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Decentralized Smart Market Design

Identification and Evaluation of Design Alternatives within a Local Flexibility Market by Application of Blockchain Technology

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Abstract

A Smart Market Platform (SMP), as introduced in this thesis, provides the basic infrastructure for market-based allocation of grid-supportive flexibility. Besides the existing concept of a Local Flexibility Market (LFM), the SMP extends the functionalities by introducing additional functions. With the intention to efficiently integrate renewable energies in the distribution grid, it provides the possibility to access (small-scale) flexible assets to be used in the congestion management process of the distribution system operator.

Relevant but still untapped flexibility potential is already available, especially in the lower voltage levels. Nevertheless, the variety of plant types and their granularity demand a high degree of automation, standardized access, and aggregation. Platform-based solutions are able to provide these features to both sides, providers and demanders of flexibility. Blockchain (BC) as the emerging distributed ledger technology offers a basic technical infrastructure. Therefore, a potential added value through the application of BC technology is analyzed based on different decentralized implementation options.

Requirement specifications form the basis for the intended SMP development and result from market, participants', technology, and energy-economic or regulatory demands. Different SMP functions are then developed and tested. *Aggregation* and pool formation provide an integration mechanism for small decentralized flexibilities based on statistical simultaneity factors. *Market Monitoring* is introduced through dynamic evaluation of the market structure and identification of potential market power based on key metrics. *Matching* as the core function provides an efficient allocation method between flexibility offer and demand based on constrained optimization. To prove the functionality of the proposed implementations, the platform is modeled and simulated using realistic input data derived from a field test and applied in four scenarios. Decentralized operation through the regional application is already system-inherent to an SMP. A complementary dimension of decentralization is the distributed technical implementation using BC technology. Therefore, different BC-based implementation approaches are analyzed and implemented in a proof-of-concept state. *Distributed Data Management and Storage* sets the basis for identification and user administration, self sovereign identity management, and trusted data provision. *Proof of Data Integrity* offers a verification platform that provides transparent state documentation using Merkle-proofs. *Proof of Data Properties through Verifiable Computation Techniques* can finally realize a decentralized market process including complex computations like distributed optimization. Besides the advantage of a trusted common infrastructure that allows verifiable and tamper-resistant transparency, particular challenges are identified for BC-based large-scale adoption, i.e., regarding scalability or privacy issues. New technological developments already promise solutions to these aspects but significantly increase complexity at the current state of development.

Finally, an evaluation of the proposed implementation and architecture options is carried out regarding their degree of decentralization, including the application of a developed system cartography framework.

Zusammenfassung

Eine Smart Market Platform (SMP), wie sie in dieser Arbeit vorgestellt wird, stellt die grundlegende Infrastruktur für eine marktbasierte Allokation von netzdienlicher Flexibilität bereit. Mit der Einführung zusätzlicher Funktionen erweitert die SMP das bestehende Konzept lokaler Flexibilitätsmärkte (LFM). Durch den möglichen Zugriff auf (kleine) flexible Anlagen und deren Einsatz im Engpassmanagementprozess des Verteilnetzbetreibers wird die Grundlage für eine effiziente Netzintegration erneuerbarer Energien geschaffen.

Relevante, aber noch ungenutzte Flexibilitätspotenziale sind bereits vorhanden, insbesondere in den unteren Spannungsebenen. Die Kleinteiligkeit und Diversität der Anlagentypen erfordern allerdings einen hohen Grad an Automatisierung, standardisierten Zugriff und Aggregation. Plattformbasierte Lösungen sind in der Lage, diese Eigenschaften für beide Seiten – Anbieter und Nachfrager von Flexibilität – bereitzustellen. Die Blockchain (BC) als prominentester Vertreter der Distributed-Ledger-Technologie verspricht potenzielle Mehrwerte bei der Bereitstellung der grundlegenden Infrastruktur. Ein möglicher Einsatz der BC-Technologie wird anhand verschiedener dezentraler Implementierungsmöglichkeiten analysiert.

