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Harnessing the Full Potential of Industrial Demand-Side Flexibility: An End-to-End Approach Connecting Machines with Markets through Service-Oriented IT Platforms

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Featured Application: Manufacturing companies with high energy consumption can contribute significantly to balancing energy demand and supply while generating monetary benefits for themselves at the same time. In the case of a voltage drop caused by a lack of electricity for example, a market participant, e.g., an aggregator, can request some negative energy flexibility, which is offered by industrial consumers at a specified price. If the offer is accepted, a typical example would be disrupting or delaying an industrial oven process in order to temporarily reduce energy consumption. In doing so, it also has to be ensured that the product quality and other manufacturing objectives, such as logistical deadlines, are not affected.

Abstract: The growing share of renewable energy generation based on fluctuating wind and solar energy sources is increasingly challenging in terms of power grid stability. Industrial demand-side response presents a promising way to balance energy supply and consumption. For this, energy demand is flexibly adapted based on external incentives. Thus, companies can economically benefit and at the same time contribute to reducing greenhouse gas emissions. However, there are currently some major obstacles that impede industrial companies from taking part in the energy markets. A broad specification analysis systematically dismantles the existing barriers. On this foundation, a new end-to-end ecosystem of an energy synchronization platform is introduced. It consists of a business-individual company-side platform, where suitable services for energy-oriented manufacturing are offered. In addition, one market-side platform is established as a mediating service broker, which connects the companies to, e.g., third party service providers, energy suppliers, aggregators, and energy markets. The ecosystems aim at preventing vendor lock-in and providing a flexible solution, relying on open standards and offering an integrated solution through an end-to-end energy flexibility data model. In this article, the resulting functionalities are discussed and the remaining deficits outlined.

Keywords: industrial load management; demand-side management; demand-side response; energy flexibility; IT concept; platform-based ecosystem

1. Introduction and Motivation

The mitigation of climate change is without a doubt one of the biggest challenges facing humanity [1]. The effects of global warming are already perceptible, e.g., the global increase in extreme weather events [2]. Climate change will not only cause irreversible damage to our environment, but will also have a big financial impact on the world economy. Thus, global warming of 1.5 degrees centigrade is expected to cause damages of 72 trillion U.S. dollars by 2060 [3]. This leads to growing environmental awareness and puts pressure on political and economic leaders all over the world to increase their efforts for a sustainable energy system, because power generation contributes one third of global emissions [4]. As a consequence, the renewable energy consumption in Europe, for example, has more than doubled in the last twenty years. Nevertheless, there is still a long way to go, as renewables still held a relatively small share of 13.2 percent of the total energy consumption in 2018 [5].

Germany was one of the first industrial countries to initiate an ambitious energy transition and increase the share of electricity from renewable sources up to 80 percent by 2050 [6]. Currently, 38 percent of the electricity is generated from renewable sources [7]. Of this, two thirds are contributed by wind and solar, which are therefore key to achieving the sustainability goals. However, power generation from these sources depends strongly on the instantaneous weather conditions and thus fluctuates significantly. As conventional power plants are easier to control and can be adapted to the actual energy demand, this characteristic presents a new challenge for balancing electricity supply and demand in the power grid. Thus, to match the increased share of wind and solar power, the grid operators are making greater efforts to ensure the power grid stability by temporarily activating reserves or turning off power plants. The costs for such measures have more than doubled in the last five years [8].

Besides the reactive management on the power generation side, the flexible adaption of energy demand is a way to balance the power grid. This mechanism is commonly known as DR and is usually supported by IT. Triggered by external incentives, e.g., price signals, electricity consumers have to reduce their power demand in times of low energy availability and vice versa. Since industry consumes the biggest share of electricity globally, this sector has also the biggest potential for balancing the power grid [9]. However, this calls for a new collaboration approach between industry and energy providers, which requires new mechanisms and interaction types for cost-competitive energy procurement against the background of increasing uncertainty and volatility. To enable industry to adapt its energy consumption actively, the technical and organizational preconditions must be developed into an eligible platform ecosystem, in which all stakeholders can take part.

In this paper, an overview of existing platform ecosystems in this field is given, and corresponding research is initially presented in Section 2. In the next step, a detailed specification analysis summarizes the current conditions of industry and the energy markets. In Section 4, additional requirements are analyzed before the research deficit is derived. The results with regard to addressing the identified deficits are presented in Section 5, and the paper concludes with a summary in Section 6, as well as an outlook on future research in Section 7.

2. State-of-the-Art

2.1. Fundamentals of Demand-Side Management and Demand-Side Response

In the past, changes in the electrical load were matched by controlling the power generation of conventional power plants [10]. Currently, due to the intermittent and hardly controllable nature of renewable energy sources, this control mechanism no longer provides a sufficient option anymore. This trend is described by Papaefthymiou et al. [10] as a "flexibility gap". Commonly, four options are available to reintroduce the necessary flexibility into the system [11,12]:

- Generation: new flexibility on the supply side
- Transmission: flexibility through the expansion of the power grid
- Storage: flexibility through storage

- Sector coupling: flexible conversion of energy between energy sectors
- Consumption: flexibility through DR

Due to the lack of sufficient deployment to expand the supply side [13], the high social costs of grid expansion [14], the still very high cost of electricity storage [15], and slow progress in interconnecting the energy sectors (power-to-gas, electromobility, etc.) [10], DR is a competitive option.

DR is a category of DSM and is generally understood as a generic term for measures that influence the level or timing of power consumption. These serve to adapt the electricity demand to the electricity supply, especially to the current generation. Hence, possible DSM measures mainly concern the short term, but also the long term. A very short-term control power could provide balancing energy within seconds [16]. In the long term (several months to years), DSM will also be allocated to programs that promote energy saving or efficiency measures on the part of consumers [17].

More short-term adjustment effects focus on DR measures, which are understood as a subcategory of DSM. By means of incentive payments or variable electricity prices, DR activities initiated by grid operators and energy providers cause changes in electricity demand [18,19]. Motivated by such price signals, participating electricity consumers autonomously choose to provide flexibility in their energy demand [16]. However, the consumption adjustment covers a period of minutes to hours. The so-called "load control", which includes the load connection, load disconnection, and load shift initiated by the utility company or grid operator, goes one step further with the same term [20]. Especially, in the industrial sector, which holds the largest share of electricity consumption [9], the DR potential can be provided at comparatively low marginal cost [21]. Energy-intensive companies are already using DR, albeit to a small extent [10,22].

2.2. Industrial Energy Procurement

For most companies, electrical energy procurement is the first and sometimes only contact point with energy planning and energy markets. As part of the procurement of electricity, companies usually pursue different and sometimes even conflicting goals. For example, a key objective of procurement can be to ensure financial and demand-driven planning security. This would require a fixed price for a certain planning level, resulting in a higher cost. Another key objective of procurement is to reduce costs by optimum exploitation of price fluctuations [23].

Historically, companies understood electrical energy procurement as a unidirectional process, in which electricity is bought from the market based on a fixed-price model, procuring the necessary amount of energy for a given period of time for a fixed price on a reference date. More advanced procurement models, such as a tranche or portfolio model, in which the procured energy is split up and bought in different tranches, are only attractive for energy-intensive industries, since they require more know-how about energy markets and, therefore, give rise to additional administrative expenses [24].

In recent decades, energy markets have become much more volatile and, therefore, uncertain (see Section 1), exposing companies to much higher risk when procuring energy. This not only leads to an increase of interest in intermediary entities, such as electricity providers and aggregators, by offering electricity procurement solutions [23], but also service providers addressing the need for additional decision support systems. This way, the company outsources the administrative efforts of analyzing markets and wins back planning certainty with regards to the electricity price.

2.3. Requirement Profiles for Industrial Demand-Side Response

In addition to improving the information base (e.g., through forecasting and better optimization) and outsourcing risk of energy procurement to intermediary entities, flexibility through DR plays an increasingly important role [25]. Table 1 shows four requirement profiles for DR together with the required request duration and remuneration possibilities. DR offers an attractive option by being able to react to short-term (minutes to hours) market price signals, and thus, it can be used as an insurance against unforeseen market volatility and even for arbitrage purposes for the intraday- or day-ahead-market (see Nos. 1 and 2, Table 1) [26,27]. Besides the use of DR in the energy-only market, industrial DR plays an important role in balancing power markets, in which loads are offered for compensation in the case of system instability [28]. Moreover, new marketing opportunities, such as opening up special markets for interruptible load, have also been created [29] (see No. 1, Table 1). With increasing deployment of renewable energies, the grid becomes exposed to systemic risks with respect to the security of supply. This is due to a higher possibility of prolonged periods (1–5 days) with an excess or lack of (renewable) energy generation. It is expected that extreme market prices will incentivize the activation of large-scale manufacturing flexibility (see No. 3, Table 1). Moreover, DR can be used to reduce peak load during the peak-time windows, which are prescribed by the system operator. This is already a common practice used by companies in order to reduce network charges and the contracted demand charge tariff (see No. 4, Table 1). Despite the variety of applications for DR, the current rate of demand flexibility realized by companies is far below the level required for the successful realization of the energy transition [12,30].

