [22] and Kupzog et al. [30] point to a range of factors that contribute to the technological obstacles dimension described above. According to Panetto et al. [22], the lack of a complete solution that enables communication between different actors and devices limits its adoption. This is despite the existence of standards such as Open ADR [31] and Green Button [32]. Kupzog et al. [30] highlight that communication issues exist even within smart grid solutions due to several communication pathways that increase the importance of interoperability.

In addition, many studies are researching aspects and solutions of information fragmentation, which refer to the same aspects related to the lack of standardization and interoperability. This applies not only to the energy and power sector [33,34], but also to the construction sector [35,36], or directly to information management systems [37]. In this context, Cennamo et al. [16] highlight both the challenges and the opportunities of avoiding information fragmentation and the reduction of complexity – an important consideration for DR – from a digital platform perspective. However, regardless of the potential of any DR solution, Nolan and O'Malley [38] highlight the importance of deploying, testing and evaluating DR solutions in real-world scenarios. This will increase understanding of the real potential of DR.

2.2. Energy-related digital platforms

In recent years, the rise of digital platforms has had a transformative effect across various business sectors. This trend is known as "platformization" [39,40]. Although DR systems are gaining attention as a critical mechanism for balancing energy supply and demand, current research highlights significant limitations that hinder their broader adoption. We conducted a literature review, in which we searched for reviews of energy-related digital platforms in well-known databases such as IEEE Xplore, Scopus or ACM. This approach ensured the relevance of our findings and provided a comprehensive overview of existing platforms.

Despite the availability of numerous energy-related digital platforms – as summarized in Table 2 – a key challenge remains: existing solutions focus on isolated issues, which in many cases lead to significant lock-in effects [17,19,41–47].

Lock-in occurs when users depend on a particular platform or vendor, a situation which significantly increases switching costs and reduces flexibility to adopt alternative technologies or systems. For DR systems, lock-in is a significant entry barrier for new users and innovators [13]. Once organizations have invested time and resources integrating a specific DR solution, unifying additional systems or switching to more advanced or cost-effective alternatives often becomes prohibitively expensive and technically challenging. The fragmented nature of existing platforms exacerbates this vendor-lock-in challenge, as most solutions are designed in silos, thus making cross-compatibility a daunting challenge. This fragmentation significantly hinders the potential for scaling DR services, and limits innovation in the broader industrial energy management landscape. In addition, regulatory barriers further complicate efforts to achieve multi-service integration, particularly in highly regulated energy markets. This adds another layer of complexity for end users. Due to these lock-in and integration challenges, startups and incumbents seeking to offer advanced energy management solutions face significant constraints.

Moreover, as the importance of DR grows in energy systems, current research may not adequately address the critical need for an overarching, interoperable platform that can streamline industrial DR applications. Thus, a gap exists in work related to the developement of a platform concept design that tackles the challenges of vendor lock-in and integration. By addressing this gap, we strive to unlock significant untapped potential by reducing integration costs, mitigating lock-in risks, and encouraging wider adoption of DR services, particularly in industrial settings.

Table 1
DR barrier groups as identified by Leinauer et al. [13].

DR barrier	Definition
Economic	Barriers related to the economic aspects of industrial DR implementation, such as: competition with alternative measures and projects in a company context; small cost savings (e.g., due to small price-spreads on spot markets); and costly flexibility investments.
Regulatory	Barriers related to complex, restrictive, or contradictory regulatory frameworks, as well as the lack of access to time-variable electricity prices.
Technological	Barriers related to disrupting production processes, lower product quality, and the lack of information technology (IT) standardization and interoperability among different technologies used for DR provision [12,13,22,30].
Organizational	Barriers related to power procurement policies, involvement of multiple decision-makers in decision processes, and the relative low priority given to energy management by senior management.
Behavioral	Barriers related to the lack of employee acceptance, and the perceived inconvenience of DR provision.
Informational	Barriers related to the lack of standardized baseline calculation for DR markets, uncertainty regarding financial implications and price forecasts, and information asymmetry and transparency issues.
Competence	Barriers related to the lack of resources, skills, and knowledge about production processes and flexibility potential.

Table 2
Research on real-world examples of energy-related digital platforms and their limitations.

Source	Scope of work	Identified limitations
[17]	Reviewed 46 European energy platforms and 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.	Streamlining automated DR requires features across all archetypes that do not yet exist on the market. Digital platforms typically use proprietary interfaces which have the effect of both limiting interoperability between different digital platforms [22], and complicating data exchange processes [48], thus contributing to vendor lock-in problems.
[19]	Examined 240 start-ups offering XaaS models in Germany covering various services, from data analytics software and charging network stations, to peer-to-peer energy trading and DR solutions.	A dynamic start-up scene in this country is working increasingly with emerging digital technologies, and using them to implement energy management systems. In the process, a large number of isolated solutions are being developed that benefit from internal network effects.
[41]	Analyzed 217 digital platforms in the European Union energy sector.	Despite being established at a relatively early stage – in the 1990s – digital platforms in the European energy sector are still small, and are concentrated in certain regions. Market success depends on digital readiness and regulatory factors.
[42]	Conducted a review of 44 IoT energy platforms.	Interoperability is a challenge when seeking to support cross-domain applications. Existing energy platforms are tailored to specific applications.
[43]	Developed a classification of different DR programs, offering guidelines for program selection.	The presented research does not mitigate vendor lock-in issues on DR platforms.
[44]	Investigated the use of IoT and blockchain for improving DSM services, with a focus on technical innovations.	The study emphasizes technology use, neglecting integration challenges that result from a lack of interoperability.
[46]	Analyzed 221 DR-related business models from 135 scientific papers, focusing on practical business applications.	Models are mostly conceptual and not widely applied in practice. The presented solutions remain fragmented, resulting in interoperability issues.
[45]	Research on lowering barriers to implementing DR programs with a focus on multi-energy systems.	Focuses on multi-energy systems without proposing interoperable solutions across different platforms or sectors.
[47]	Provide a review of peer-to-peer energy trading projects.	The proposed projects are decentralized, isolated approaches, yielding strong lock-in effects.

2.3. Design principles for digital platforms

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

Regarding development approaches, Drewel et al. [49] 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 & Cronholm [50] propose three 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' points of view. Blaschke et al. [51] 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. [52] conduct a literature review and create four design requirements clustering 20 design requirements. At the same time, they map their four design requirements to the seven design principles from Göbel & Cronholm [50] and Blaschke et al. [51]. Consequently, these four design requirement categories provide a solid conceptual guideline for developing new digital service platforms.

In parallel to domain-agnostic platform development and design principles, some research focuses on energy-related issues. Senna et al. [23] propose a conceptual architecture model for an holistic and interoperable digital energy management platform in manufacturing. Their concept consists of four pillars (factory driver IO; Human–Machine interaction; energy data modeling; and standardization and data driven services). They consider interoperability, emerging technologies (such as artificial intelligence), digital twin modeling, simulation, and augmented reality. These elements aim to improve their concept, while also remarking that their concept platform should support different analytical services (i.e., predictive and prescriptive). However, their concept lacks the specification of its components and service interactions, as well as practical validation. It also omits integration with other services not focused on analytics, such as aggregators as a service. Building on a literature review of the characteristics of 44 IoT energy platforms, Martín-Lopo et al. [42] derive relevant hierarchical blocks for designing new energy platforms and outline design options and strategies. However, their research also lacks empirical validation, and is slightly distorted by its focus on applications in the residential sector. Piserà et al. [53] outline an overview of relevant features for designing digital platforms for renewable energy communities in Italy. They derive four categories: input; output; optimization; and openness. Piserà et al. conclude that the latter is critical for a platform's success. Cali et al. [54] analyze digital energy platforms, focusing on the cybersecurity perspective. Their research emphasizes that digital privacy and security aspects should be embedded throughout all platform design and operation phases, and provides a generic platform architecture for flexibility services.

While numerous studies focus on technical aspects of digital energy platform design, Canelón et al. [55] propose a design process for digital innovation platforms in the energy sector. Their process is structured along the disciplines of analysis, design, and digital platform implementation.

To summarize, existing platform development research ranges from domain-agnostic business-level design options to detailed technical and architectural aspects of digital energy platforms.

3. Research approach

Our primary objective is to design and develop a reference architecture concept for automated industrial DR, which we will refer to as the ESP. In the context of systems and software engineering, a reference architecture describes a high-level design of a product line (i.e., software or system) that outlines the architectural structure and the rules and constraints that apply to all its components [56]. As mentioned by Cloutier et al. [57] regarding reference architectures in general, the ESP also serves as a blueprint to support practitioners and researchers as they seek to replicate its concept or its components.

It is necessary to note that developing the ESP concept was part of a large research project in Germany called the "Kopernikus-project SynErgie" [58]. Around 60 partners from industry and the research community aim to create technical and market conditions, in line with legal and social aspects, to effectively synchronize German industrial energy demand with volatile energy supply.

Given our objective, we used design science research (DSR) principles as a foundation for our research approach [59]. DSR is a problem-solving paradigm that allows researchers to design and develop novel artifacts [60], in our case, the ESP. To that end, we considered the guidelines from Hevner et al. [59] to understand, execute and evaluate our research.

The method (i.e., embodying the practical steps) we have chosen in this DSR context, is the DSRM process model [61]. It provides an iterative, step-oriented design development process through which learning from each step can enhance the final artifact. In total, the process model has six steps. In Fig. 1, we illustrate the six design steps adapted to our study. For each step, we have indicated the stakeholder involvement. We differentiate between the consortium experts (CE) and the external experts (EE). The CE are a multi-disciplinary expert group from various sectors, including energy, manufacturing, production, IT, cybersecurity, management, economics, and finance, among others. All experts are part of the "Kopernikus-project SynErgie". Meanwhile, EE are experts from academia and industry outside of the consortium. The CE participated in the first five steps, while the EE participated only in the sixth step, providing feedback. In the following, we give a detailed explanation of each of the six steps.

The DSRM process model starts with a problem identification step. Based on five discussion meetings with the multi-disciplinary CE on the participation in DR and a literature search, we identified common challenges: a lack of automated industrial DR service-oriented platforms; the prominent problems related to potential vendor lock-in and unique service offerings; the interoperability challenge faced by companies and platforms; and the rising complexity for industrial companies of participating in energy flexibility.