Die angestrebte SMP-Entwicklung erfolgt auf Grundlage von Anforderungsspezifikationen. Diese ergeben sich aus den Bedürfnissen verschiedener Standpunkte und beinhalten neben Faktoren wie Markt, Teilnehmer und Technologie auch energiewirtschaftliche und regulatorische Anforderungen. In diesem Kontext werden die verschiedenen SMP-Funktionen entwickelt und getestet. *Aggregation* und Poolbildung bieten einen Integrationsmechanismus für kleinteilige dezentrale Flexibilitäten auf Basis statistischer Gleichzeitigkeitsfaktoren. Das *Market Monitoring* ist in der Lage, aufgrund dynamischer Bewertung der Marktstruktur strukturelle Marktmacht zu identifizieren und anhand von Schlüsselkennzahlen zu bewerten. *Matching* als zentrale Kernfunktion bietet eine effiziente Allokationsmethode zwischen Flexibilitätsangebot und -nachfrage auf Basis einer restringierten Optimierung. Um die Funktionalität der vorgeschlagenen Implementierungen zu prüfen, wird die Plattform anhand realistischer Eingangsdaten aus einem Feldtest in vier Szenarien modelliert und simuliert.

Der Betrieb der SMP ist durch den regionalen Anwendungsbereich bereits systemimmanent dezentral organisiert. Eine ergänzende Dimension der Dezentralisierung stellt die verteilte technische Umsetzung mittels BC-Technologie dar. Deshalb werden verschiedene BC-basierte Implementierungsansätze analysiert und prototypisch umgesetzt. *Verteilte Datenverwaltung und -speicherung* bilden die Grundlage für dezentrale Benutzerverwaltung, selbstbestimmtes Identitätsmanagement und vertrauenswürdige Datenbereitstellung. Durch den *Nachweis der Datenintegrität* mittels Merkle-Proofs wird eine Verifikationsmöglichkeit zur transparenten Zustandsdokumentation eingeführt. Mittels *Nachweis von Dateneigenschaften durch überprüfbare Datenverarbeitung* kann schließlich ein dezentraler Marktprozess, inklusive komplexer Berechnungen wie der verteilten Optimierung, realisiert werden. Neben dem Vorteil einer vertrauenswürdigen gemeinsamen Infrastruktur, die Transparenz durch Überprüfbarkeit und Fälschungssicherheit schafft, werden besondere Herausforderungen für eine BC-basierte großflächige Einführung identifiziert, z.B. in Bezug auf Skalierbarkeit oder hinsichtlich des Datenschutzes. Neue technologische Entwicklungen versprechen hierfür bereits Lösungsansätze, erhöhen aber zum derzeitigen Entwicklungsstand die Komplexität erheblich.

Abschließend wird eine Bewertung der vorgeschlagenen Implementierungs- und Architekturoptionen hinsichtlich ihres Dezentralisierungsgrades vorgenommen. Dies beinhaltet u.a. den Einsatz eines eigens dafür entwickelten Systemkartographie-Ansatzes. Die vergleichende Analyse mündet in Empfehlungen für eine zukünftige Implementierung und fasst die Chancen und identifizierten Herausforderungen zusammen.

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Acronyms

ANO	Access Network Operator
AP	Evaluation Scenario “Autonomous Prosumer”
BC	Blockchain
BNetzA	Bundesnetzagentur
BSI	Bundesamt für Sicherheit in der Informationstechnik
CA	Certification Authority
CHP	Combined Heat and Power
CM	Congestion Management
CR	Concentration Ratio
DER	Distributed Energy Resources
DG	Distribution Grid
DID	Decentralized Identifier
DLT	Distributed Ledger Technology
DSO	Distribution System Operator
EC	Evaluation Scenario “Electrified Consumer”
EHV	Extra High-Voltage
ESH	Electric Storage Heating
EV	Electric Vehicle
FO	Flexibility Option
GDPR	General Data Protection Regulation
HHI	Herfindahl-Hirschman Index
HP	Heat Pump
HSS	Home Storage System
HV	High-Voltage
iMSys	Intelligent Measuring Systems
IOC	Incentive-driven Off-chain Computation
IPFS	InterPlanetary File System