Table 1. Requirement profiles and potential remuneration for DR.

Requirement Profile	Short Description	Request Duration	Remuneration
1. Short-term load adjustment	Flexibility can compensate short-term fluctuations in generation or demand.	5 min–1 h	Balancing power markets, interruptible load market, intraday-market
2. Load adjustment over several hours	Mismatch of renewable generation and demand lead to significant fluctuations in electricity prices.	3 to 12 h	Day-Ahead-Market, derivatives
3. Reduction/increase of load over several days	Relevance for flexibility over longer periods increases with regard to the security of supply.	1–5 days	Day-ahead-market, derivatives
4. Atypical grid usage	By avoiding grid usage at congested times, the grid and procurement costs can be reduced.	Several hours per day	Reduction of network charges

2.4. Energy Flexibility for Industrial Companies

The identification of flexibility measures, the technical and economic assessment, as well as the subsequent marketing on the energy market present a complex challenge for companies [31]. On the one hand, the different use cases for flexibility are characterized by an individual product design and compensation methods. On the other hand, on the manufacturing level, different machines or manufacturing processes inherit different forms of flexibility measures and therefore a divergent level of flexibility potential. The characteristics are most commonly distinguished by their controllability. Hence, the potential measures are categorized into uncontrollable (no flexibility), curtailable, shiftable, buffered, and freely controllable loads (full flexibility) [32]. Curtailable loads, for example, are those that do not need to recover the curtailed energy once they are reconnected. In contrast to that, shiftable loads are those that can be moved in time. However, the amount of consumed energy does not change; it only gets shifted in the time domain. In addition, the identification and implementation of measures for DR are quite complex. The technical processes define many different boundary conditions and dependencies, such as a minimum or maximum period of interruption due to quality issues, which have to be considered [33]. In addition, DR can also counteract the main objectives of manufacturing, such as throughput or delivery reliability [34]. The high number of dependencies between individual flexibility measures and a large number of manufacturing parameters represents a major challenge in the manufacturing industry. This includes planning horizons, temporal resolutions, and maximum permissible runtimes [35]. At the same time, the complexity of the boundary conditions and the abstraction level increase with higher automation levels [36]. Moreover, data from a wide range of heterogeneous sources on the shop floor (e.g., machine control, manufacturing planning, etc.) is required for industrial DR. As manufacturing

IT platforms have been proven to provide such features, the existing ecosystems in this field are examined below.

2.5. Platform Ecosystems

In recent years, platforms have arisen in many business fields in order to bring together customers and providers and offer innovative services. In this respect, the term platform is used very frequently; however, its meaning is not clear and consistent [37]. In the scientific literature, three perspectives on platforms from the fields of engineering, economics, and organization can be found [38]. Considering this, platforms offer a medium of interaction for business partners based on software, hardware, organizational processes, and standards [39]. Platforms are characterized by a layered architecture [40] and act as a central cornerstone, which supplies core functionalities [41]. In this way, they offer a common access point for users and a set of basic services [42]. Ecosystems and platforms are closely connected with each other because ecosystems are platforms in which numerous firms can contribute components (e.g., apps) to a technical platform [43]. Hence, the term "platform ecosystems" is also frequently used [44,45].

From an economic perspective, platform ecosystems offer several major benefits, especially the co-creation of business value by encouraging complementary invention and exploiting network effects, as well as increasing flexibility [42]. The fact that five out of the ten most valuable brands are built on platform business models demonstrates these outstanding advantages [46]. Regarding platform ecosystems, there are several aspects to consider. Platforms may result in a winner-takes-all situation, where eventually, the free competition of different vendors is eliminated and substituted by a single dominator [47]. However, there are also systems aiming at co-evolution promoting symbiotic situations, which provide benefits for all participants. In this way, the complementors, which contribute, e.g., applications to the platforms are crucial, because they moderate the competition [48]. Therefore, platform users should be able to easily exchange services from different vendors and, in doing so, avoid so-called vendor lock-in. Another characteristic of platform ecosystems is the indirect network effects, where the value of a product increases with the total number of users [42], e.g., platforms with a high number of potential customers are very attractive for vendors. Consequently, the thresholds and obstacles for participants need to be minimized, in order to make it easy for new partners to participate in an ecosystem. This effect was for example studied by [49], where the pricing of gaming hardware, which indicates the entry hurdles for a video game console, was proven to be crucial for the success of vendors. Moreover, platform ecosystems benefit highly from complementary inventions from other partners and thereby value co-creation, as by this means, new and innovative services can be offered [50].

To coordinate the variety of platform participants, a suitable governance approach is also required. The governance of a platform ecosystem is of contingent and dynamic nature and has to be carried out by the platform operator [51]. Thereby, standardization is an important element for governance. Moreover, due to the situational and temporal contingencies, establishing self-selection is very effective [52]. This means the participants self-select the different partner levels and define the appropriate rules for their business.

Overall, platform ecosystems play a very important role in the business world and bring some major advantages. Nevertheless, establishing and running a platform ecosystem includes some challenges. Platform ecosystems are already widespread in the manufacturing sector and energy markets; the existing solutions are outlined below.

2.5.1. Manufacturing IT Platforms

Modern manufacturing systems require multiple IT systems, which operate on different operational levels, to make the complex and numerous processes controllable. A commonly-used reference model to structure these manifold software solutions in a functional and hierarchical manner of five levels is the automation pyramid [53]. As every level may consist of several individual elements, shaping a suitable architecture to achieve an integrated information flow and meet all functional requirements is challenging. In line with the increasing digitization, cyber-physical systems, which merge the physical and virtual world through embedded hardware and software, present a new approach [54–56]. Thus, the conventional pyramid architecture is supplemented or replaced by a decentralized and non-hierarchical structure with increasing agility and flexibility [57]. Nevertheless, an architecture following the automation pyramid is still common in present-day manufacturing system architectures, which may also be indicated by its adaption within the Reference Architectural Model Industry 4.0 [58].

In order to handle increasing complexity and in line with the trend of digitization, manufacturing IT platforms, which cover all levels of the automation pyramid, are commonly applied. In addition, customers and suppliers are able to interact on these platforms, shaping complex ecosystems [59]. Driven by the recent trend towards increasing service orientation, also referred to as XaaS [60], many authors [61–64] and companies have begun to work on service-oriented and often cloud-based platform ecosystems. They focus on the efficient provision of functionality in the form of software services for end users and are, therefore, well suited for applications in manufacturing. Compared to consumer-grade software platforms, industrial-grade manufacturing IT platforms have additional requirements [65,66]. Reliability and security are central. While reliability ensures that the platform is capable of supporting 24/7 manufacturing, information and data security are necessary to protect the intellectual property of the company.

Manufacturing IT platforms are offered by leading equipment and software vendors such as Predix by General Electric (https://www.ge.com/digital/iiot-platform), MindSphere by Siemens (https://siemens.mindsphere.io), IoT Suite by Bosch (https://www.bosch-iot-suite.com), and Axoom by Trumpf (https://marketplace.axoom.com), as well as by new developments in research such as the Industrial Data Space (https://www.internationaldataspaces.org) or Virtual Fort Knox (https://virtualfortknox.de). These platforms aim at supporting manufacturing companies in networking their manufacturing and generate added value through digital services such as process optimization or predictive maintenance. Most existing and commercially available manufacturing IT platforms are tailored to products and services offered by the respective vendor [65,66]. They utilize proprietary interfaces and protocols instead of open ones. As a consequence, neither interaction with external systems nor interoperability with other platform vendors are possible. This causes vendor lock-in effects for the customer, which is one of the largest barriers that companies face when introducing cloud platforms [67,68].

Besides manufacturing IT platforms, EMS are also widely spread in industrial companies [69,70]. It is their task to gather and preprocess data of the current and historical energy consumption, in order to increase transparency and uncover trends or outliers. Thus, the main scope of the EMS is to increase energy efficiency. However, these systems are not able to introduce any control actions, and so far, there is no linkage to the shop floor [68,71]. Consequently, in order to adapt the energy consumption flexibly, EMS needs to be enhanced and linked to the conventional systems for manufacturing management and execution.

2.5.2. Market-Side Platforms and Services

As described in Section 2.2, intermediary entities are of increasing importance for companies. However, not only third-party energy suppliers and aggregators are commissioned. Service providers, e.g., decision support or forecasts, are also at the focus of increasing attention. Companies are focusing on their core business, and thus, on-site support processes are increasingly outsourced to third parties [72]. Additional reasons for outsourcing are the reduction and control of costs, risk minimization, and benefits from the best practice of others.