The second DSRM process model step is to define the objective we intend for our solution. We defined the objective and requirements based on the identified problem in the previous step and refined it with the multi-disciplinary CE of about 20 institutions from research and industry in bilateral and multilateral meetings. The resulting objective is to create an agnostic and interoperable platform through which to streamline automated industrial DR based on services. In another iteration of this step, we set the requirements for the ESP. Subsequently, this list of requirements serves as a checklist to enable the assessment of the development of the ESP. We detail these requirements in Section 4.1.

The third DSRM process model step regards design and development. We designed and developed our artifact using an iterative process, with refinements based on the design requirements (see Section 4.1). To that extent, we engaged some of the CE in rounds of discussion. These discussion rounds took place almost every month over 2.5 years (the holiday season limited the frequency). On average, eighteen CE participated. Each discussion round had a different focus, inluding the overall architecture, individual components, organizational topics and more. Moreover, given the extensive nature of the project initiative, the entire project featured a yearly consortium meeting to discuss findings and set future steps.

The fourth DSRM process model step involved demonstrating our artifact, i.e., the ESP. It is important to note that due to the extensive nature of the SynErgie project, we limited the implementation of our designs to a model region: an area around Augsburg, in the south of Germany. This region represents a typical industrialized region of the country. Although regions similar to Augsburg account for only 20% of the land in Germany, they account for 50% of Germany's industrial electricity demand [11]. In general, the industrial sector in Germany accounts for 43% of total electricity demand in 2022 [7]. Furthermore, aside from being a typical industrialized region, it offers a scientific test-bed for examining the potential benefits, impacts, challenges, and barriers associated with the operation of energy-flexible factories in a regional context. Within the model region Augsburg, we implemented subsystems of the ESP in laboratories and at company sites (see Section 6). The companies involved in this step are part of the CE. Experts from the design and development team provided guidance for the companies. The guidance ensured that implementation was carried out correctly, and that the experience gained during the conceptual tests was taken into account for further development.

The fifth DSRM process model step is evaluation. We evaluated our artifact and used the evaluation results to iteratively refine the objectives (i.e., step 2) and design (i.e., step 3). The companies that conducted the conceptual test operation during the demonstration (i.e., step 5) were actively involved in the evaluation. In line with the recommendations from Hevner et al. [59], we used a number of methods for the observation, analysis, experimentation, testing, and description of our solution. Within this scope, we specifically focused on evaluating the architecture's design and information flows of the ESP for two primary reasons. Firstly, the evaluation of the architecture's design underscores the advantages of an iterative design process. It reveals valuable insights gained from laboratory settings and deployments in industrial companies, knowledge which is instrumental for the realization of effective implementation strategies. Secondly, we evaluate information flows (as we consider them to be the foundational blocks of this process) before examining energy flows. We define information flow as the sequence of events that lead to the initiation of the operation of an industrial machine with a view to delivering a service, independent of actual energy demand. Conversely, energy flow pertains to the actual operation of an industrial machine for the provision of a service. This distinction is crucial for understanding the interplay between informational and operational dynamics within industrial systems. Moreover, we acknowledge specific limitations in

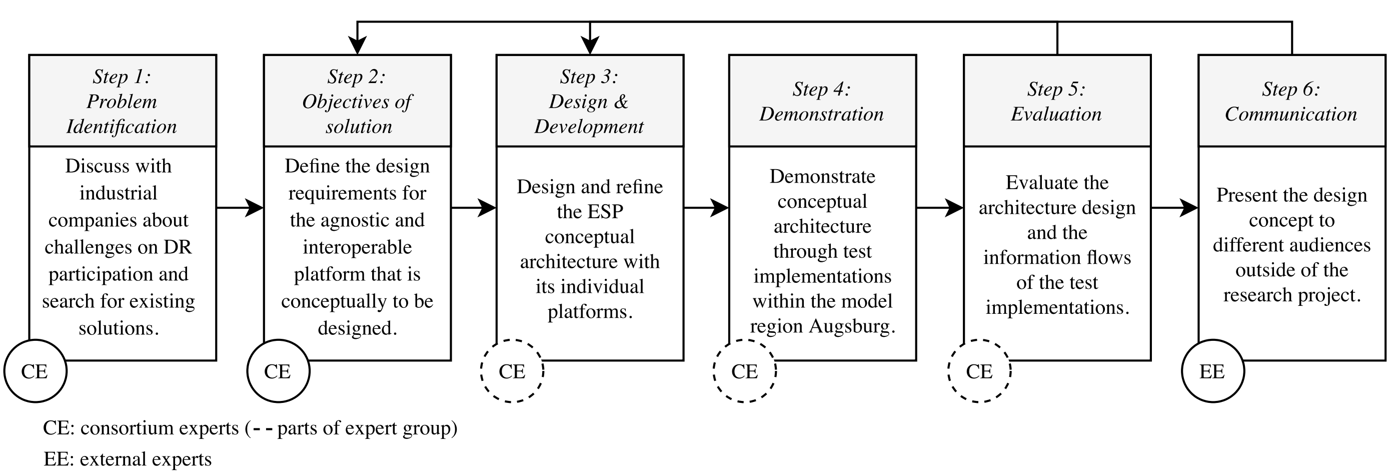

Fig. 1. Adapted DSRM process model according to Peffers et al. [61].

evaluating energy flows. This is due notably to the need for regulatory frameworks for sandboxing, and economic incentives for such evaluations, even though the model region only represents a test-bed. This scenario presents a significant risk for industrial companies, especially when industrial flexibility is not their primary focus.

The final DSRM process model step is communication. Following the DSRM process, we presented the initial design concepts in several venues. We gathered feedback from EE outside the consortium and reached out to international audiences to broaden our horizons. Based on the feedback received, we iteratively refined the design of our artifact in step 3. Overall, we presented our initial and subsequent design updates in [18,62,63] and in this publication.

4. Energy Synchronization Platform: A reference architecture concept

We introduce the ESP, a novel digital integration platform, designed to enable the interoperable and agnostic integration of diverse services for automated industrial DR. Central to the ESP's architecture are two primary digital platform types: the company-side platform (CP) and the market-side platform (MP), each playing a central role in the ESP's ecosystem. The CP and MP engage with external market-side services supporting industrial DR. The CP is aimed at industrial companies. This platform enables (1) the technological connections to control manufacturing processes, and (2) facilitates communication with external market-side services. The MP, on the other hand, functions as a connectivity hub, granting an overview and access to external market-side services without directly delivering these services. For the exchange of information on the service use, CP and external market-sided services mainly use a generic standardized data model to describe energy flexibility, the EFDM. Fig. 2 visually depicts the interplay between the CP, MP, and external market-side services illustrating their connectivity and function within the ESP.

Hereafter, we first list the design requirements that steered the design and development process of the ESP. Afterwards, we then classify the ESP and its characteristics using the digital platforms taxonomy for industrial DR provided by Duda et al. [17]. Finally, we provide a detailed description of the CP, MP, EFDM and external market-sided services.

4.1. Design requirements

We employed the four design requirement categories outlined by Fischer et al. [52] to generate the design requirements needed for our development process. However, these design requirement categories can appear abstract or theoretical, and may require further elaboration to achieve comprehensive understanding. In that sense, we translate the four design requirement categories into actionable requirements to achieve our objective. To this end, we used insights from literature (see Section 2) and discussion rounds with experts (see Section 3). In Table 3, we provide our mapping between the four design requirement categories and the actionable requirements envisioned for the ESP.

Table 3
Mapping between the four design requirement categories from Fischer et al. [52] and the actionable requirements envisioned for the ESP.

Design requirement category	ESP actionable requirement
Facilitating service innovation in the solution	- Multi-sided - Service-oriented
Supporting co-creation in the design process	- Community of practice - Online community
Identifying mutual problems and needs	- Minimize vendor lock-in - Foster interoperability - Modularity - IT security
Easing the entry for new actors to the solution	- Documentation - Support material - Standardization (information flows)

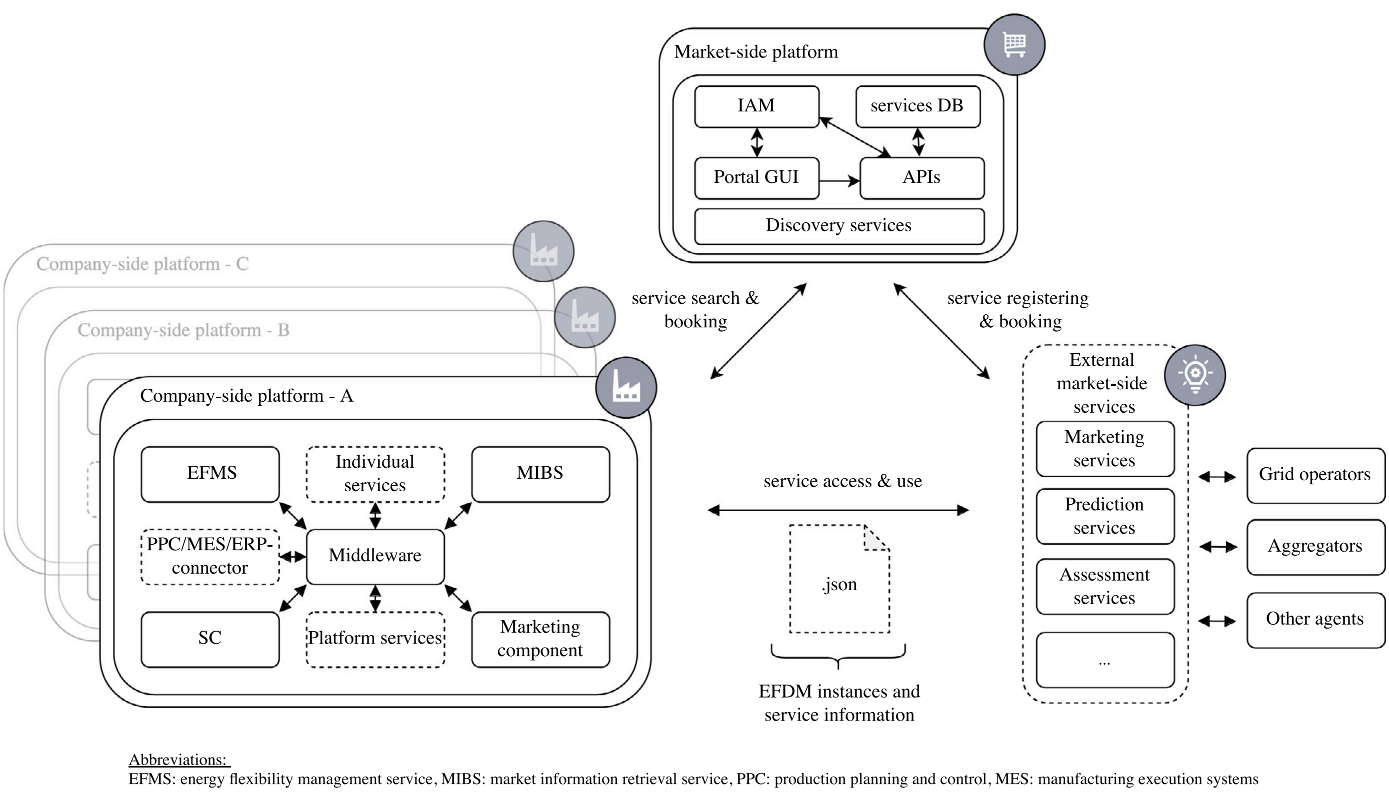

Fig. 2. Simplified architecture of the ESP.