LFM	Local Flexibility Market
LoS	Level of Security
LV	Low-Voltage
mME	Modern Measuring Equipment
MPC	Multi-Party Computation
MV	Medium-Voltage
P2P	Peer-to-Peer
PKI	Public-Key Infrastructure
PM	Evaluation Scenario “Market-oriented Prosumer”
PoA	Proof of Authority
PoS	Proof of Stake
PoW	Proof of Work
PtH	Power-to-Heat
PV	Photovoltaics
RA	Registration Authority
RE	Renewable Energy
RSI	Residual Supply Index
SG	Smart Grid
SGX	Software Guard Extensions
SMGW	Smart Meter Gateway
SMP	Smart Market Platform
SP	Evaluation Scenario “Solar Producer”
SSI	Self Sovereign Identity
TEE	Trusted Exection Environment
TG	Transmission Grid
TSO	Transmission System Operator
VC	Verifiable Computation
ZKP	Zero Knowledge Proof

1 Introduction

A successful energy transition sets the central goal for overcoming climate change. The ongoing expansion of decentralized renewable energies and the integration of new, distributed loads such as power-to-heat technologies or electric vehicles pose a major challenge, especially for the distribution grid through emerging bottlenecks. On the other hand, the rising number of these decentralized systems that can be controlled digitally and operated flexibly also provide a solution to these challenges. One approach to addressing this challenge is the implementation of market- and platform-based approaches for an efficient evolution of the current Congestion Management (CM) processes. Based on the following motivation in Sec. 1.1 and a recap of current state of science and research in Sec. 1.2, the objectives and derived research questions of this thesis are presented in Sec. 1.3.

1.1 Motivation

The energy system is undergoing fundamental change, determined by the four factors decarbonization, decentralization, digitalization and democratization (the 4 D's), as identified by several sources[1] [18, 19, 20, 21]. As these drivers represent key development trends in the energy sector for the envisioned step towards a sustainable energy future, they create both new opportunities and challenges, as described in the following.

Decarbonization The extensive emission of greenhouse gases will lead to anthropogenic climate change and finally significant global warming [22]. This fact is impressively validated by numerous research and regularly presented in recent reports of the United Nations' Intergovernmental Panel on Climate Change (IPCC) (see, e.g., [23]). Decarbonization, therefore, indicates the aim of reducing carbon emissions as the main impact factor to climate change in the industrialized world by increasing energy efficiency and the substitution of fossil fuels through renewable and, therefore, carbon-neutral energy sources. A major step to this goal was set in 2015 at the COP21 UN Climate Change Conference in Paris where an international and universal agreement on climate change mitigation was achieved. With the aim to "limit global warming to well below 2 °C, preferably to 1.5 °C, compared to pre-industrial levels" [24], it was adopted by 196 parties as a legally binding international treaty [25].

Within the European Union, the "European Green Deal" [26]—as an update to the "2030 climate & energy framework" [27]—defines a greenhouse gas emission reduction

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[1] In some references, democratization is neglected (3 D's) or substituted/extended by "decreased use" [18] or "deregulation" [19].

goal by at least 55% by 2030, compared to 1990 levels and to finally reach climate neutrality by 2050. Germany even tightened its goals to green house gas neutrality by 2045, with the recent amendment to its Climate Change Act [28]. It further laid out its path to climate neutrality (-65% CO_2-eq. by 2030, -88% CO_2-eq. by 2040), after a ruling of the Federal Constitutional Court in March 2021 [29].

The "German Energiewende" reflects the related trend to reach a sustainable energy future based on renewable energies. With the Renewable Energy Sources Act (EEG) introduced in 2000, the large-scale expansion of renewable energy plants kicked off as economic incentives were introduced. Based on the German government's energy concept for an "environmentally friendly, reliable, and affordable energy supply" [30], on the one hand, the recent decade was characterized by the ongoing increase in the share of renewables [31, p. 51-53], the nuclear phase-out [32] combined with necessary electricity grid expansion programs, e.g., within the "Netzausbaubeschleunigungsgesetz (NABEG)" [33]. On the other hand, there has been intense political discussions regarding optimal pathways for the energy system's decarbonization, including fossil phase-out (see [34]), the optimized management of Distributed Energy Resources (DER) [35], and the role of digitalization [36].