For energy procurement, plenty of decision support service providers offer a wide range of software solutions. These range from electricity market forecasts to solutions for manufacturing planning optimization, taking into consideration different horizons of electricity market prices. Such service providers are, for example, Kisters (https://www.kisters.de/en), N-SIDE (https://www.n-side.com), DNV-GL (https://www.dnvgl.com/power-renewables/services/index.html), Software AG (https://www.softwareag.com), and Siemens Industry Services (https://www.industry.siemens.com/services). These services are usually limited to decision support and do not interact with markets. Following the process of optimization, a company can generally market the flexibility on its own or via an intermediary, such as a direct marketer or an aggregator [73]. Aggregators provide comprehensive solutions, incorporating energy supply contracts, optimization of manufacturing flexibilities, and the final trading of the same. Examples include Next Kraftwerke (https://www.next-kraftwerke.de) and e2m (https://www.e2m.energy). These solutions build on current market designs and scarcely integrate new potential flexibility markets, such as local flexibility markets. Moreover, the solutions provided with regard to the interfaces, data models, and processes used for communication between the company and aggregators are not standardized.

For this reason, public projects are aiming to establish reference frameworks, which deliver a common standard for systems to ensure interoperability for flexibility trading and integrating all potential flexibility customers. Several publicly-funded research projects are focused on developing open source flexibility platform solutions in order to standardize the processes and protocols for flexibility usage, including DR in the commercial and residential sector. For example, the non-profit organization USEF (https://www.usef.energy) developed an open standard for transparent communication procedures fitting on top of most energy market models, extending existing processes to offer the integration of both new and existing energy markets. It is designed to make flexible energy a tradeable commodity. Thus, its focus lies on the marketing processes for potential customers, such as system operators and balance responsible parties after the flexibility was identified. The OpenADRproject (https://www.openadr.org), on the other hand, very much focuses on the implementation of DR and final execution of the flexibility measure by providing a common language communication data model incorporating different DR programs, such as critical peak pricing for spot markets or fast demand response for ancillary markets.

On the one hand, the USEF and OpenADR approach are making an important contribution to the standardization of interfaces and communication within the flexibility value chain, but on the other hand, they do not provide the IT solutions needed to bring together manufacturing machines and flexibility markets.

2.6. Preliminary Conclusions

It can be summarized that (1) industrial demand flexibility plays a key role in overcoming the current flexibility gap in the electricity sector and (2) demand flexibility has not yet been harvested to its full potential. Moreover, (3) in order to implement DR in industrial companies, the complex impact of single measures on the whole manufacturing system and its interdependencies on all organizational levels have to be considered. (4) A large number of manufacturing IT platforms already exists. They are, however, predominantly designed as closed ecosystems. Proprietary interfaces are used, and there is no interaction with external systems. (5) EMS, however, only focuses on gathering and preprocessing information on the energy consumption and is not capable of executing adapting actions. (6) On the other hand, platforms targeting aggregation and marketing of demand flexibility lack the complexity management required for industrial manufacturing processes and thus only partially address the value chain of DR (see Figure 1).

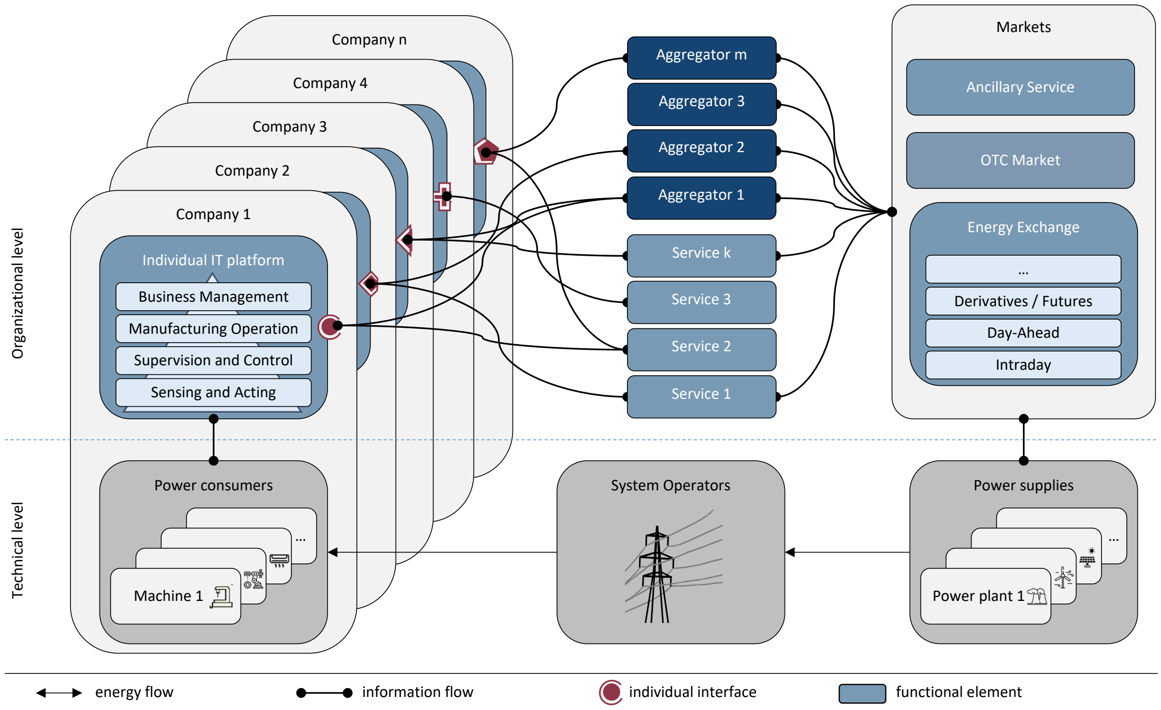

Figure 1. Current landscape of IT platforms, services, aggregators, and energy markets.

3. Industry Specification Analysis

The previous section showed that there remains much unused potential for industrial DR. In order to determine why this potential is currently not being exploited, the existing barriers are identified below. To achieve this, the method of structured interviews and workshops was applied. These were conducted with different companies and stakeholders, which were elicited in focus group interviews comprising representatives of manufacturing companies and the energy market. The information was collected in the context of "SynErgie" (https://www.kopernikus-projekte.de/synergie), a large German research project, and beyond that discussed, filtered, and consolidated in internal workshops with numerous researchers from different disciplines. In doing so, the creation of an integrated approach for industrial DR, which includes all relevant providers, consumers, and other market participants is the central goal [74]. As more than 80 partners from industry, energy markets, research, and society were involved, a substantiated specification could be prepared that records the demands of all relevant stakeholders. The requirements identified by the method described above are summarized and outlined below:

1. Functionality: The automated synchronization of industrial energy consumption and supply requires several different partners and functional levels from the energy market down to single machines to be involved. The increasing number of participating companies and the increasing challenges to balance the power grid make automated synchronization necessary. For this reason, an end-to-end approach is required, which defines the continuous information flow throughout all relevant stages and maps the following three central use cases: procurement of market information (e.g., price forecasts), evaluation of flexibility (e.g., ideal marketing time), and marketing of flexibility (on the appropriate target market). In addition, information on energy consumption needs to be equally considered within manufacturing. Thus, appropriate functionalities throughout all organizational levels of a company are required.
2. Interoperability: Currently, a variety of communication protocols, data models, and IT systems are used in manufacturing. On top of that, energy markets and grid providers apply several interfaces and data models. Consequently, interoperability is another important requirement to enable a high number of heterogeneous companies to take part in a flexible manner. The integration of

existing standards, shaping a transferable and robust architecture, as well as the harmonization of data models are crucial for the development of a new ecosystem in the context of energy flexibility.
3. Free competition: To achieve wide acceptability and to offer incentives for companies to participate in the energy markets, a solution needs to be offered that ensures free competition. Accordingly, obstacles for new market actors need to be minimized, and an open ecosystem must be offered that provides flexible access to the services of different providers. In addition, industrial companies and other participants should be able to extend independently the functionalities of and solutions to their and their customers individual needs.
4. Privacy and security: Privacy and security are key requirements for companies to participate. The detailed energy consumption contains crucial information about a manufacturing company, because for example, the given utilization or the used technology can be derived. Thus, no confidential information about energy consumption, etc., should be provided to external competitors. Besides privacy, security probably plays an even more important role. As energy systems are part of the critical infrastructure, the highest security standards need to be adopted, and given specifications need to be fulfilled, e.g., [75]. In addition, data leaks have to be prevented to ensure that personalized information does not fall into the wrong hands.
5. Credibility and trustworthiness: The pursued solution should offer the possibility to purchase and sell energy flexibility automatically. Therefore, signing legally-binding digital contracts is an additional essential requirement. For this purpose, appropriate services and processes need to be established that at the same time provide proper technical solutions to ensure trustworthiness in terms of traceability and transparency.
6. Market entry threshold: The specification analysis also involved the current market design and resulted in requirements for key changes. In order for demand flexibility to be used to its full extent, sanctioning flexibility by network charges needs to be eliminated. Furthermore, a non-discriminatory access to all flexibility markets needs to be ensured.
7. General architecture requirements: Considering the discussed requirements for IT-based automated industrial DR, additional specifications regarding the architecture can be derived. In particular, modularity and extensibility are very important in order to provide the required reusability, adaptability, and scalability of the solution. These requirements can be summed up with the concept of service-oriented architectures. In addition, near real-time processing, as well as robust and reliable communication flows are essential. Furthermore, different deployment models, e.g., private or public cloud solutions, should be possible.