We translated the first design requirement category, "facilitating service innovation in the solution", into creating a reference architecture that embodies a *multi-sided platform*. This planned reference architecture connects various user groups (primarily industrial companies) with DR-oriented service providers. Additionally, we envisioned the solution as a *service-oriented platform*, enabling the coexistence of any DR-oriented service within this multi-faceted ecosystem. The underlying motive for this requirement is to encourage competition among service providers. This should stimulate innovation by facilitating connections between numerous actors (with industrial companies playing a central role) and allowing service providers to compete based on merit.

To address the second design requirement category – "embrace co-creation in the design process" – we translated it into two actionable requirements. Firstly, it necessitates engaging a broad spectrum of experts to incorporate diverse knowledge and perspectives in a *community-of-practice* approach. In our context, this involves convening expert discussion rounds where stakeholders (i.e., CE) gather to conceptualize the ESP, deliberate on its design, and collect internal documentation to chronicle the process. Secondly, the actionable design requirement advocates for establishing an *online community*. The online community aims to perpetuate the community-of-practice ethos, enabling stakeholders to exchange views and lessons learned. This feedback becomes invaluable for refining the solution and addressing challenges identified through empirical testing. It is important to note that although the ESP does not incorporate an internal online community module by design, we have facilitated this aspect by linking an external website to the ESP, which enables features such as registration and user management.

Building upon the previous requirement, the third design requirement category, "identify mutual problems and needs", enabled us to discern issues ranging from technical (optimal component design) to operational challenges via our CE discussions. These discussions highlighted the necessity to *minimize vendor lock-in, fostering interoperability* throughout the solution, and adopt a *modular* design approach. Additionally, CE underscored in the design discussion rounds the criticality of *IT security*, considering the platform's digital, multi-sided, and service-oriented nature.

Lastly, regarding the design requirement category to "ease the entry of new actors into the solution", our expert discussions further affirmed the significance of simplifying access to our solution for newcomers; a common hurdle for the adoption and utilization of any solution [39]. This insight led to the development of three strategies: maintaining comprehensive *documentation* in a centralized repository; creating accessible *support materials* such as guides and videos for new participants; and, from a design standpoint, ensuring that the processes and communications within the ESP are *standardized*.

4.2. Novelty and categorization

The ESP is different from other platform concepts in three main aspects. First, the ESP integrates both "data-centric" and "transaction-centric" dimensions, as defined by Duda et al. [17] in their taxonomy of energy platforms. This integration provides the necessary functionalities for automated industrial DR at the interface between industry and energy markets, positioning the ESP as a multi-sided platform to connect various stakeholders. It facilitates standardized information exchange by supporting the EFDM, enabling information exchanges that are information interoperable and vendor-agnostic, which thus minimize vendor lock-in. Second, the ESP supports a wide array of services for automated industrial DR, including external market-side services, IoT platform services, and energy management services. It thereby establishes itself as a service-oriented platform. Its open and modular architecture aims to foster a diverse ecosystem within the platform and allows companies to compete. Third, the ESP accommodates a wide range of flexibility types within the industrial landscape. It avoids restricting flexibility provision to specific machine types and supports various DR programs, aiming for an open market design. In order to distinguish the ESP concept from other platform concepts in a comparable fashion, and to emphasize its characteristics, we utilize the taxonomy proposed by Duda et al. [17]. We illustrate the characteristics of the ESP mapped to the taxonomy in Table 4.

Both platform types, the CP and MP, can be assigned to the "general dimensions". They have similar characteristics, but not necessarily the same. The choice of the operating mode depends on, e.g., characteristics of the company or regulatory requirements. There is no single platform operator for the ESP. Instead, we delegate the operation to each platform type, the CP and MP. They can be operated either by a company or a consortium. Platform access for both platform types is possible through a web app or specific interfaces. The access requirements are not uniform on platform instances and may also depend on the type of platform access. In the case of the web app, the search for external market-sided services does not require any restrictions. When searching via specific interfaces, industrial companies need to fulfill certain criteria. The operational concept of platform instances varies between on-premises platforms, platforms hosted in a public cloud or hybrid platforms that combine on-premises and cloud solutions. For both platform types, CP and MP, the architecture (i.e., platform structure) is modular and includes external interfaces for communication with other platforms or services.

When mapping the ESP's characteristics to the "data-centric dimensions" and the "transaction-centric dimensions", we split them into the CP's characteristics and MP's characteristics, including external market-side services, respectively, as they align.

Regarding the "data-centric dimensions" associated with the CP, the CP operates as a PaaS. Unlike SaaS solutions that focus primarily on

Table 4
Characteristics of the ESP mapped to the taxonomy of Duda et al. [48].

	Dimensions	Characteristics				Ex[1]
General dimensions	Platform operator	Company	Consortium	Aggregator		E
	Access	Web-App	Native-App	Specific interface		NE
	Operational concept	On-Premises	Cloud	Hybrid		NE
	Access requirements	Free Access	Certain criteria to fulfill	Certain devices necessary		NE
	Platform structure	Fixed structure	Modular structure without externalinterfaces	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 services	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

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

software execution, PaaS aims to offer an environment for hosting various software applications. Our CP platform type includes connectors for integrating IT systems or machines, emphasizing the CP's role in facilitating technological integration. As later Section 5 outlines, the CP supports a many-to-many and bidirectional communication flow. In other words, communication occurs not only from the CP to the ESP participants, such as industrial users, devices, services and platforms, but also in reverse, from ESP participants to the CP, and even among ESP participants themselves. Data processing within the CP can be either transactional or analytical. Transactional processing allows for the activation or deactivation of flexible-load measures. In contrast, analytical processing enables data visualization for flexible-load measure activations, or serves as a basis for further computational tasks, such as the aggregation or disaggregation of flexible-load measures. The data source for the CP spans devices or cloud services, underscoring the CP's versatile data integration capability.

In terms of the "transaction-centric dimensions", which correspond to the MP and external market-sided services, the principal role (i.e., main function) of the MP and the external market-sided services is to facilitate energy flexibility trading. This aligns with the ESP's goal of streamlining automated industrial DR. It is necessary to clarify that the MP is not responsible for flexibility trading; rather, this is the role of the external market-sided services, which can connect industrial users to traditional or new power markets (i.e., trading venue) via their established interfaces. The flexibility types supported depend on the selection of external market-sided services and are not restricted by the MP. The MP and ESP's design philosophy is to promote an open market environment (i.e., market design). This approach does not confine users to the ESP as their sole avenue for marketing energy flexibility. Moreover, the MP does not prescribe pricing for energy flexibility; service providers are free to set prices based on their unique business models, ensuring flexibility and diversity in the market options available to users.

However, as a final remark, the use cases envisioned that the ESP addresses all of the following flexibility types: (1) flexibility activation in response to market signals (i.e., market flexibility); (2) to maintain the stability of the power grid via system services such as those for maintaining the frequency or the voltage level (i.e., system flexibility); or (3) to reduce the network costs (i.e., grid flexibility).

4.3. Overview of the reference architecture concept

The ESP supports numerous CPs from one or multiple companies. Yet, it accommodates only a single MP to avoid information fragmentation that could arise from multiple MPs. This design ensures a streamlined flow of information and services. The MP's primary role is to act as the initial contact point for industrial companies and external market-side service providers. It simplifies the process for industrial companies searching for, booking, and accessing external market-side services while allowing external market-side service providers to register their services on the MP. This operational model of the MP distinguishes the ESP from other known platforms. These include market platforms, such as EPEX [64], where direct trading of power occurs, or aggregation platforms that manage the flexibility control and operation on behalf of companies. Similarly, it distinguishes itself from newly developed solutions such as local flexibility market (LFM) platforms supporting system operation services [33], as it considers these platforms as services that can be offered in the MP. However, such market platforms can be brokered through the MP as external market-side services.

In the following Sections, we describe the standardized data model (i.e., EFDM) used as the main information exchange format within the ESP. Afterwards, we then detail the architecture of both platform types (i.e., CP and MP). Finally, we provide an overview of the external market-sided services that can be integrated into the ESP.

4.3.1. Generic industrial flexibility data model to standardize information flow

The EFDM is a generic and standardized data model to describe energy flexibility [65]. We consider energy flexibility in the manufacturing industry as "industrial flexibility". The generic nature of the EFDM results from the fact that it is not limited to a specific industrial process or sector. Any industrial flexibility can be described with the EFDM as a means to reduce the information interoperability challenge when communicating industrial flexibility. The standardization relates to its usage within the ESP, but the EFDM is also applicable to other use cases. The EFDM is used mainly for information exchanges: (1) inside the CP and (2) between the CP and external market-side services (i.e., services for data processing). Nevertheless, it is important to emphasize that our design approach addresses the interoperability challenge. It does this by requesting the use of the EFDM for interfaces that manage information exchanges between the CP and external market-side services. We depict the logical structure of the EFDM in Fig. 3. Two classes describe industrial flexibility: (1) *flexibility space* and (2) *flexible-load measures package*. JavaScript Object Notation (JSON) schemas specifying both classes are accessible in [66].