Decentralization In the energy sector, decentralization is one of the dominant development trends directly related to the energy transition. The constant addition of small-scale generation plants and the integration of new electrical loads make the energy system increasingly granular and thus more complex. Also, energy management tools develop towards a more cellular organization with autonomous levels of aggregation and optimization [37, pp. 30-33]. These aspects also come into consideration for the design of energy data management processes, built on decentralized, digital metering infrastructure.

In contrast to the energy system, in information technology, an opposite development towards more centralization has prevailed in the last decade. Cloud computing relies on concentrating computing capacity to process large amounts of data in a centralized infrastructure to enable economies of scale. Only in recent years, a reverse trend can be observed, back to decentralized or distributed structures, driven by discussions about data protection, resilience, data integrity, and data sovereignty.

For clarification, a distinction between centralized, decentralized, and distributed (network) structures is essential. In a centralized system, a central authority or intermediary is necessary to coordinate interactions between network participants. In a decentralized setup, this central instance is substituted. As certain hierarchical levels still exist (cf. electricity grids), direct interaction between the participants is not yet possible in every case. In a distributed system, all network participants are basically equal. A hierarchy does not prevail (cf. Peer-to-Peer (P2P) networks). [4] Nevertheless, as distributed systems describe a specific form of decentralization, the two terms are often used synonymously.[2] Recent concepts of distributed (energy) coordination systems are often linked to the developments in Blockchain (BC) technology as the most prominent representative

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[2] Within this thesis, the term *decentralization* intends to include a distributed system setup.

of Distributed Ledger Technology (DLT). Its value proposition includes the provision of a base infrastructure that enables transparent and tamper-resistant coordination schemes involving a large number of independent actors. Nevertheless, a direct inherent value in decentralization can not be defined per se. In consequence, only a distinct evaluation of specific advantages and disadvantages related to the addressed use case can provide these insights.

Digit(al)ization Digitalization can be the enabler for new functions (e.g., data analyses or efficient control of technical units), but always relies on appropriate digital infrastructure [38, p. 2]. In the energy sector, the introduction of smart metering holds the potential of providing a standardized, secured, and reliable backbone to innovative use cases. Energy transition needs digitalization to efficiently orchestrate an increasingly complex and dynamic energy system [39]. On the other hand, digital energy use cases also provide new business models.

Although often used synonymously, the English language provides two different terms addressing the digital transformation: *digitalization* and *digitization*. By definition, digitization refers to “the process of changing from analog to digital form (...) without any different-in-kind changes to the process itself” [40] in contrast to digitalization as the “the use of digital technologies to change a business model and provide new revenue and value-producing opportunities; it is the process of moving to a digital business” [41]. Within this thesis, only the latter term is considered as digital process development needs to prove added value.

In 1987, Robert M. Solow, Nobel laureate in economic sciences, stated: “You can see the computer age everywhere but in the productivity statistics.” [42]. This popular quote describes the phenomenon that potentially expected productivity increase is hardly to be directly tracked down as a result of the introduction of computer technology. It finally became known as the “Solow Paradox”. Although the paradox partly resolved one decade later through a renewed productivity growth in the developed world, it showed that improved processes and therefore expected efficiency benefits through the application of information technology requires a certain time to take effect. A McKinsey study from 2018 picked up the described phenomenon and announced a “round two of the Solow Paradox” with regard to the ongoing digitalization process [43]. As a result, they projected a productivity growth of at least 2% p.a. for the 2020s, with approx. 60% resulting from digitalization [44]. Regarding the energy sector, a 20–30% profitability increase is estimated through the introduction of “smart meters and grids, digital productivity tools for employees, and automation of back-office processes”, whereas “investments in digital technologies are still subscale” [43].

Besides the undeniable potential advantages of digitalization, the (global) exchange of information also holds certain risks. Compromises regarding privacy demands, missing data sovereignty, and unwanted data usage are only few examples. This finally leads to a digitalization trilemma resulting from conflicting priorities between *informational self-determination* vs. *societal interest in data exploitation* vs. *economic interest in data exploitation* as described in [45].