4. Research Deficit

In the previous two sections, the state-of-the-art was analyzed (see Section 2), and a broad specification analysis (see Section 3) was presented. Based on these findings, the need for action and research deficits are derived below, as the next methodological steps. In their practical form, these deficits represent obstacles to companies making full use of demand flexibility and to marketing it economically. These obstacles need to be addressed in the research in order to provide more demand flexibility in industry, thereby contributing to a successful energy transition. The deficits identified are described below.

4.1. End-to-End Approach

Regarding existing frameworks and standards for market demand flexibility, it must be pointed out that there is no approach covering information flows and automation from machines to energy markets. However, such an end-to-end approach from machines to energy markets is necessary to achieve consistency and interoperability with all technical entities and stakeholders involved.

- Information flows: All bidirectional information flows between machines and energy markets, including every intermediate stage, must be covered to achieve an end-to-end approach. Bidirectionality because demand flexibility must be offered in the markets and, in addition, the purchase signals must subsequently be converted into load profiles within the company and ultimately into control signals for the machines and equipment. The information flows do not only cover company in-house processes as described by the automation pyramid [35,53]. Therefore, the concept of the automation pyramid needs to be broadened to include external processes with regard to marketing demand flexibility (see Nos. 1 and 2, Section 3). In addition, decentralized approaches also need to be considered as these concepts are increasingly common and provide more flexibility for companies (Section 2.5.1).

- Multi-level optimization: In order to regulate complex information flows and control the efficient use of flexibility, different levels of optimization are necessary. These levels decompose the overall optimization problem of efficient flexibility usage into sub-problems considering characteristics such as planning horizons, temporal resolutions, and maximum permissible runtimes. It is important that optimization levels can be implemented dynamically, e.g., depending on the target process and the company's infrastructure, some of the optimization levels may be left out or split, e.g., into sub-optimizations. However, with decomposition, new challenges arise. First, restrictions made at certain levels must be respected by the following levels. Second, the·interaction between various optimization levels needs to be coordinated by a corresponding architecture (see No. 1, Section 3).
- Generic data model: To ensure consistency within the end-to-end approach for information flows and the interaction of different optimization levels, a generic data model covering a wide range of demand flexibility is necessary. However, not every communication between technical entities in the described end-to-end approach needs to be mapped in this data model. Rather, it is a matter of using the data model where it creates added value. Data models for further communication must then be designed in such a way that they can be derived from this generic data model or transferred back to it (see No. 2, Section 3).
- Traceability: While information flows and the data model ensure technical interoperability, the communication within the described end-to-end approach needs to be credible and trustworthy. Therefore, technical solutions meeting these specifications are necessary, e.g., step-by-step traceability of transactions. From a company-side perspective, this is to ensure that commercialized flexibility has really been implemented and the contract fulfilled accordingly. From a market-side point of view, the fulfillment of the contracts is equally important to ensure balanced groups in the energy system (see No. 5, Section 3).
- Encapsulation: Industry and the energy sector are completely different domains with diverse knowledge, methods, and technologies. To realize automated flexibility commercialization, both domains need to be connected and work interlocked. Consequently, approaches to encapsulate both domains without affecting the system's performance are necessary. This includes, but is not limited to, commercializing load profiles without revealing manufacturing secrets and ensuring free competition on markets, etc. (see No. 4, Section 3).

4.2. Company-Side

Even without the use of demand flexibility, industrial manufacturing and the associated supply networks are very complex. Demand flexibility adds another dimension of complexity to this, which is why manifold research deficits can be identified:

- Vendor lock-in: Most existing manufacturing IT platforms are tailored to products and services offered by the respective vendor and lack interoperability with other platform providers or integration of external systems. To prevent vendor lock-in, open platforms with the ability to connect proprietary (e.g., Siemens S7, SAP BAPI, etc.) and open protocols (e.g., OPC-UA, REST, etc.) for hardware and software flexibly are required (see Nos. 2, 3 and 7, Section 3).
- Interoperability: To ensure interoperability, communication must be protocol independent, and the platform must be able to harmonize data models. For platforms to incorporate the described end-to-end approach, this does not only apply to internal interfaces and data models, but also to

external communication. This allows, for example, the vendor-independent integration of PLC by Siemens and Bosch Rexroth with an EMS by econ solutions and an ERP by SAP. Additionally, it should be possible to establish a connection between platforms of different vendors. At the same time, since various stakeholders, vendors, components, and services are involved, the concepts for security and privacy become crucial. (see Nos. 2, 3, 4, and 6, Section 3).

- Energy as a decisive target: Existing platforms do not necessarily consider energy as a decisive target in manufacturing (see Section 2.5.1). Yet, with an increasingly volatile energy supply and the resulting need for greater demand flexibility, energy and its related availability and costs must be taken into account. Therefore, the functionalities of existing platforms need to be enhanced to consider energy aspects and to provide solutions for the synchronization of energy demand and supply (see No. 1, Section 3).
- Technical flexibility assessment: The variety of industry sectors yields a wide range of manufacturing processes with individual flexibility measure patterns. Besides the lack of adequate flexibility products on the energy markets, the technical assessment and integration into a flexibility portfolio within a complete flexibility management approach still requires high individual efforts, resulting in unpredictable project costs for companies. Even though aggregators and other service providers already offer audits to identify flexible loads for potential commercialization, the focus mainly lies on large-scale manufacturing plants, leaving unused potential (see No. 1, Section 3).
- Flexibility management: Due to the synchronization of energy demand and supply, the traditional magic triangle of time, cost, and quality becomes more and more volatile. Demand flexibility offers a possibility for cooperating with the rising importance of energy procurement. Therefore, platforms must enable an integrated management of demand flexibility within the company, integrating energy-related data with other manufacturing data for an adequate technical assessment. Consequently, the acquisition, aggregation, analysis, and optimization of process and manufacturing data are necessary to achieve energy-synchronized control of the systems, plants, and components (see No. 1, Section 3).
- Energy-synchronized control: Covering automated marketing of demand flexibility, functionality at all levels of the automation pyramid needs to be considered. Key features of this energy-synchronized control of manufacturing are the transformation of process data into flexibility measures and the aggregation by combining, splitting, and adapting the flexibility measures for optimized usage. In addition, a communication interface to the energy markets is required, which ideally is implemented using standardized and open protocols to automate the access to different offers of demand flexibility marketing, e.g., day-ahead-market, and information procurement, such as market price forecasts (see Nos. 1 and 2, Section 3).
- Entry hurdles: While the workload of administrators is reduced by the cloud offerings of certain manufacturing IT platforms, there are still significant entry hurdles for users. On the one hand, due to probable vendor lock-in and, on the other hand, due to the availability of functionalities in the field of manufacturing and the necessary effort for connection and usage. For these reasons, platforms should be designed as open development, sales, and operating platforms. Available functionalities can thus be obtained and operated via the platform, while missing functionalities can be developed by the user or software partners. (see Nos. 1, 2, 3, and 6, Section 3).

4.3. Market-Side

The reasons for the slow expansion of industrial DR are manifold: First, complex regulatory frameworks and weak market incentives on the market side; second, the lack of integrated economic assessment of flexibility, from machine to the flexibility market, as part of the manufacturing planning; third, the uncertainty in price forecasts and the resultant risk to manufacturing planning. The resulting research deficits on the market side are outlined below:

- Market design: The step towards trading flexibility from a market and regulatory perspective is subject to a number of obstacles. Three main obstacles to developing an efficient energy market embracing demand flexibility can be identified [76]:

    1. As the energy sector is subject to a complex regulatory system, a high uncertainty exists with regard to the continuity design of energy laws, subsidies, taxes, etc. This uncertainty is currently reflected by the indecision on the part of companies to invest.
    2. Energy market design aims to treat different technologies equally. However, in reality, the nature of flexibility measures (as described in Section 2), dependent on the type of machine or manufacturing process, does not imitate conventional generation schemes. The result is a distortion of flexibility options and technologies.
    3. The complexity of the energy sector is also reflected in the price structure. Daily price fluctuations on the electricity market are only partially visible to consumers. The high fixed cost share (electricity taxes, network charges, etc.) is leveled, the price fluctuations are reduced, and the profit margin of the demand flexibility project is reduced.

    Further research is needed to highlight the inefficiencies and weaknesses of the current market design and to identify solutions for obtaining economically-viable demand flexibility options (see No. 6, Section 3).
- Economic flexibility assessment: Participation in the energy market is attractive when the value of the flexibility measure, i.e., the electricity cost savings that can potentially be achieved through load shifting, is higher than the opportunity costs that the company incurs by making the process more flexible and possibly losing value due to the flexibility measure. If the value of flexibility signaled on the market is below the opportunity cost, a flexibility measure will not be stimulated. Therefore, the internal financial assessment of the flexibility needs to have both information on the manufacturing costs (including all implied potential costs if used) and real-time market prices. The information on the optimization combines the two prices and indicates which flexibilities should be drawn from an economic point of view. Regardless of whether the optimization takes place on the company-side or market-side platform, some kind of data model for communication of flexibilities is used. To ensure consistency in communication while maintaining a high level of functionality and traceability, a standardized description and modeling of industrial demand flexibility is required. (see Nos. 1, 2, and 5, Section 3).
- Energy market forecast: To ensure planning security, the role of forecasting energy market prices is crucial. However, a predictability of more than five days, e.g., the day-ahead-market, due to the intermittent nature of renewable energy sources, is difficult. In some company cases, predictions of more than five days, regardless of the forecast quality, are needed. Currently, plenty of forecast service providers are competing for the growing market of demand flexibility. The forecasting service market is not yet transparent, and therefore, it is not easy to compare different services. This might be suitable for individual service providers; however, it does not contribute to a performance-based free market embracing free competition (see No. 3, Section 3).