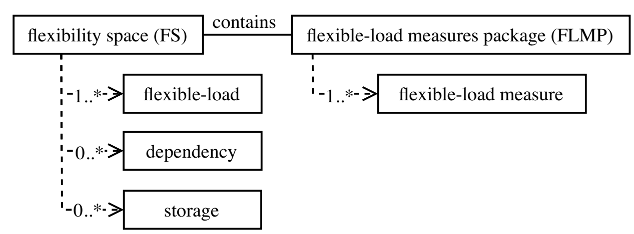

Fig. 3. Simplified class diagram of the EFDM.

The class *flexibility space* describes the potential and the options of an industrial system to deviate from its energy demand compared to a reference operation. The three sub-classes *flexible-load*, *storage* and *dependency* restrict options both technically but also regarding the commercialization of flexibility. The subclass *flexible-load* describes the core of the *flexibility space* and is mandatory. Examples of entities that describe a *flexible-load* include the power states, the duration, gradients for load modifications, and the prices at which the load is to be commercialized. The optional subclasses *storage* and *dependency* can also be used to describe complex industrial flexibility. They are always linked to objects of the class *flexible-load*. The subclass *dependency* can be used to describe dependencies between different machines as they occur in many production systems, as expressed by Bahmani et al. [67]. For example, entities are triggering and target flexible-loads and the duration for which a dependency lasts. The subclass *storage* can be used to describe any type of storage, including but not limited to thermal, electrical, or material storage. Examples of entities are initial energy content and usable capacity.

The class *flexible-load measures package* describes a specification (i.e., the flexible-load measure) of the potential described in the *flexibility space*. It contains one mandatory subclass called *flexible-load measure* with entities such as the load change profile and the potential reward associated with activating this load change profile. It contains all the information necessary to fulfill an activation signal.

4.3.2. 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 [68]. The CP has five core components: (1) middleware, (2) smart connector (SC), (3) energy flexibility management service (EFMS), (4) market information retrieval service (MIBS), and (5) the marketing component. It primarily utilizes EFDM instances for communication purposes to foster information interoperability across components and systems [68]. Hereafter we provide an overview of each component.

The middleware is the central core component for information distribution, facilitating service orchestration. All components and services in the CP connect to the middleware. The functionality of the middleware facilitates the integration of existing individual services, platform services, and other core components. The CP underpins a network that supports multiple open and standardized communication protocols [68]. The functionality of the middleware extends to the management of different data sources and sinks from the manufacturing environment. It includes the management of data from various sensors, actuators, and legacy IT systems, as well as the above-mentioned individual services such as load forecasting or optimization services. The management of data and data flows includes oversight of all inbound and outbound data flows, which is essential for seamless integration. In addition, the middleware streamlines communication between different services, significantly reducing integration effort and time. Integration concepts such as publish–subscribe models, workflow-based integration and event-driven communication allow this to be achieved. Harmonized information flow is another functionality of the middleware. It reconciles disparate information flows from different services, requiring the merging or translation of data models such as the EFDM between interconnected systems and services. In terms of technical communication requirements, the middleware is compatible with multiple communication standards, including RESTful API and WebSocket API, and protocols such as Open Platform Communications Unified Architecture (OPC-UA) and MQTT Message Queuing Telemetry Transport (MQTT). The design of the middleware also emphasizes non-functional requirements that are critical to industrial operations. Its multi-tenancy capabilities ensure separate management of multiple users within the platform. Generic interfaces are a key feature of the middleware, providing flexibility and eliminating the need for specific data models tailored to individual use cases.

The second core component is the SC (see in Fig. 2). It enables the integration of enterprise IT systems, industrial equipment, machinery, and plant data terminals with the central middleware. It is important to note the different objectives between connectors in general and middleware. While the middleware is a central orchestrator for information distribution and service integration, connectors act as a point of contact and critical integration component for specific industry protocols and data sources. The SC acts as a software integration component, translating proprietary communication and network protocols, such as Siemens S7 that is used in programmable logic controllers (PLCs). It has embedded application logic that can automatically (1) identify energy flexibility potentials based on machine and operational data and (2) transform these raw data into EFDM instances used to communicate energy flexibility potential for participation in flexibility markets such as DR programs. This automation is critical to enable the subsequent enactment of control measures, particularly after the successful marketing of identified flexibility. The SC thus acts as a data intermediary and an active execution component for the signals from the energy markets. It transforms the received EFDM flexible-load measures into control commands and executes them in line with the commercial transactions that have taken place.

The EFMS is the third core component. It functions as a repository for storing EFDM instances and acts as a broker to communicate requested EFDM instances through the middleware. All services and components communicate generated or modified EFDMs to the EFMS, which retains the most recent state of EFDMs and serves as their single point of truth.

Two core components facilitate the CP's connection with external market-side 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 market-side services using EFDM instances, and to receive activation signals. It translates them into EFDM instances and distributes them within the CP using the middleware.

In addition to the five core components, the CP also contains optional components. 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 [69].

The CP offers three modes of operation based on company size, budget, and industrial plants and processes. The default option is (1) 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 demand or limited IT infrastructure.

4.3.3. Market-side platform overview

The MP is a digital and modular platform that provides a centralized repository of DR-oriented services. Its goal is to establish contact between flexibility providers (such as industrial companies) on the one hand, and service providers on the other hand. DR-oriented service providers can be flexibility users (e.g., aggregators and SOs) or market players offering support in terms of DR provision (e.g., economical assessment of flexibility, price forecasting). The MP is a marketplace where service providers can register their services and industrial companies can search and book them [11]. But also services can establish contact with each other and make use of the offerings of other service providers.

Unlike existing solutions that focus primarily on service operations, the MP emphasizes the integration of information about services.This approach addresses information fragmentation related to external market-side services. The benefit of having a cumulative service overview is a potentially greater reach for the service providers, and a less time-consuming and more effective service selection for the companies. Furthermore, the MP offers uniform descriptions of the services' functionality and communication interfaces. Once an industrial company has identified 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) increasing operational efficiency by routing direct service communications away from the MP and mitigating the risk of the platform becoming a bottleneck in the provision of services; (2) simplifying regulatory compliance, as this configuration avoids categorizing the MP as critical infrastructure; and (3) increasing governance flexibility by decoupling the service interactions from the MP.

The characteristics of the MP are its modularity and the use of standardized communication. The modular structure of the MP allows us to easily integrate (i.e., register) existing services already available through other platforms and new emerging services. We design it to be future-proof and foster market transparency and encourage competition [18,65,68]. Standardized communication interfaces allow the seamless integration of services from various providers and are intended to prevent vendor lock-in for companies or services [62,68].

The MP's key functions are the administration of the service catalog, including new service registrations, the administration of service searches and service bookings, and identity and access management. To fulfill these functions, the MP consists of five core components (see Fig. 2). The first is the identity and access management (IAM) component. It is responsible for identity validation, authorization, and ensuring trust and security. Whereas the search functionality is publicly accessible, entities that want to register or book a service need to be authorized by the IAM. The second is the service database (S-DB). It stores metadata related to registered services, including properties, descriptions, technical specifications, contact information, and life cycle data. The third is the application programming interface (API) component, offering APIs for search, booking, and service administration that interact with the S-DB. The fourth is the graphical user interface (GUI) component complementing the API by providing a user-friendly interface for interaction. The fifth is Discovery Services, which allows companies to locate, compare, and access services using protocols like UDDI or JAXR to minimize human intervention.

The management of the MP can be undertaken by either a single entity or a multi-organizational consortium, thus offering governance agility.

4.3.4. External market-side services

External market-side services (see Fig. 2) support industrial companies in providing their flexibility as DR. Service providers can register their services at the MP. In Fig. 4, we distinguish between two main classes of external market-side services based on the data exchanged between the service user and the external market-side service.

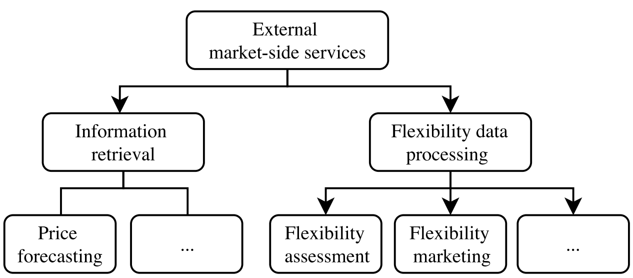

Fig. 4. External market-side service classification.

External market-side services belonging to the first class *information retrieval services* do not require any flexibility-specific data from the service user. The aim of these services is the provision of information. One example of an information retrieval service is a *price forecasting service*. In order to receive forecast price data, the service user sends a request specifying a time period and the energy market from which it wishes to receive the forecasted price data. External market-side services belonging to the second class *flexibility data processing services* require flexibility-specific data from the service user in order to provide their service. The aim of these services can be manifold. Example services of this class are *flexibility assessment services* or *flexibility marketing services*. The listed service examples are not exhaustive. As the energy market evolves constantly, this classification can be adapted as new services emerge.

However, the following requirements apply to all services that wish to be included in the MP catalog. In addition to the suitability with regard to the application area, the services need to be well-documented in terms of their functionality and utilization. We support service providers by offering templates to ease the process. An open API specification is required for services with an API interface (which is desirable in terms of the ESP). In addition, service providers need to specify their point of contact to answer possible questions and assist with application examples. To ensure that only authorized service users have access to the service, they also need to implement a process for managing keys (see Section 5 for further details).

Before services can request the inclusion of a service to the MP, the respective service provider must register with the MP as a first step. As the ESP is not implemented in a production environment and only the concept is tested, this authentication is not yet implemented / further considered / tested.

5. Interactions in the Energy Synchronization Platform

Given the large number of potential interactions within the ESP, and following the expert-guided design approach, we provide a series of illustrative interaction examples. We evaluated and validated these examples during our expert discussion rounds and used it for internal distribution. However, we limit our series of illustrative interaction examples to exemplify the interactions between the different ESP components (CP, MP and external market-side services) required to use external market-side services. These steps are, 5.1 Registering a service, 5.2 Finding a service, 5.3 Booking a service, 5.4 Using a service.