Democratization The understanding that energy transition is only possible with engagement of all relevant parties leads to the need of an active stakeholder involvement on the one hand [46, 47]; on the other hand, the responsibilities are shifting from pure consumers or generators towards flexible prosumers [48]. In consequence, this must also have an impact on the definition of new roles and opening energy markets to these actors. The integration of new participants to the energy market is one dominant goal of European energy legislation and market design evolution, inter alia by introducing the concept of "active energy citizens" [49, (76)] and "energy communities" [50, (43)]. With the goal of active participation and diversity of actors the hitherto restrictive access to the energy market is to be opened up. The "Directive on common rules for the internal electricity market" requests the empowerment of consumers and the provision of tools to participate more in the energy market [50, Art. 10]. This also applies to the provision of flexibility services through demand-response and storage [51]. Integrating an increasing number of small-scale energy units and operators finally leads to more diversity, democratization, and reduced market dominance of existing major actors.

Besides the energy democratization, in information technology, also a democratization tendency can be observed. The intended empowerment of users is closely related with a demand for autonomy, data sovereignty, and privacy in an increasingly interconnected online world. Decentralization is one potential answer to this demand. Data minimization, e.g., as defined in *Art. 5 (c) General Data Protection Regulation (GDPR)*, provides another fundamental approach [52].

1.2 State of Science and Technology

Following these development trends, current research projects and technology achievements directly address the associated challenges and opportunities in the energy sector. The increased penetration of DER and new flexible assets, combined with digitalization advancements and new ways of individual involvement, must finally lead to an evolution of current system architectures and regulations. New concepts to integrate renewable energies into the energy system and avoiding grid bottlenecks are needed and can be reached by applying digital (platform) technologies, potentially combined with the value proposition of new technologies like DLT and BC.

Dealing with the fundamental change of the energy system's structure is the prevailing field of application-oriented energy research. The intelligent management of the electricity grid is a key task. Several recent projects work on grid optimization (e.g., [53]), the use of grid-supportive flexibility (e.g., through flexibility platforms [6]) or fathom the chances of blockchain technology (e.g., in P2P energy trading with active network management [54]).

1.2.1 Energy Transition and System Integration of Renewable Energies

The fundamental challenges in the energy system, in particular within the German electricity grid, are directly related to the change from a top-down supply to a more distributed, bottom-up organized, and interconnected ecosystem that needs to be orchestrated. The ongoing and future expansion of installed generation power and its shift from a fossil generation focus in the Transmission Grid (TG) towards renewable generation in the Distribution Grid (DG) are illustrated in Fig. 1.1 (left axis).[3]

As the current network layout is still designed towards a centralized system, the extensive application of congestion management measures is the result. Driven by fluctuating and eventually high simultaneity factors in renewable energy generation (although in a limited number of times during the year), curtailment of renewable power plants (feed-in management) and related costs are constantly rising within the last years. Fig. 1.1 (right axis) depicts the recent development of curtailed energy due to feed-in management, differentiated according to the grid level of its cause[4]. As an update for 2020, the total costs for grid and system safety measures amount to around €1.4 billion, with feed-in management contributing 54% of the compensations and 46% due to redispatch [66, pp. 147-148][5]. Especially, feed-in management costs significantly increased within the recent years, from €635 million in 2018, €710 million in 2019, and finally €761 million in 2020.