5. Concept of the Energy Synchronization Platform

Considering the state-of-the-art (see Section 2), required specifications (see Section 3), and existing research deficits (see Section 4), the ESP as depicted in Figure 2 is proposed. This platform ecosystem enables the industry to participate actively in energy markets through both a faster and more accurate scheduling of its energy consumption (consumer role) and by offering DR potential (supplier role). Therefore, the ESP allows a proactive and continuous synchronization between companies' offer of flexibility and the markets' demand for flexibility, as well as between energy consumption and energy supply. In this way, the platform supports companies in ensuring that only the flexibility for which it is economically viable is marketed. At the same time, the reliability and stability of the power grid are increased from a system perspective.

To fulfill all requirements, especially regarding free competition, the ESP is designed as an ecosystem with extensive functionalities preventing vendor lock-in and ensuring interoperability. Currently, the energy market is decentralized, and there are individual service providers and aggregators with different interfaces, which results in the displayed disadvantages (see Section 4). To overcome this, the ESP aims to bundle all necessary services on one platform and integrate all service providers as complementors. In doing so, the evolution of the ESP should be initiated by the publicly-funded project "SynErgie" (see Section 3) and later be transferred to an independent platform ecosystem with a community as the platform operator. Consequently, the ESP grows the flexibility market by increasing offered and demanded flexibility, as well as by synchronizing both. This networking and communication in particular is expected to have a huge effect on the market growth [42,77].

The technical concept of the ESP was developed with regard to security by design and consists of two logical platform types: the CoP as described in Section 5.1 and the MaP as described in Section 5.2. The division into two logical platforms ensures privacy and security by encapsulating their specific domain knowledge, technologies, and methods while, at the same time, maintaining a safe state without affecting the operation and performance of the overall system. Summarizing, the ESP describes the interaction of several CoPs on a central MaP to carry out transparently IT-supported demand flexibility trading.

Both logical platform types are connected via an interface, allowing the exchange of necessary data for automated DR by a specified data model. This data model is universally valid, as well as generic for various flexibility measures and applicable in all data-handling steps for automated DR from machines to energy markets. Such an EFDM is proposed by [78]. Especially for comprehensive processes, this EFDM can be applied end-to-end. However, this EFDM is not designed as the single source of truth, but much more as a superordinate data model from which further data models can be derived. A prerequisite for this is that the derived data models can be translated back into the generic EFDM at any time. A use case for the derivation of data models is the multi-level optimization of the use of flexibility. In the following, the two logical platform types are described and then merged to form the end-to-end approach.

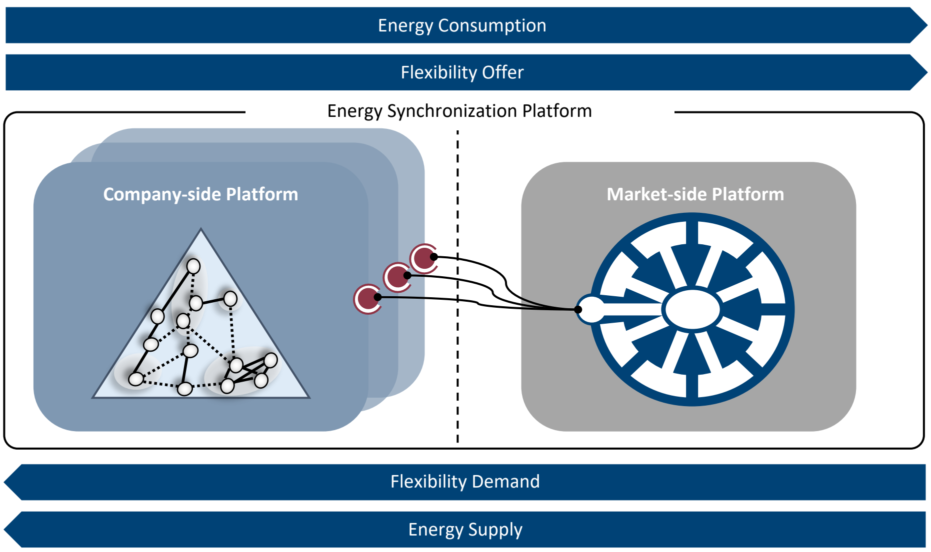

Figure 2. Concept of the energy synchronization platform.

5.1. Company-Side Platform

As part of ESP, a CoP offers the necessary functionalities for the IT connection and control of energy-flexible manufacturing processes and infrastructure in a service-oriented architecture. Therefore, it represents the modular, service-oriented, secure, and externally-encapsulated IT system within a company. Compared to other manufacturing IT platforms, the CoP is characterized by the fact that energy is explicitly taken into account or focused as a decisive target for manufacturing. Consequently, it includes acquisition, aggregation, analysis, and optimization of process and manufacturing data, on the one hand, and energy-synchronized control of the systems, plants, and components, on the other hand. The functionalities represented by services thus cover all levels of the automation pyramid, and information can be distributed in both ways, bottom-up and top-down. Hence, demand-flexible behavior in the future electricity system is enabled for technical entities in manufacturing companies. Thereby, information from both manufacturing and the energy system is brought together. The architecture of the CoP is depicted in Figure 3 and described below.

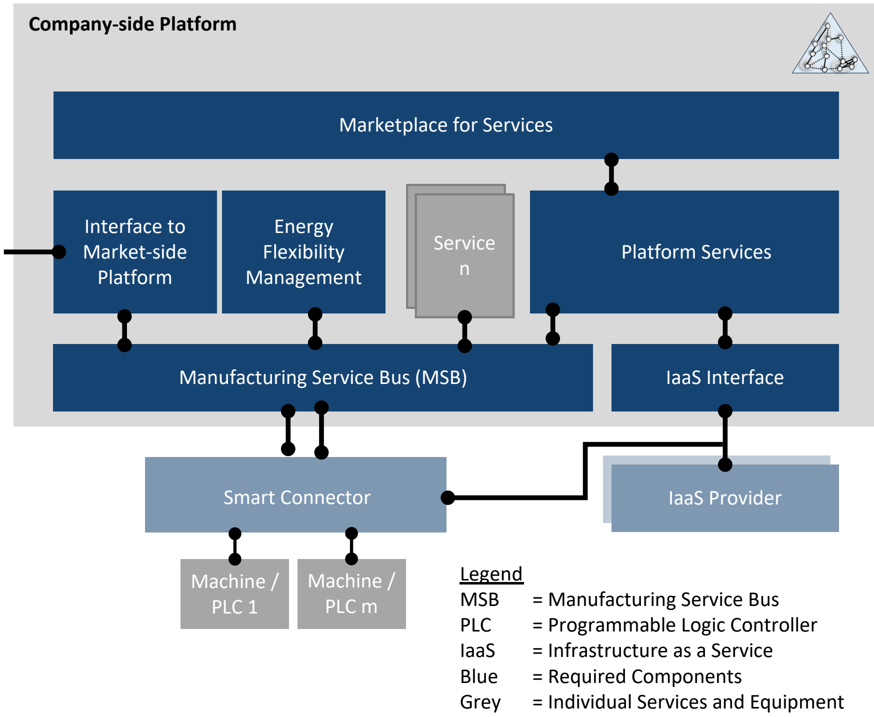

Figure 3. Architecture of the company-side platform.

Most important for ensuring the interoperability and preventing a vendor lock-in is the open, extensible, and modular architecture of the platform itself together with the integration layer MSB. First, the modularity of the platform allows a flexible configuration, including only necessary components (blue in Figure 3), as well as the possible enhancement by individual additional components and services (gray in Figure 3). The development of these additional services is fostered within the ESP's ecosystem through close cooperation between manufacturing companies and software vendors. Second, each component of the platform can be deployed by different operators. This enables deployment models ranging from operating the CoP as a private instance on-premise to a public cloud operated by an independent third party, as well as multiple hybrid forms. Additionally, the deployment model is not set for all times, but can be adjusted at any time in the event of changed boundary conditions, by exchanging or adding individual modules instead of exchanging the entire platform. Companies are able to use a wide range of existing services suitable for their platform without their own extra development effort and often also without a considerable integration effort.

The previously-described modular, service-oriented approach and the consideration of energy as a target variable runs through all components of the platform:

- Marketplace for services: The marketplace for services is comparable to the well-known concept of app stores and represents the web-based point of entry for users. It enables obtaining new services and deploying them automatically in conjunction with the platform services. Due to the simple booking of services on demand, entry hurdles for new participants are reduced. Offering a wide range of services from different independent services vendors, the marketplace ensures free competition.