5.1. Registering a service: External market-side service – MP interaction

In this interaction, we consider an external market-side service provider already registered with the MP. The external market-side service provider submits their service details, including descriptions, technical specifications, and contact information, through the service-administration-API. These details are subsequently stored in the S-DB, making the service easy to discover by other ESP users, most of which are industrial companies. This streamlined process enhances the visibility of new services within the MP, ensuring efficient access for potential users.

5.2. Finding a service: CP – MP interaction

In this interaction, we assume an industrial company wants to (1) optimize its production schedule based on electricity price forecasts and (2) market (sell) its flexibility using the services of an external market-side service provider. For this interaction, we assume, as an example, one industrial company with one CP. For further clarification, we illustrate the simplified process in Fig. 5 as a sequence diagram with the *getServiceInfo* frame. Initially, the industrial company requests information about (1) electricity price forecasting services and (2) 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, filters suitable services, and returns all information to the MIBS. Based on information from the qualifying external market-side services that match the request, the industrial company can choose the appropriate external market-side services they prefer for (1) electricity price forecasting and (2) marketing their flexibility.

5.3. Booking a service: CP – MP – external market-side service interaction

Continuing with our previous example, once the industrial company decides on a service it wishes to book – in this case, either a price forecasting service or the LFM service to enable it to market its industrial flexibility – it takes the following steps, as visualized in the simplified process in Fig. 5, under the *bookService* frame. It is important to reiterate that the price forecasting service and LFM service are not operated by the MP itself. Instead, a third-party company runs the services and utilizes the MP as a marketplace for these services.

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 respective service provider, which in this example is either the price forecasting service provider, or the LFM service provider.

Both service providers (price forecasting or LFM service provider) then generate a unique API key tailored explicitly for the requesting industrial company. This key is returned to the company's CP. Equipped with this API key, the industrial company can access and utilize either the price forecasting or the LFM services.

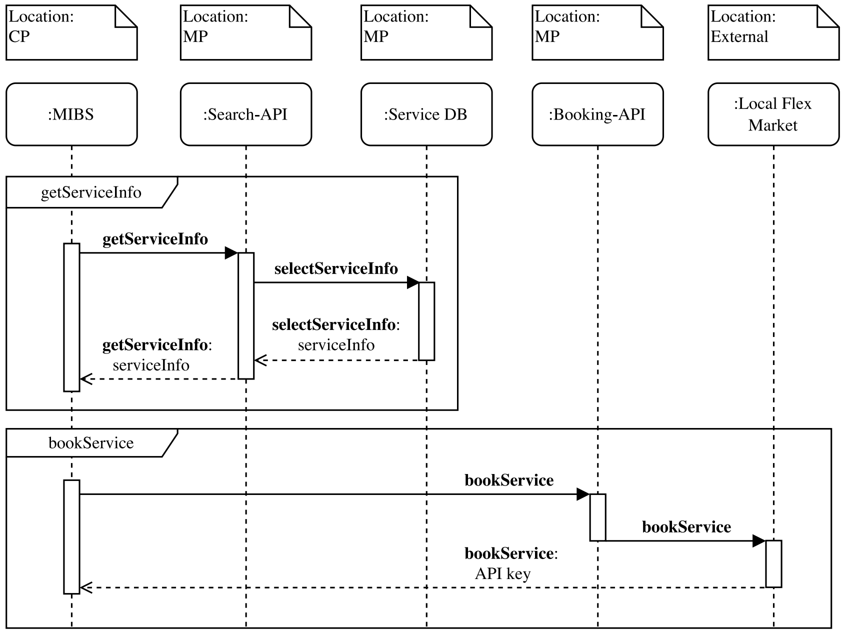

Fig. 5. Simplified service search and booking sequence diagram in the ESP.

5.4. Using a service: CP – external market-side service interaction

After confirming the booking, the industrial company can utilize the selected service, which could feature various activities depending on what the service entails, such as data exchange, energy market transactions, or other specific interactions. To illustrate these possibilities, we provide two different examples. We assume for these examples that a hypothetical industrial company operates multiple flexible machines under one CP. For the first example (see Fig. 6), the industrial company aims to receive forecasted price data to optimize its process scheduling accordingly, using the CP internal "production control service".

The process starts within the CP, where the SCs generate EFDM flexibility space instances. They register them with the EFMS. The EFMS sends notifications to the "production control service" that requests forecasted price data from the MIBS. The MIBS is a CP component that interfaces external information retrieval services, requesting the price data from an external price forecasting service registered at the MP. Therefore, it converts the information from the EFDM flexibility space instance into the required request format, and forwards it together with a specific API key to the price forecasting service. Along the same path as the request, the forecasted data is returned to the "production control service" via the MIBS. After the optimization of the production schedule, the "production control service" sends the updated production schedule (in the form of an EFDM flexible-load measures package) to the respective SCs, that then initiate the control actions which follow this updated production schedule.

For the second example (see Fig. 7), the industrial company aims to market its energy flexibility through an external market-side service provider, using, in this case, an LFM external market-side service.

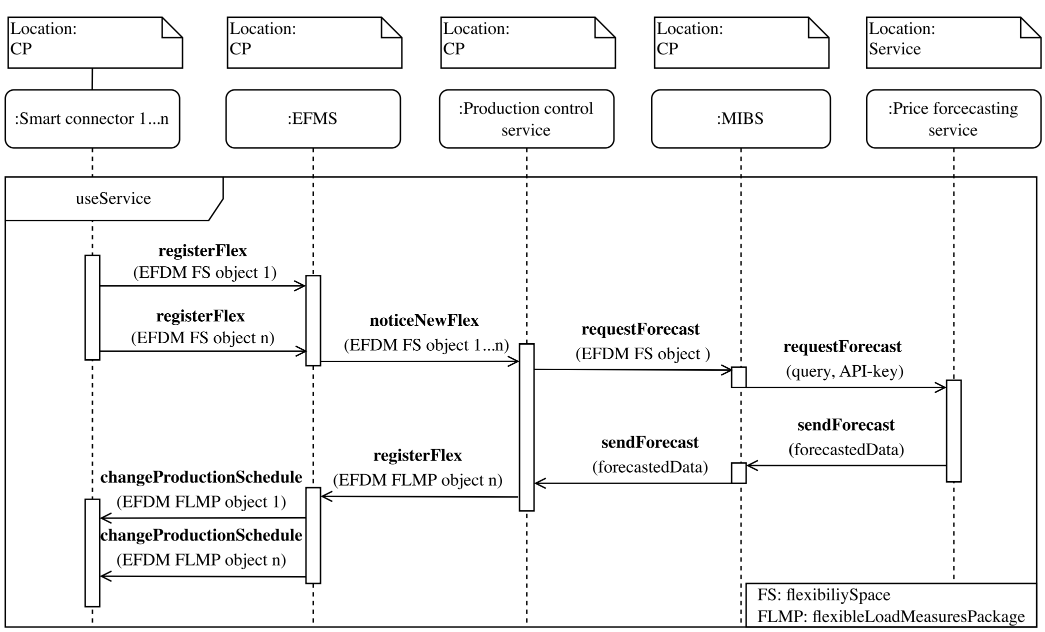

Fig. 6. Simplified sequence diagram for using the price forecasting service.

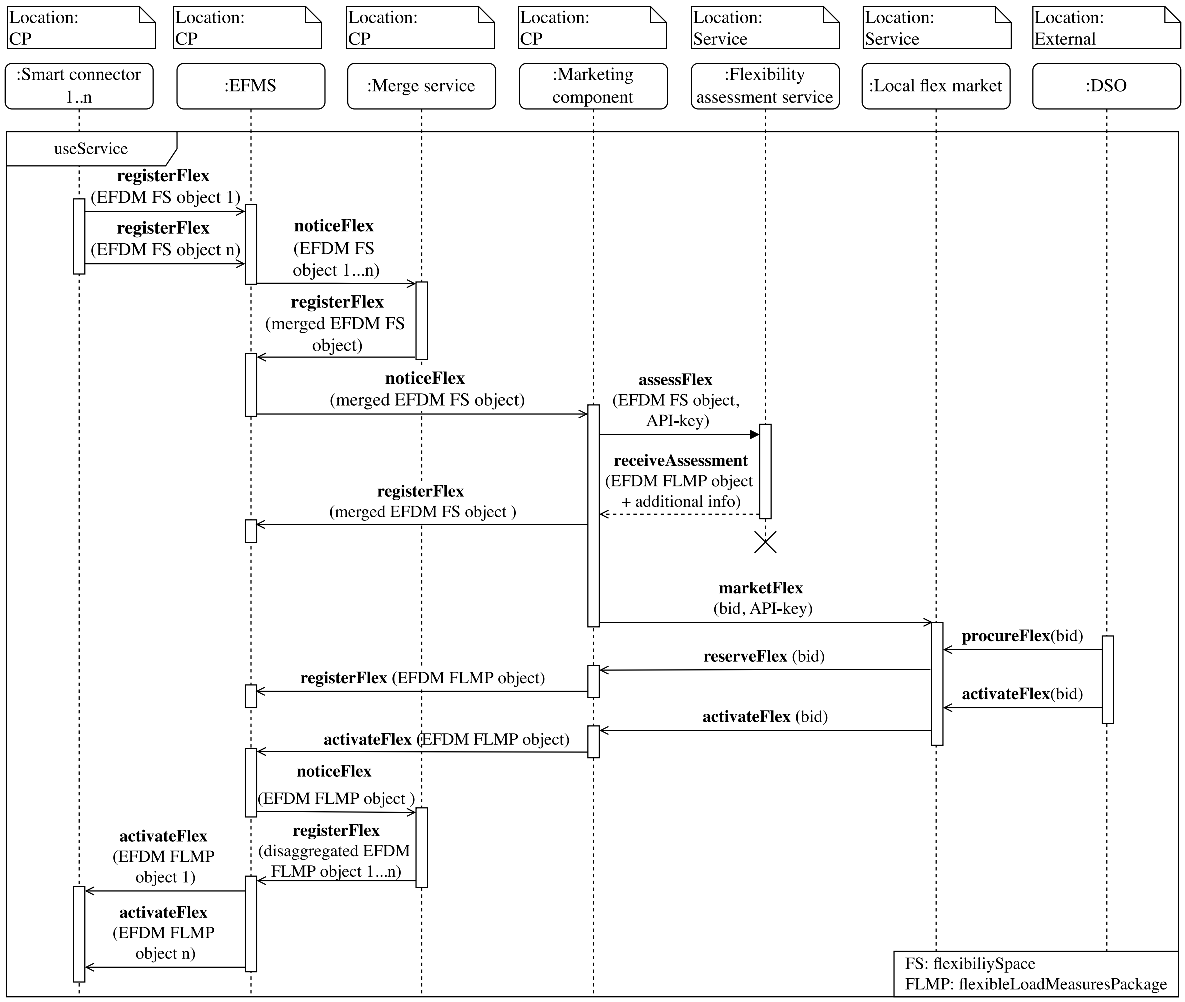

Fig. 7. Simplified sequence diagram for industrial flexibility marketing.