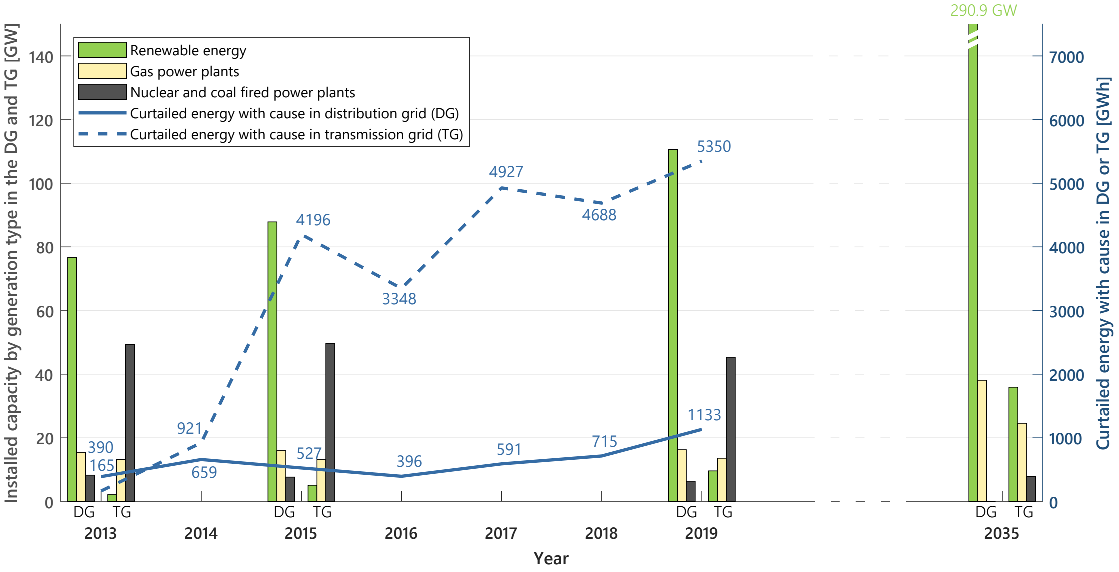

Figure 1.1: *Left axis:* Development of generation capacities and types in the DG and TG
Right axis: Development of curtailed energy with cause in DG or TG
(see references in footnote)

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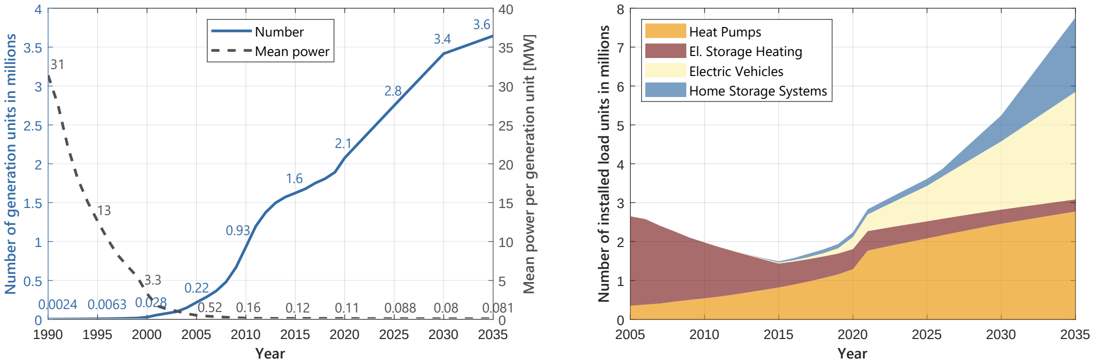
[3] References for generation capacities (Fig. 1.1, left axis): renewable energy in 2013, 2015, 2019: [55], conventional generation in 2013, 2015, 2019: [56], renewable energy 2035: [57, scenario "solidEU"] , share of installed capacity to grid level in 2035: [58, p. 1]

[4] References for curtailed energy (Fig. 1.1, right axis): 2013: [59, p. 80], 2014: [60, p. 110], 2015: [61, p. 106], 2016: [62, p. 117], 2017: [63, p. 144], 2018: [64, p. 159], 2019: [65, p. 152]

[5] 2020 expenses for redispatch: €221 million (16,561 GWh), countertrading: €134 million, grid reserve: €88 million for retrieval (635 GWh) plus €195 million for capacity reserve (6,596 MW), feed-in management: €761 million (6,146 GWh)

Besides the related compensation costs and the loss of energy, the coordination and control of the plants become increasingly complex. The challenge lies in the orchestration of the significantly increased number of small units that can be remotely controlled through digital technologies as illustrated in Fig. 1.2 (a)[6]. The pressure to the grid is further exacerbated through a large number of new electrical loads within the electricity system as depicted in Fig. 1.2 (b)[7]. Driven by new dynamic tariffs linked to wholesale market prices in a zonal electricity market, this eventually results in high simultaneity that potentially leads to local load-induced bottlenecks.