- Services: In contrast to existing approaches, which do not consider energy as a decisive target for manufacturing [79,80], additional services on the CoP, such as manufacturing planning and control or various optimization services, are designed taking it into account. A typical approach with respect to logistic operating curves in manufacturing planning and control was described in [81]. Since these additional services are highly individual and vary greatly between use cases, they are flexibly orchestrated using the MSB and integrated into the handling of demand flexibility by the energy flexibility management. As complementors can flexibly contribute their services, the ecosystem is able to profit from co-evolution. In addition, the central role of the complementors prevents from winner-takes-all situations (see Section 2.5).
- Platform services: The operational functions of the CoP are summarized in platform services. Among them are identity and permission management, service repository, service life cycle management, as well as service accounting and service monitoring. Platform services are well described in the literature, e.g., in [62,82].
- Interface to the market-side platform: The interface to the market-side platform enables services on the CoP to access data and services on the MaP via a single standardized interface. Services on the CoP benefit from this by only having to implement a single interface instead of multiple interfaces to all requested services on the MaP. Furthermore, this represents a security barrier between companies and energy markets.
- Energy flexibility management: The CoP's hub for aggregating and managing all demand flexibilities and their dependencies is represented by the energy flexibility management. First, it includes an overview of the company's flexibility. Second, it supports the technical assessment of flexibility. Third, the energy flexibility management provides an API to combine, split, and adapt flexibility for optimized usage. However, the optimization is not part of the energy flexibility management and is provided by third party services instead. Furthermore, the energy flexibility management is responsible for controlling the implementation of demand flexibility measures and communication with energy markets. Most likely, the functionality of the energy flexibility management will be integrated or at least closely connected to a company's EMS.
- Manufacturing service bus: An integration layer for manufacturing companies needs to ease reconfiguration, enable a loose coupling, allow for asynchronous communication, and offer standards-based integration [83]. The MSB meets these requirements, as well as additional ones as described in [84]. It provides an abstraction layer for different protocols, which can easily be extended by additional interfaces. The purpose of this abstraction layer is to harmonize data models by allowing individual data objects to be mapped flexibly to each other. This mapping can either be modeled automatically via a self-description or manually. Furthermore, the easy extensibility enables effortless additions of protocols, which can either be proprietary or open. Consequently, the MSB can also be used to translate proprietary protocols (e.g., Siemens S7) to open protocols (e.g., OPC-UA). Summarizing, the MSB ensures interoperability between all components of the CoP in the sense of a close cooperation of independent, heterogeneous systems in order to exchange information efficiently and in a usable manner.
- Smart connector: The smart connector is designed as a bidirectional interface to access machines and their respective PLCs from higher-level IT systems. Therefore, it extends the MSB by translating proprietary PLC protocols to open IT protocols and allows for process data and machine data acquisition. Additionally, the smart connector's machine interface is designed to process energy data and to transfer it to the generic EFDM to model demand flexibility. Moreover, orchestrated by services on the CoP, the smart connector is also capable of an energy-synchronized control of the process, e.g., triggered by price signals.
- IaaS interface: The IaaS interface represents an abstraction layer between the CoP and its underlying infrastructure. It enables the CoP to distribute the deployment of services,

ranging from in-house infrastructure to external cloud infrastructure such as Amazon Web Services and edge devices such as the smart connector.

If a service, e.g., the energy flexibility management, is ordered via the marketplace for services, its deployment and provisioning on an IaaS provider, as well as its orchestration with other services via the MSB are done by the platform services. Furthermore, process data from machines are integrated using the smart connector. Therefore, with the architecture described above, it is possible to automate all activities regarding energy flexibility marketing on the company side by virtualizing flexibility and distributing it via services.

5.2. Market-Side Platform

The MaP represents the second main part of the ESP. In contrast to the CoP, it is designed as a single multi-sided platform solution, connecting and integrating a variety of CoP, existing energy markets (e.g., balancing power market, electricity exchange), and third-party services (e.g., optimization and forecast services, software providers, energy supplier, aggregators). The MaP, which was co-designed by the participating companies, fosters the monetization of industrial flexibility on power markets in a B2B market setting.

The MaP is connected to the CoP via an interface that allows data exchange and should enable automated trading of flexibility in the future. In contrast to the CoP and services, which in principle can occur in an unlimited number on the ESP, only one logical instance of the MaP is provided. Its multi-sided architecture enables direct interactions between two or more distinct sides. Each side is affiliated with the platform [85]. The platform itself consist of various components, such as hardware, software, or service modules with specific arrangements and rules. Figure 4 shows the modular and flexible configuration, featuring two main layers and their respective components.

- Runtime layer: This represents the active component of the MaP, which has the necessary interfaces to the outside. On the one hand, the runtime layer is the basis for system-related and domain-specific services; on the other hand, it also implements the routing to the corresponding services and data.
- Persistence layer: The persistence layer acts as a scalable data management component and allows writing and reading access from the runtime layer. It represents the passive "database" component of the MaP.

Within the layers in Figure 4, components define the functionality of the MaP. The key components are highlighted and explained in the following:

- Portal (access layer): The portal represents the component, which allows users to communicate with the platform through a graphical user interface. Besides basic features, such as registration and login, it provides an input mask for information transfer to other components, API documentation, the possibility to execute test calls, community functionalities (e.g., rating), and the monitoring of offered services. It is connected to the platform services for access management and authentication, as well as the service broker for further access to functionalities.
- Service broker: The service broker acts as a central access point for market participants implementing the API gateway, makes inquiries to registries, and forwards the request of the current market participant according to the response from the registries. The core task of the service broker is to establish contact between flexibility providers and their users by integrating supporting services. As the core of the multi-sided architecture, it is also exposed to threats and requires threat protection against cyber attacks, such as distributed denial of service attacks, SQL injections, etc. Moreover, it is the logical instance that regulates access control policies and enforces policies related to subscriber authentication and authorization of access to services. Thus, the service broker uses services of operational components from platform services.

- Platform services: The operational functions of the MaP are summarized in platform services. They inherit control and contract services, in order to monitor and maintain the platform, but also oversee the access management, which regulates access to sensitive data according to the respective authorization. In order to monitor the access authorizations, the platform services access the system data containing the log, user, and contract data, market services, the service broker, and the access layer.
- Market services: These are the services offered on the MaP by third parties and allow service providers and platform users to analyze what features have been used and what registered users are looking for. It is important to note that market services are only addressed from the service broker. The connection to platform services is for authentication reasons only. Market service-related data are stored within the component service data. This comprises among others the storage of flexibility data in the form of a filterable list, e.g., in the form "market participant X has offered flexibility Y of quantity Z [for time interval T]".
- Customer services: In order to provide an interface to the external services or datasets offered by market participants, but not directly published on the market platform, the customer services complement the service broker by a collection of virtual services that bijectively map to these external services. In this way, the service broker can address the virtual services and datasets and thus communicate with the external ones. It has a connection to custom data and a database to store the required information.

The architecture embraces standardized communication between all user groups, standard data models for the distinct communication of flexibility such as the EFDM, as well as guidelines, which enable an open-integration hub, similar to the CoP. The MaP is not only compatible with the existing power system, integrating APIs with the electricity exchange and the balancing power markets, but also implements solutions for the local marketing of demand (building upon concepts of USEF) in so-called local flexibility markets. The local aspect is especially interesting for system operators, which can utilize the flexibility for grid applications.

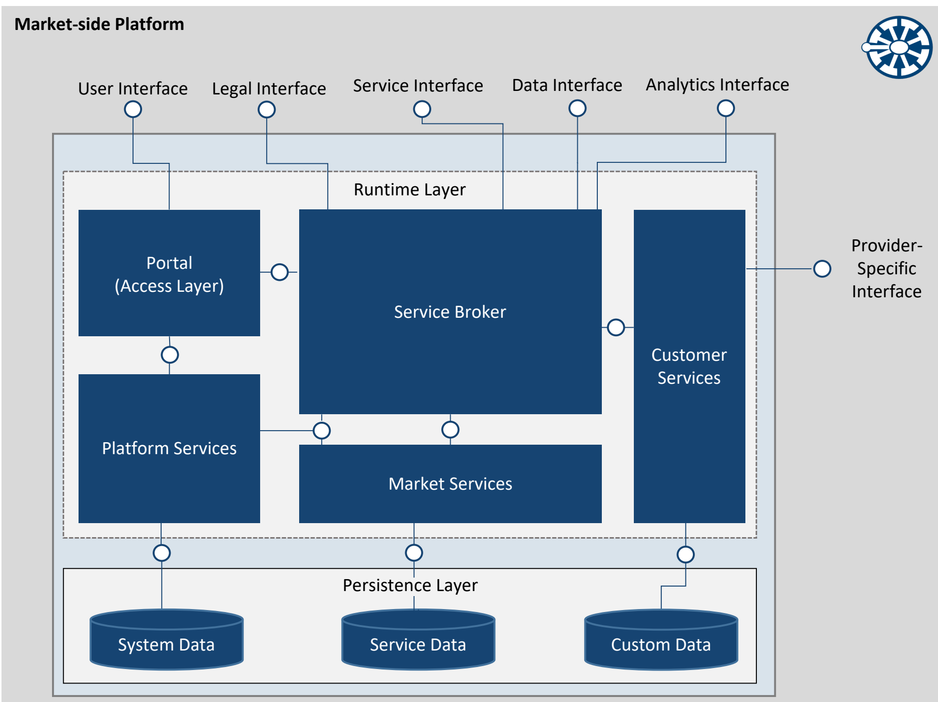

Figure 4. Architecture of the Market-side Platform.