The process starts within the CP, where the SCs generate EFDM flexibility space 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 space instances, thereby creating aggregated flexibility potential.

With its flexibility offering consolidated, the industrial company uses a marketing component to interface with the LFM. Before converting this information into offers which are compatible with the LFM, the marketing component requests an economic assessment of the industrial company's flexibility potential. This is required to select the optimal product and activation time. The flexibility assessment service receives the request with the EFDM flexibility space instance and a specific API key and performs the calculation. It sends the EFDM flexible-load measures package with information about the most profitable market and expected revenues to the requesting marketing component. The marketing component now takes the information received from the flexibility assessment service and converts them into offers compatible with the LFM. Then, it forwards them with a specific API key to the LFM.

The distribution system operator (DSO), another LFM user, selects the most suitable offer to solve their problem, e.g., a congestion problem. The LFM sends a reservation request for the selected offer to the marketing component that forwards it to the EFMS. Once the DSO confirms the activation of that reserved offer, the LFM sends a flexibility activation signal to the CP targeting the marketing component. This marketing component translates the LFM signal into a corresponding EFDM flexible-load measures package instance, which is registered in the EFMS for further action.

Finally, the merge service within the CP receives this new EFDM flexible-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. Evaluating the Energy Synchronization Platform within Augsburg's energy flexible model region

According to the fifth step of the DSRM process model, we assess the ESP through a conceptual test operation in a model region in Germany. Following the introduction of the model region, we provide a list of the evaluations focused on the information flows, and an example of one specific implementation carried out by an industrial company.

6.1. The energy flexible model region Augsburg

The model region Augsburg (i.e., the energy flexible model region Augsburg) represents a scientific test environment in Germany. A total of 38 partners in this study are based in this region. These partners are actors from industry, research, and civil society, who are willing to work together to investigate the potential, benefits, impacts, challenges, and barriers associated with energy-flexible factories in a regional context. The model region Augsburg extends beyond the city of Augsburg and includes a significant part of the local DSO network area. It has a growing number of actors from manufacturing, research, the energy sector, the IT sector, and various interest groups. These stakeholders work closely together, focusing on the local marketing of energy flexibility – from the machine level in factories to the energy market. Energy-flexible factories within the model region Augsburg can test conceptually the operation and marketing of energy flexibility measures.

6.2. Evaluation overview

Within the model region Augsburg, we conducted a conceptual test operation of the ESP to evaluate the architecture design (as described in Section 4) and the information flows. The conceptual test operation consists of the implementation and operation of subsystems of the ESP in laboratories (i.e., research institutes) and at company sites as listed in Table 5. The evaluation of the conducted conceptual test operation is focused on the analysis of the information flows between components, platforms, and services (internal and external). The information flow evaluation helps us to check whether the functionalities and implementation of components in different environments (i.e., laboratory or company site) operate as intended.

The two laboratory evaluations focused primarily on the internal components and the specific services provided by the CP. For the subsequent seven evaluations with companies, the focus shifted towards examining how the CP interacts with various external market-side services available through the MP. Two of these evaluations focused on an electricity price prognosis service used for internal plant optimization and an optimal flexibility scheduling service based on market signals (see [67]). The remaining four evaluations examined the interactions for marketing flexibility within a conceptually developed LFM. This LFM aimed to support the local grid's capacity to mitigate congestion issues by supporting the local DSO in enhancing the planning and operational stages.

The time required for implementation, installation, parameterization, and launch of the CP at each company site was an average of 25 days. The effort involved increased with an increasing number of company-individual systems for which communication interfaces had to be implemented.

During our assessment of information flows in the model region Augsburg, we recorded over 12,500 interactions ranging from component interactions to interactions from the machine to the external market-side service. These interactions helped us improve the implementation of crucial communication components (such as the marketing component), as we identified similar errors across various companies. Some of these errors were due to faulty EFDM information conversion between components. In contrast, others were related to configuration issues between the CP and external market-side service communication via APIs. In addition, we analyzed the experiences of the ESP implementation process and the conceptual test operation through discussions with the participating industrial companies. Overall, the stability, reliability and usability of the platform during operations were emphasized positively despite the challenges during implementation. Similarly, the evaluation of the ESP's functionality revealed a very positive rating from companies whose requirements were fully covered by the platform's capabilities. However, companies whose requirements had to be partially supplemented by individual developments tended to rate the platform's functionality as neutral to slightly negative. These observations provided us with insights and reasons to refine our implementation as well as its documentation, and add video material to guide users on service requirements.

6.3. Information flow evaluation case example: Alois Müller and the local flexibility market

Alois Müller is a medium-sized company in the energy and building technology and industrial plant engineering sector. It operates its main industrial plant (i.e., factory) in the model region Augsburg. The factory comprises a flexible energy system geared towards renewable energies with infrastructure and manufacturing processes enabling and fostering adaptation to available energy (see Appendix for further details).

Alois Müller evaluated the external communication between CP and external market-side services, explicitly targeting the LFM functionality. For this purpose, they set up a singular, dedicated instance of the CP, integrating it with their pre-existing commercial energy monitoring and load management solutions as illustrated in Fig. 8.

Notably, these solutions were not open-source, necessitating special connectors for interfacing with the CP's central middleware. Due to the development of individual connectors, the implementation took an above-average value of 30 days in this use case. However, such integration was critical for testing the feasibility of marketing their energy

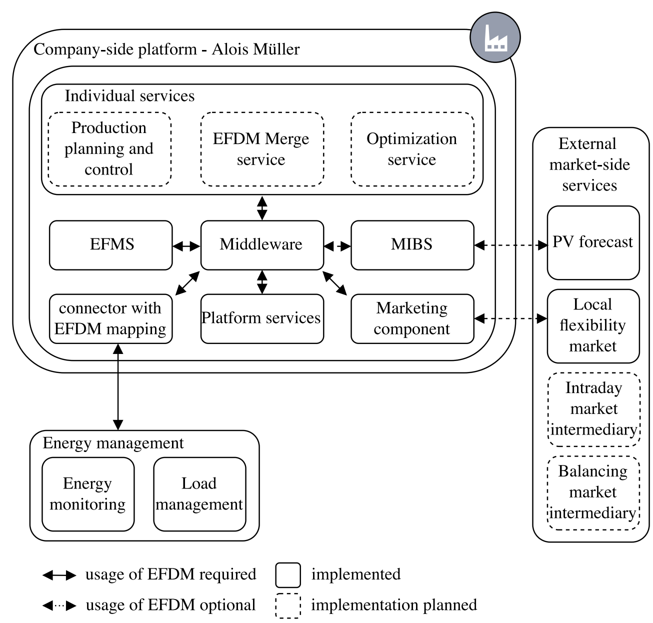

Fig. 8. Implementation of the ESP in the use case.

Table 5
Overview of the information flow evaluation within the model region Augsburg for the ESP.

Type	Flexibility source	Information flow	Component/Service
Lab[1]	Technical supply systems	Internal CP components	PPS connector (optional component)
Lab[1]	Mass forming process in automotive component	Internal CP individual services	Internal machine optimization
C[1]	Melting furnaces in magnesium die castings	CP - External market-side service	Price prognosis concept
C[1]	Aluminum electrolysis	CP - External market-side service	Flexibility assessment tool
C[1]	Electric vehicle fleet	CP - External market-side service	LFM
C[1]	Special paper production	CP - External market-side service	LFM
C[1]	Industrial plant	CP - External market-side service	LFM
C[1]	Agricultural machinery maker	CP - External market-side service	LFM

1 Lab: Laboratory, C: Company.

flexibility through the LFM. Essential to this process was ensuring that the information flow could reach the load management system seamlessly through the CP, establishing it as the primary communication channel for information exchange in their infrastructure. In the test operation (carried out over several months containing two flexibility assets), the consistency of EFDMs in the communication between services and platforms, as well as the correct generation of EFDMs from energy management, were ensured. To generate the EFDMs, load profiles of the flexibility assets were used with a 15-minute granularity. Around 100 EFDMs were therefore created per test day, sometimes significantly more in the case of dynamic behavior with many updates. In addition, activating flexible-load measures (in particular during load management) requires that signals communicated by the LFM are implemented without violating operating limits. Activation is therefore triggered via the CP but is ultimately the responsibility of load management. This ensures that no operating limits are exceeded by market signals that could, for example, result in damage to the physical systems or unstable operation.

By integrating the CP with existing energy monitoring and load management solutions, Alois Müller established a dedicated instance of the ESP that facilitated seamless information flows. Despite the complexity of developing specialized connectors for non-open-source systems – resulting in a longer implementation period (i.e., 30 days) – this integration proved essential for demonstrating the feasibility of marketing energy flexibility. Over several months of testing with two flexibility assets, the approach ensured the accurate and consistent generation of EFDMs (i.e., around 100 EFDMs daily). According to engineers at Alois Müller, who have implemented the ESP instantiation and performed the conceptual test operation, the ESP combines effectively and efficiently the requirements of the manufacturing department with energy flexibility marketing. They also state that the ESP outperforms existing solutions and paves the way for improved energy management in the industry. Additionally, the holistic approach and open interfaces of the ESP were particularly well appreciated.

7. Discussion and insight from implementation

Implementing any information system (i.e., digital platform) is a significant step for businesses. In the case of industrial companies, implementing the ESP is a step towards participating in energy flexibility trading, which demands judicious resource allocation. The iterative design process, implementations, conceptual test operations, and evaluations enabled us to capture expertise from different perspectives, including IT, manufacturing, development, facility management, and maintenance functions.