(a) Development of number and mean power of generation units (1990–2035)

(b) Development of number of different types of electrical loads (2005–2035)

Figure 1.2: Historical and projected development of generation and load units in Germany (see references in footnote)

Besides the named challenges, these small-scale energy units also bear the chance of contributing to a viable solution of efficient grid optimization based on flexibility. Network-supportive flexibility can be defined as the technical ability of a system to change (increase/decrease) its current and predicted power $[P, Q]$ based on an (external) signal to stabilize a potentially critical grid status [76, 77]. The grid status refers to current overloads or violation of the voltage limits. Frequency control is another application but shall be excluded in this context as it is part of the balance control within a European-wide network and therefore independent of delivery location [78]. In [10, p. 3], a literature overview of network-supportive use of flexibility is provided. The introduction of the "flexible prosumer" as a combination of an energy consumer and producer, providing flexibility by different means, underlines the increasing role of new stakeholders within the energy system [48]. Political initiatives further back these transformations.

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[6] References for development of generation structure (Fig. 1.2 (a)): renewables until 2020: [67] and future: [68, scenario NEP B]; conventional until 2021: [56] and future: [68, scenario NEP B]

[7] References for development of loads (Fig. 1.2 (b)): Heat Pump (HP) until 2020: [69] and future [70, scenario FUEL]; Electric Storage Heating (ESH) until 2020: [71] and future [70, scenario FUEL]; Electric Vehicle (EV) until 2020: [72] and future [73]; Home Storage System (HSS) until 2017: [74] and future [75]

Political and Regulatory Background The development towards a decentralized, electrified, and flexible energy system is driven by a political and regulatory framework setting the goals and strategies. First proposed in November 2016 and finally adopted in March 2019, the European Commission published its political framework “Clean Energy for all Europeans”, the so called “Clean Energy” or “Winter Package” [79]. Within the package, the EU Energy targets by 2030 are named with a minimum reduction of greenhouse gas emissions by 40%, a share of at least 32% renewables in energy consumption and more than 32.5% of energy efficiency increase. To achieve these targets, distinct measures are proposed to “ensure a clean and fair energy transition at all levels of the economy—from energy generation all the way to people’s homes, such as increasing renewable electricity and encouraging the use of smart meters.” [79, p. 1] Therefore, the goals of improving energy efficiency, expanding renewable energies, and shaping the EU as an “Energy Union” are described. Besides this, the expansion of consumers’ rights and participation opportunities are a key element of the strategy. Another key aspect lies in the promotion of a “smarter (, more flexible) and more efficient energy market” that is better suited for the integration of increasing amounts of intermittent renewable energy and flexible assets [79, p. 2, 8].

Integration Mechanisms for Flexibility in Future Grid Operation Defining high-level strategies only gives a basic framework. In order to achieve the postulated targets, solutions need to be developed on systemic, operational, and technical levels. Besides the further development of the energy system, e.g., through the expansion of the grid infrastructure, the existing systems and processes need to be adapted to the altered circumstances. The DER and flexible loads are a key to this adaption. Power adaption of flexible energy units provides a possibility for grid relief. While potential grid-supportive flexibility is available, appropriate mechanisms to tap this potential are still missing. As proposed flexibility exploitation concepts reach from, e.g., service or contraction models or flexibility quota models to intrinsic incentivization, market approaches receive the most attention. Besides intense discussion in research and the German energy industry, the European Commission explicitly promotes market based flexibility mechanisms such as a Local Flexibility Market (LFM). Consequently, different approaches are already available in a variety of ways [80]. Nevertheless, most of them are still in concept stage and lack a scientifically substantiated recommendation for implementation. Within this thesis, a detailed and evaluated proposal for the implementation of a Smart Market Platform (SMP) based on an LFM concept is presented and discussed.

1.2.2 Digitalized Energy System

In the last years, several relevant studies and government programs discussed the future of a digitalized energy system and new energy economic approaches. Ref. [81] describes a “digital real-time energy economy” as a target model for the future energy system. This includes the proposal of three main components: “open market access and a high degree of market integration”, “diversity of markets, market segments and system services” and “a high degree of market-driven business model innovation” [81, p. 8]. The application of digital platforms in energy use cases can set the foundation to these aspects. A digital basic infrastructure is inevitable to provide detailed information and (real-time) data of the energy infrastructure and assets. Furthermore, existing operational processes need to be adapted to meet these needs.