The modular design of the MaP enables a wide range of possibilities and a flexible and company–individual extension of the interaction with regard to the degree to which the company wants to interact with the MaP. While some companies with greater flexibility potential will access several markets simultaneously and without an intermediary agent, other companies just need service providers, such as optimization or forecast services. The low entry hurdles are important to provide non-discriminatory access to all actors in the ecosystem and to foster the acceptance and reduce the threshold for participation. The MaP could be perceived as an app store, in which services can be tried on a low- or non-binding agreement level, aiming to promote excellent services through competition. The MaP not only increases transparency in the complex landscape of the power ecosystem, it also lowers the market entrance barrier for industrial power flexibility providers, while also considering (and maintaining) the regulatory framework, as well as the physical requirements.

5.3. Synthesis to an End-to-End Approach

The ESP is designed as an integrated concept including data, information, and energy flows between machines and energy markets (see Figure 5). At a technical level, the electricity flows from power plants via the system operator's public grid to the power consumers, e.g., manufacturing machines. The information flow at an organizational level is entirely managed by the ESP. The company–individual CoP offers extensive functionalities to control the power consumers and aggregate their energy flexibility potential. Due to the standardized interface between MaP and CoP, companies can easily commercialize their energy flexibility via an aggregator or services on the MaP. Here, the service broker is the central connector between energy markets and manufacturing companies. Thus, vendor lock-in is avoided because companies can easily replace aggregators or apply new services, and free competition is ensured. Beside direct trading on the energy markets, the usage of flexibility lists to reduce local grid congestion and infrastructure investments, as well as the application of optimization tools and forecast services is also possible.

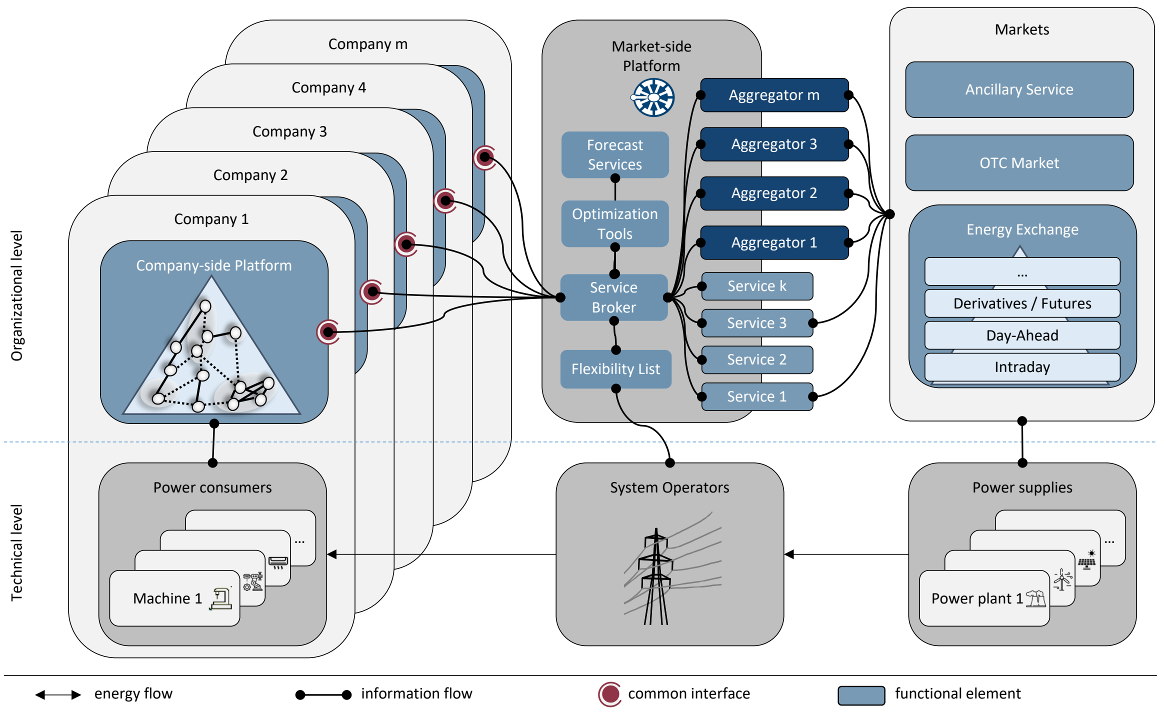

Figure 5. End-to-end approach of the energy synchronization platform integrating IT platforms, services, aggregators, and energy markets.

With respect to the end-to-end approach, processes on both MaP and CoP have been identified and modeled using BPMN. Subsequently, it was possible to design a process map for the ESP (see Figure 6). The process map ranges from the need for flexibility (customer requirements) to the reliable delivery of flexibility (customer satisfaction) and, therefore, matches the goal of the ESP as described in Section 5. Within this process map, processes are divided into comprehensive processes that affect the whole ESP and those that affect only one sub-platform. Besides this classification is based on the affected platform, processes are clustered into core processes, support processes, and management processes [86,87]. Core processes are the processes creating value for the customer, on the ESP ranging from the assessment of flexibility to its delivery and, therefore, fulfill the purpose of the ESP by synchronizing demand and offer of flexibility. It is important to note, that the core process is a cross-platform process. Hence, the successful interplay of MaP and CoP is crucial for achieving the purpose of the ESP. Support processes are necessary to ensure the successful interplay. In Figure 6, three different levels of support process are distinguished. Firstly, overlapping support processes are mainly focused on the cross-platform communication and optimization between the platforms and to third parties. Secondly, MaP and CoP support processes comprise processes that are platform-specific and do not interact with other platforms, e.g., internal management of flexibility data or user authentication. Possibly, the support processes of the ESP constitute the operations with regard to servicing tasks such as IT-management, controlling, accounting, as well as customer relationship management, but also initial processes such as company on-boarding to the ESP. The ESP community is a complementary service, in which ESP participants can exchange best practice and knowledge. Management processes set the framework for core and support processes by deciding a strategy, establishing development processes, ensuring reliable quality management, and providing a financial scope of the ESP.

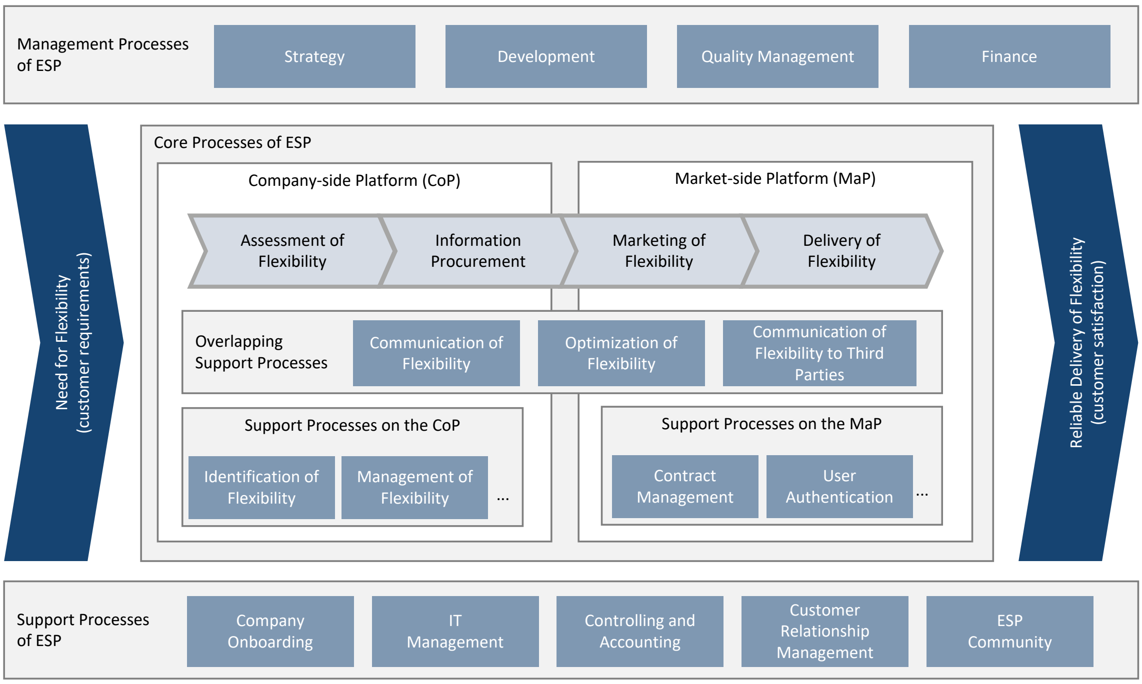

Figure 6. Process map of the energy synchronization platform.