We introduce our insights gained from monitoring and discussing with six industrial companies that implemented and tested conceptually ESP components and platforms (see Section 6). We evaluated these information flows based on the following questions: (1) What influences the deployment of the ESP? and (2) What is the influence of the ESP post-deployment?

7.1. What influences the deployment of the ESP?

The deployment process for companies (including setup and configuration) averages around 25 person days. This process involves establishing an energy flexibility management service and setting up component configurations. The time and effort required varies depending on a company's digital maturity. Consequently, the impact on the deployment and evaluation outcome of the ESP in the different locations is driven mainly by (1) specialized knowledge within the company and (2) the existing IT architecture of the company. We provide an overview of the identified factors influencing the deployment of the ESP in Table 6. We have linked these to the challenges encountered and to ways of mitigation. Factors F1 to F3 relate to the influencing factors discussed in Section 7.1.1, while factors F4 to F6 relate to those outlined in Section 7.1.2.

7.1.1. Specialized knowledge within an industrial company

Providing energy flexibility through external market-side services, supported by the ESP, requires a significant cultural shift within industrial companies. This highlights the need for a well-structured change management program to effectively integrate this new operational element [70]. The transition is smoother in organizations with well-trained and knowledgeable personnel, especially when employees are motivated to achieve energy flexibility (see F1 in Table 6). Involving skilled personnel in these processes proves to be a critical factor in overcoming competence barriers, as also highlighted by Leinauer et al. [13]. Having trained personnel (see F1 in Table 6) accelerates the identification of flexibility potential and streamlines the process of developing a business case. These experts quickly and efficiently recognize the dynamics of energy costs, which is an essential step in realizing the financial benefits of energy flexibility trading. Additionally, experts are better equipped to evaluate external market-side services offered through the MP, enabling them to filter relevant data and address uncertainties by directly engaging with service providers [70]. Interdisciplinary collaboration – between researchers, ESP developers, service providers, equipment manufacturers, and industrial companies – further enhances the identification of energy flexibility potential, while reducing entry barriers [70]. The development, implementation, and evaluation of the ESP within the model region Augsburg provided invaluable contribution in fostering cross-departmental cooperation [70] and transferring knowledge to companies with less energy-focused expertise (see F1 in Table 6). This approach also empowered less-developed industrial companies to identify energy flexibility opportunities and learn from the experiences of others. For example, companies were able to recognize similar processes or machinery within their own operations with potential for energy flexibility.

Likewise, the lessons learned from our evaluations highlight the critical importance of involving both key personnel and key stakeholders (see F2 in Table 6). For a successful transition to provide energy flexibility with the support of the ESP, it is essential to analyze its impacts on the workplace at an early stage (see [70] for further details). Additionally, the evaluation phase also resulted in a significant reduction in information fragmentation concerning external market-side services. The MP acts as a centralized repository, offering

Table 6
Overview of factors influencing the ESP implementation, challenges and ways of mitigation.

ID	Influencing factors	Challenges	Mitigation
F1	Trained personnel and knowledge sharing	Promote cultural shift, assess costs and external market-side services, assess flexibility potential	Community of practice, documentation and interdisciplinary collaboration
F2	Stakeholder involvement	Time of implementation process	Community of practice, participation in concept evaluation
F3	Existing documentation	Creating connectors	-
F4	Existing IT/OT infrastructure	Integration time and effort	-
F5	Standardized interfaces	Interoperability	Standardized data model: EFDM
F6	Configuration	Deployment time	Onboarding, community of practice, support material

clear descriptions and procedural guidance. This further reinforces the strategic decision to establish a multi-sided, service-oriented platform. It simplified preliminary interactions between industrial companies and service providers.

Another factor is that supporting documentation, especially regarding the various systems and controls already in use, also proved to be a key factor for success (see F3 in Table 6). Given the diversity of plant systems and existing IT landscapes in industrial companies, such documentation ensures smooth integration, particularly in organizations running parallel systems like energy management systems.

7.1.2. Existing IT architecture of an industrial company

Concerning the IT architecture, in those cases where companies have already placed management systems (see F4 in Table 6), our experience during its implementation found that integration is a rather straightforward process. Not only is this due to the personnel being familiar with the objective, but the IT architecture supports information retrieval and flows from several systems to the CP. For instance, from our monitoring and discussions with the companies that implemented the CP, in some cases we found that integration was achieved in less than a day. On the contrary, those systems that lack connectivity require additional hardware and software resources. However, the perceived effort for deploying a CP is minimal. This is with the exception of individual solutions which demand extensive coordination, mainly when multiple companies within a precinct jointly offer energy-flexibility potential.

However, in any IT architecture, interoperability plays a crucial role in deployment (see F5 in Table 6). Although our architecture design prioritized interoperability, it did not completely eliminate the associated challenges. In turn, it reduced its dimensionality by consolidating the complexities into a few specific components, as internally, the ESP uses the EFDM as the data model standard to foster information interoperability. Such an approach allowed companies to identify and allocate personnel rapidly to configure these internal components and use the EFDM from the outset. However, configuration could severely impact deployment time in cases when personnel have limited experience (see F6 in Table 6). Nevertheless, the community of practice and the documentation which had been created facilitated the configuration and use of the EFDM.

7.2. What is the influence of the ESP post-deployment?

After the companies deployed and evaluated their information flows, we learned about the impacts as summarized in Table 7. The platform's visualization capabilities, combined with production data, enabled companies to explore additional optimization potential in their processes (see I1 in Table 7) using internal services (i.e., within the CP) and external market-side services (i.e., offered in the MP). For example, some optimizations resulted in strategic energy procurement decisions and enhanced participation in the market.

Furthermore, given that the ESP supports flexibility for both new and existing markets, it allowed companies to explore scenarios outside of central evaluations. These included factors such as improving autonomy and self-consumption rates (see I2 in Table 7).

Another impact of using the ESP is the improvement of transparency across companies' processes (see I3 in Table 7). Many companies exhibit a similar low level of transparency before successfully identifying flexibility potential. This must progress to a higher level if the successful implementation of energy flexibility is to be achieved. Transparency is crucial for leveraging flexibility, given that it requires a deep understanding of the flexibility potential of industrial plants or processes.

Similarly, as we designed and developed the system, several market-oriented companies, such as aggregators, started developing their own services to integrate them at the MP. The MP's openness towards enabling the simple integration of new and pre-existing services has a positive impact. It encourages service innovation and market competition (see I4 in Table 7), benefiting users by potentially elevating service quality, value, and diversity. Moreover, the emergence of services influenced by the deployment of services has an additional implication: the reduction of problems related to vendor lock-in. Industrial companies have reduced dependency on one set of unique external market-side service offerings (see I5 in Table 7) due to: the heterogeneous nature of services offered (even competing providers); the use of the EFDM; and the established market connector between companies' CP and external market-side services. For instance, companies can choose between offerings from aggregators, and shift from one offering to another without compromising the nature of their IT architecture.

7.3. Limitations and future research

Naturally, as with any research endeavor, our study has limitations and offers prospects for future research. In the following, we discuss four limiting aspects concerning the development of the ESP:

First, we focused only on industrial energy flexibility in Germany, limiting the platform to a single jurisdiction due to its impact on the design. For instance, a direct connection of the MP to the wholesale markets in the ESP concept would have required a pre-qualification of the platform, which would have imposed the burden of sole responsibility for the MP. We drew knowledge and experiences from international literature since our goal was to develop a generalizable solution. Therefore, we designed the ESP to not directly enable information exchange between companies and energy markets, but rather with market-related services. This enables international companies to participate in the ESP with their services. However, the tests we conducted were limited to conceptual operations in Germany, which limits the types of services tested. Future research could incorporate additional services that provide functionalities for markets beyond the German electricity market.

Second, the requirement to use the EFDM for information exchanges within the EFDM is based on the design choice to achieve information interoperability with agnostic information exchanges. However, using the EFDM requires companies to develop additional software in order to integrate its instances into their legacy systems. Researchers and practitioners can work on reducing this integration burden by developing data model mapping tools and connectors for widely used IT systems in the field.

Third, while our study focuses on the technical feasibility of the concept (i.e., designing a reference architecture and testing its information flow), we did not consider the economic perspective nor business cases for potential users (i.e., flexibility providers). Economic viability depends mainly on two factors: costs and potential revenue. The costs are highly dependent on the existing IT landscape and the depth of integration, as well as on the specific type of flexibility and the envisioned market participation. However, the insights we have gained in the ESP's

Table 7
Overview of impacts of the ESP implementations.

ID	Impact	Resulting from
I1	Additional potential for optimizing further internal processes	Visualization of companies' processes
I2	Improving autonomy and self-consumption rates	Flexibility for new and existing markets
I3	Transparency of energy-related data	Identification of flexibility potential
I4	Service innovation and market competition	Simple integration of new and pre-existing services
I5	Reduced dependency on specific service offerings	Heterogeneity of services, EFDM, market connector

test implementations regarding integration efforts are limited to the number of person-days required to integrate the ESP into the existing IT systems. Future research may develop tools that allow customers to estimate their integration costs and potential platform and service subscription fees. Future research could also develop automated tools to quantify the potential profit of flexibility in different markets and use cases.

Fourth, the concept of the ESP is based on the status quo, and is limited to the technologies and the authors' knowledge available when writing this manuscript. We acknowledge that with potential changes in regulation, technology, and political outlook, the design of the ESP may need to be adapted. In particular, framework conditions such as those of the European Union and, specifically, Germany could change the requirements that need to be taken into account.

8. Conclusion & outlook

The transformation of the power system offers opportunities for industries to provide DR through market services. In this paper, we introduce the ESP concept, which enables any industrial company to connect with service providers focused on the provision of DR. Its multi-sided architecture addresses challenges such as customized solutions, vendor lock-in, and limited interoperability. The ESP enhances compatibility across different platforms, and facilitates interoperable and agnostic information exchange on energy flexibility through its modular and service-oriented design. Additionally, the use of a standardized data model supports the integration of diverse market-related services.

We developed the ESP through an iterative process involving a multi-disciplinary consortium and external experts. Based on evaluations of the architectural design and information flows, we iteratively refined the platform concept and its architecture. The architecture of the ESP consists of two synergistic digital platforms: the CP and the MP. The CP enables the technological connection to control manufacturing assets. It also facilitates communication with external market-side services, of which the MP provides an overview. To support the use of the external market-side services listed in the MP, and to enable interoperable and agnostic exchanges of information on energy flexibility, the ESP employs the generic EFDM.