There is much communication within and between the processes. Due to the complex nature of industrial manufacturing, a multi-level optimization is necessary to foster an effective and efficient use of demand flexibility. The resulting sequence is shown in Figure 7. The decomposition into multiple levels (Market-side optimizer, ERP optimizer, MES optimizer, Machine-side optimizer) allows for a specific optimization at each level of the automation pyramid, taking into account characteristics such as planning horizons, temporal resolutions, and maximum permissible runtimes.

Consequently, an optimization at the manufacturing planning level will target different energy markets rather than an optimization at the manufacturing control level. Long-term planning (weeks to months) on the ERP level corresponds to the time horizon of the derivatives market (see 1 in Figure 7). Optimization horizons of MES and machine-side optimizer compare to the one of day-ahead-market. Thus, the prices on the day-ahead-market are already known at noon of the previous day. Consequently, flexible adaption of production processes as a reaction to volatile prices based on this market is no longer necessary from this moment on (see 3 and 5 in Figure 7). The residual flexibility can be traded as reactive flexibility on balancing (control) power markets (see 6 in Figure 7). However, with this distributed approach, the integration of a wide range of optimization services in the described end-to-end approach becomes crucial. A solution considering all restrictions of previous optimization steps was described with detailed information flows in [56]. According to this approach, decisions on classic logistic, as well as energy goals can be made, and this with the necessary foresight. Optimization steps are chronologically ordered (marked by steps 1–7 in Figure 7), and strategic decisions, which are made at a higher level of the automation pyramid, are passed to the lower levels as given requirements. This enables an energy-oriented optimization on all levels of the automation pyramid without violating constraints defined at previous levels and, therefore, supports companies in marketing flexibility in the optimum possible markets.

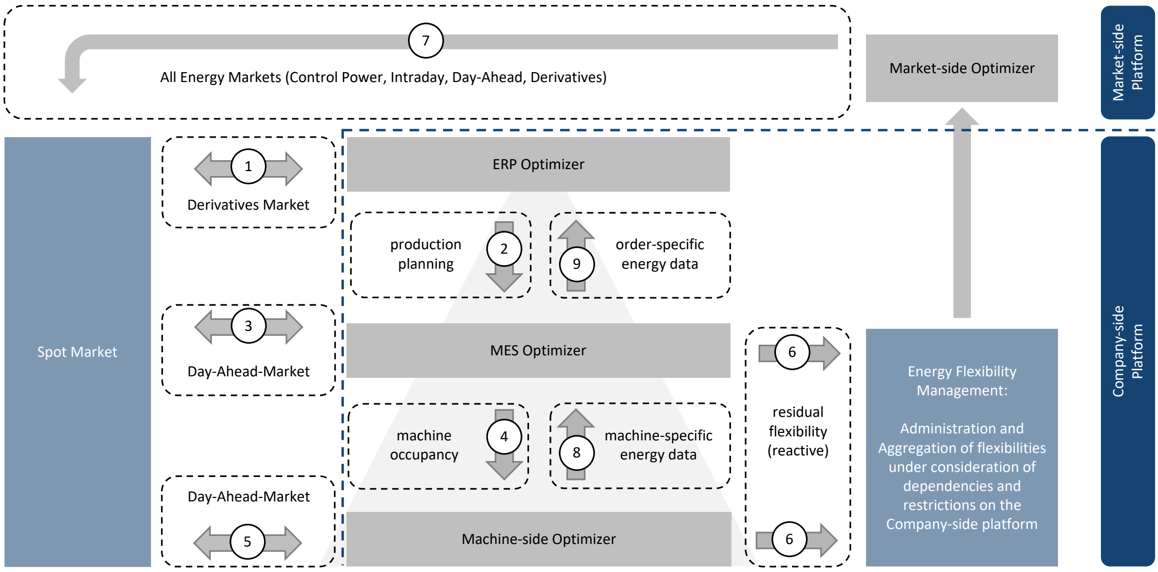

Figure 7. Approach for multi-level optimization on the ESP (adapted from [56].

6. Summary

Industrial DR shows high potential for adapting the energy demand to the increasingly fluctuating power generation of wind and solar power plants and presents an economic option to stabilize the power grid. However, the given state-of-the-art and elaborated specification analysis showed that there are currently some major deficiencies preventing manufacturing companies from participating in the energy markets. Therefore, this paper described an end-to-end approach that encompasses all necessary processes, from single machines to the energy markets, based on a platform ecosystem. Here, complementors can flexibly contribute services to other platform participants. Additionally, some fundamental services are already provided, e.g., energy flexibility management. The complex interaction of processes and services was modeled using BPMN.

The designed platform ecosystem of the ESP incorporated several advantages. First, it presented a single, continuous solution to connect machines to energy markets including all functionalities such as management, optimization, and marketing of flexibility. Second, as complementors can contribute services, co-evolution and co-creation were ensured. Consequently, comprehensive and innovative functionalities can be offered. Third, due to the architecture of the ESP and the interoperability of its components and services, companies were prevented from vendor lock-in effects, and free competition between different complementors on the ESP was ensured. In a strictly regulated market such as the energy system, this is an innovative approach that has not yet been attempted. Fourth, entry hurdles for new participants were minimized by the modularity of the platform and the different deployment models of the CoP, which were well-suited to companies of all sizes. This enabled an increased provision of flexibility. Fifth, considering security aspects in the design and operation of the ecosystem was proven as a key factor for its acceptance by companies.

Therefore, the ESP's ecosystem allows industry to automate DR with a reduced effort. Consequently, this study delivered an important contribution to the successful realization of the German and global transition of power grids and the increasing integration of fluctuating renewable energies.

7. Outlook and Remaining Deficit

As summarized in Section 6, the identified research deficits were all addressed in this paper. However, there are still some weaknesses in the developed ESP ecosystem in its current state, which are currently being investigated by the authors and will be addressed in future studies:

- Governance: The concept of governance for the invented platform ecosystem is one of the most significant remaining deficits. The governance approach should be mainly based on two elements, introducing standards and a community. To enable external access and contributions, a strict standardization of all processes, services, interfaces, data models, and communication flows is necessary. The BPMN documentation presents a first step. Nevertheless, this needs to be further developed by standardizing a reference architecture. In addition, the ecosystem requires a platform carrier to coordinate future extensions, maintenance, regulation, and safeguard ongoing operations. Since the literature indicates self-selection as the most effective approach for platform ecosystems, a central task is to build a broad community, where all participants and complementors of the platform can participate.
- Additional services: The implementation and marketing of energy flexibility in manufacturing companies are complex. Therefore, the existing services on CoP and MaP are not yet all-encompassing and cannot fulfill all requirements in every use case. Consequently, some further extensions and additional services need to be implemented, e.g., for advanced price and signal predictions, aggregation of flexibility measures, hierarchical optimization at the different operational levels, evaluation costs for energy flexibility at the manufacturing level, risk assessment of flexibility measures, etc.
- Information procurement: While the existing energy flexibility management based on the EFDM is very well suited to the applications of assessing and marketing flexibility, there is a gap with respect to information procurement, e.g., market price predictions. Therefore, an approach for flexibly connecting services on the CoP with MaP has to be developed. The challenge is to make it possible to use more than a single data model such as the one described for flexibility measures, but rather a wide range of data models must be translated without affecting the operation of the existing components.
- Security: Security by design has been the main way of integrating security aspects so far. In future research, a detailed security analysis needs to be conducted in which feared events are identified and relevant counter measures derived. In addition, standardized security requirements for any kind of interface and service need to be defined. Thus, security aspects were mainly incorporated for the encapsulation of companies and energy markets. A serious threat, however, is the deliberate disruption of the energy system through manipulation of the energy markets via the ESP. As part of a critical infrastructure [75], this aspect must, therefore, also be taken into account when extending the security concept.

- Credibility and trustworthiness: The elaborated architecture and information flow guarantee high standards of credibility and trustworthiness. However, in the recent past, there has been an increase of new distributed ledger-based technologies (e.g., block chain), which show promising results in this field. Their application should be examined and implemented to further enhance the capability of the solution.

In addition, it is essential to further apply the elaborated architecture with its components and services in a wide range of industrial usage cases. This will provide several insights into how the concept can be further developed for wider industrial applicability. Subsequently, the ESP must be prepared for roll-out and scale-up to provide significant energy flexibility potential.

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Abbreviations

The following abbreviations are used in this manuscript:

API	Application Programming Interface
BPMN	Business Process Model and Notation
CoP	Company-side Platform
DR	Demand-Side Response
DSM	Demand-Side Management
EFDM	Energy Flexibility Data Model
EMS	Energy Management Systems
ERP	Enterprise Resource Planning
ESP	Energy Synchronization Platform
IaaS	Infrastructure as a Service
IT	Information Technology
MaP	Market-side Platform
MES	Manufacturing Execution System
MSB	Manufacturing Service Bus
OPC-UA	Open Platform Communications Unified Architecture
OpenADR	Open Automated Demand Response
OTC	Over The Counter
PLC	Programmable Logic Controllers
REST	Representational State Transfer
USEF	Universal Smart Energy Framework
XaaS	Everything as a Service

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