We conducted conceptual test operations of the ESP in laboratories and with industrial companies in a model region in Germany. These conceptual test operations revealed several factors influencing the ESP implementation, including the specialized knowledge and the existing IT infrastructure within the industrial company. They also revealed the impacts of the ESP implementations, such as additional improvement potential regarding internal processes.

These insights gained from these conceptual test operations can support practitioners and researchers in developing, improving, or replicating the ESP. The proposed reference architecture of the ESP can serve as a blueprint, assisting researchers and practitioners in designing digital platform solutions with the goal of streamlining automated industrial DR.

CRediT authorship contribution statement

Christine van Stiphoudt: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Sergio Potenciano Menci:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Can Kaymakci:** Writing – review & editing, Writing – original draft, Project administration, Investigation, Data curation, Conceptualization. **Simon Wenninger:** Writing – review & editing, Writing – original draft, Investigation, Data curation, Conceptualization. **Dennis Bauer:** Writing – review & editing, Writing – original draft, Resources, Project administration, Investigation, Data curation, Conceptualization. **Sebastian Duda:** Writing – review & editing, Investigation, Data curation. **Gilbert Fridgen:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition, Conceptualization. **Alexander Sauer:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Grammarly and ChatGPT in order to improve readability and language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

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

Acknowledgments

This work has been supported by: the Kopernikus-project "SynErgie" of the German Federal Ministry of Education and Research (BMBF); the Luxembourg National Research Fund (FNR), grant reference 17742284 and 17886330; and PayPal, PEARL grant reference 13342933/Gilbert Fridgen. For the purpose of open access, and in fulfillment of the obligations arising from the grant agreement, the author has applied a Creative Commons Attribution 4.0 International (CC BY 4.0) license to any Author Accepted Manuscript version arising from this submission. The authors gratefully acknowledge the project supervision undertaken by the project management organization Projektträger Jülich (PtJ) and the extensive discussions with the colleagues from the cluster on information- and communication technology.

Appendix. Case example from the energy flexible model region Augsburg

A.1. Description of the case study

Alois Müller is a medium-sized company operating in the energy and building technology sectors, as well as in industrial plant engineering. The company oversees a facility comprising a 24,000 square meter production area and a 6000 square meter office building located in Ungerhausen, within the model region Augsburg (i.e., the energy flexible model region Augsburg). The facility began operating in the summer of 2019 and was expanded in 2024. It currently employs around 250 individuals in production and administration roles. The company specializes in manufacturing ventilation ducts and technical utility components for plant construction, including steel and stainless steel piping systems, as well as mobile and modular energy units in container design. The company is committed to achieving a climate-neutral status for its site, which is aptly referred to as a "Green Factory."

The foundation for achieving a climate-neutral factory was to ensure that the main forms of energy (i.e., electricity, heating, and cooling) come from renewable and emission-neutral sources. This goal was primarily accomplished through on-site generation instead of relying on external renewable energy procurement. Multiple on-site energy systems were implemented to ensure supply which is renewable and emission-neutral (see Fig. A.1).

An initial energy flexibility audit [71] involved analyzing the energy data of all consumers, storage units, and producers within the factory, as well as assessing heat flows to connected companies. The subsequent

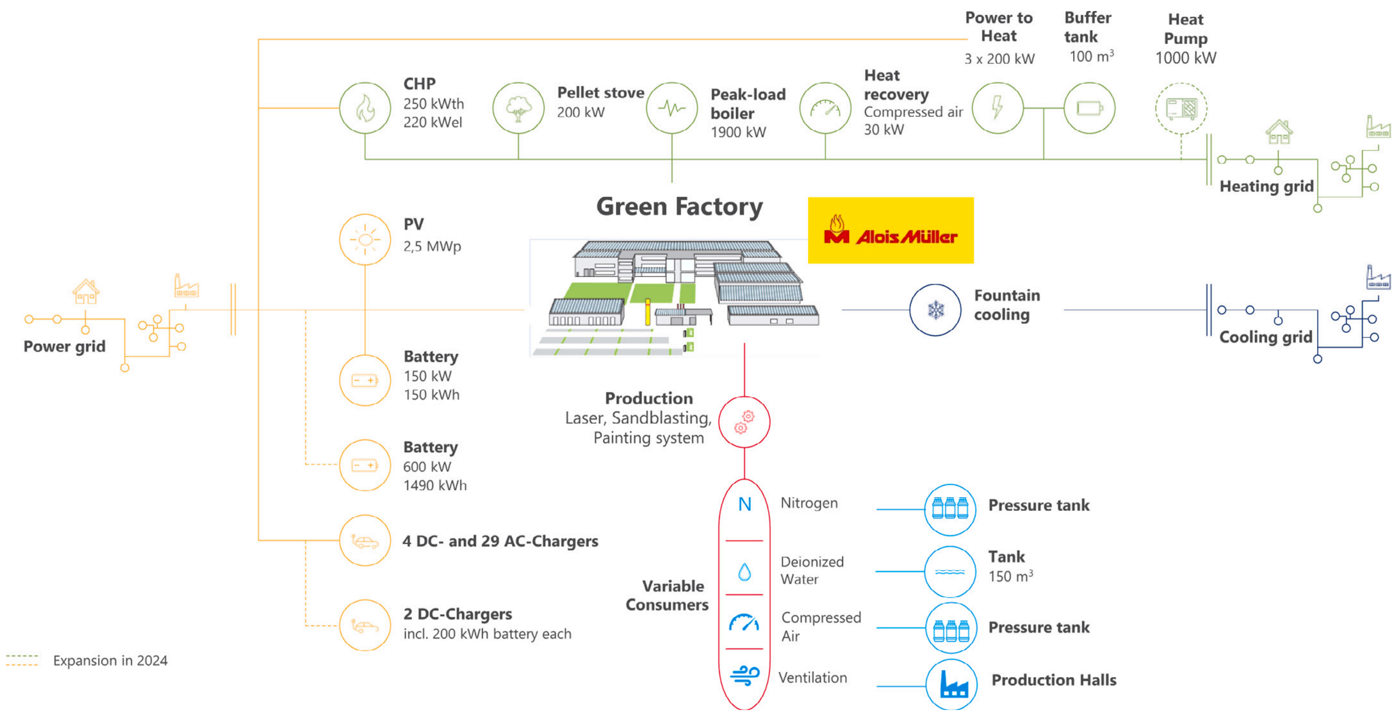

Fig. A.1. Energy system of the Green Factory.

detailed analysis identified 27 technical systems and evaluated their suitability for energy-flexible operation, considering factors such as control mechanisms, process continuity, and interdependencies with other processes. The primary objectives were twofold: (1) maximizing the utilization of energy generated in-house; and (2) marketing this energy flexibility to achieve technical and economic optimization of the Green Factory's energy demand.

Subsequently, for electricity-intensive but variable consumers, such as those using laser cutting machines, paint shops, and sandblasting operations, the timing of electricity usage coincided with the generation from photovoltaics (PV) system. To increase flexibility for constant consumers, such as welding equipment and bending and folding machines, as well as for backup power supply, two Li-ion batteries were deployed.

The examination of the technical building equipment comprises the scrutiny of four distinct systems: (1) decentralized nitrogen generation, (2) deionized water provision, (3) air compressors, and (4) ventilation systems. Each of these systems utilizes media storage units, and their operation is matched to the generation profile of the PV system. In the first system, nitrogen is produced via an air separation unit and is stored in high-pressure tanks in compressed form. By adding hydrogen, this nitrogen is used directly in production as a shielding gas for welding. In the second system, deionized water is produced by a reverse osmosis system, which is operated during favorable production times of the PV system. The deionized water is stored in tanks for later use. The third system is the compressed air system with its pressure tank and its inherent storage in the grid. It is used to compensate for periods of power shortages. The air quality and thermal inertia of the air in the production halls are used for modulating the operation of the fourth system (i.e., the ventilation systems) in relation to the PV system's generation profile.

In terms of heat supply, various systems channel their heat into the heat buffer tank. The heat can be stored for several days and accessed as needed. The redundant design of the heat generation systems allows for energy-flexible use of power-to-heat (P2H) connected to the heat buffer tank, along with combined heat and power (CHP). The interconnectivity of heat and electricity grids is emphasized, with emission-neutral energy contributing to a local heating grid and supplying neighboring companies. Future expansion plans extend to the surrounding residential areas.

The combination of P2H, CHP and the heat buffer tank serves as a use case for further analysis in this study. This selection not only embodies energy flexibility, including sector coupling, but also addresses internal dependencies between processes, necessitating comprehensive consideration and modeling.

A.2. Implementation of the Energy Synchronization Platform for Allois Müller

The basis for the realization of the use case as outlined in A.1, is the IT mapping of the relevant information flows in the company. The ESP as described in Section 4 serves as the IT foundation. From bottom to top, the existing energy monitoring and load management are connected to the CP's middleware using an individual connector with EFDM mapping (see Fig. 8). The interface for energy monitoring is unidirectional and is used to obtain energy data in order to make it available for services on the CP. In contrast, the interface for load management is bidirectional, allowing services on the CP to send control signals to systems in the factory. The connector itself comprises two subservices. The first subservice is a flexibility calculation, which generates EFDM instances using the data from the energy monitoring. The second subservice is a control logic, which translates the control signals from services on the CP into control signals for the systems in the factory.

At the CP level, the EFMS manages the energy flexibilities generated by the connector. In turn, the MIBS accesses external information, particularly a PV forecast. The marketing component uses the available energy flexibility potential (obtained via the EFMS) and the PV forecast (obtained via the MIBS) to create offers for marketing the flexibility. Future expansions are planned, in particular, to integrate PPC into the CP. As it can be assumed that the dependencies between the energy flexibilities will become more complex, additional services may become necessary to merge EFDM instances and optimize the use of energy flexibilities.

Currently, the marketing component (which contains the marketing logic and a GUI) is connected to an LFM for the conceptual test operation of the model region Augsburg. In the future, it is planned to enable connections to the balancing power market and intraday market intermediaries by extending the existing marketing component or by using new components. As a result, optimization services will have more options to place flexibility offers across various markets.

Data availability

The authors do not have permission to share data.

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