Smart Metering Infrastructure The need for increased automation and digitalization also results from the emerging complexity in the energy system combined with technical developments. Nevertheless, isolated digitalized systems will not provide the added value needed. Basic infrastructure to efficiently organize interactions of all relevant system components and actors is necessary. This aspect was also realized by political and regulatory bodies by the integration of smart metering infrastructure. The legal manifestation finally resulted in the German "Gesetz zur Digitalisierung der Energiewende" [36] based on the EU Internal Energy Market directive 2009/72/EG [82]. In consequence, these packages lead to the German smart meter roll-out. However, the implementation in Germany was significantly delayed and the roll-out of Intelligent Measuring Systems (iMSys) is still well behind statutory requirements. iMSys are smart meters consisting of an Modern Measuring Equipment (mME) and a Smart Meter Gateway (SMGW) [83]. On January 31, 2020 the positive market declaration by the Bundesamt für Sicherheit in der Informationstechnik (BSI) resulted in the "technical possibility to install smart metering systems according to § 30 MsbG" and finally the start of the roll-out [84]. Since then, the basic metering point operators are obliged to complete 10% of the mandatory installations (almost 4 million) within the following 3 years [83]. The installation of iMSys is divided into a mandatory and an optional roll-out. Mandatory roll-out applies to consumers with annual electricity consumption of more than 6,000 kWh or that make use of § 14a EnWG and renewable generation units—including Combined Heat and Power (CHP)—with an installed capacity of more than 7 kW. By 2032, at least 95% of mandatory metering points must be equipped with iMSys. [36] As already intended in the initial study that led to the decision for a selective roll-out, the combination with additional use cases is relevant for a positive cost-benefit evaluation [85, pp. 218-220]. Availability of detailed generation and consumption data enables a more specific attribution of properties and opens space to new applications. This can finally provide value to other market participants.

Optimization in (Future) Energy Market Environments Additional knowledge and specifications can lead to the potential enrichment of energy products for new market concepts. Leading the energy market away from pure commodity trading towards the consideration of further specifications enables several business opportunities. Finally, this development also evolves the mainly used merit-order approach of energy allocation in most existing energy markets (i.e., energy spot or balancing markets [86]) towards optimization-based market places. Fig. 1.3 gives a generic overview of functions and interactions in these market types, based on optimization as their central allocation logic.

There are already several examples of those optimization-based energy markets discussed and currently in development or in pilot phase, with the following examples being the most prominent representatives:

- *P2P energy markets* represent an idealized form of energy trading. Prosumers can procure and divert locally generated energy. Instead of a central entity managing the energy distribution, all participants trade their energy directly. [87, 88]. Within this use case, e.g., locality of energy generation and consumption is a property demanded by user preferences. The allocation of demand and supply, thus, describes an optimization goal. [54]
- *Energy labeling*—the allocation of renewable energy certificates and the associated guarantees of origin—can be understood as an adapted version of P2P energy trading addressing an additional secondary market. From a regulatory perspective, e.g., within Germany, its implementation provides an option to further develop the current state without major regulatory adaptions. Efficiently allocating these certificates under consideration of regional vicinity is subject to current research [89].
- *Local flexibility markets (LFM)*, as discussed within this thesis, address regionally exploitable flexible power for the application in grid congestion management. The allocation of network-supportive flexibility provided by DER via an optimization-based matching algorithm allows considering boundary conditions regarding specific effectiveness and technical constraints [90, 10, 11].

Figure 1.3: Basic functions and interactions in optimization-based energy markets [1, p. 3].

Finally, the genesis of these new market use cases involving direct (P2P) interactions are closely linked to the value proposition of DLT, such as BC, as introduced in the following section. [1, pp. 2-3]

1.2.3 Blockchain Technology

“Blockchain” (BC) describes a relatively new technology representing a “decentralized and chronologically updated database using a network-based consensus mechanism for the permanent digital securitization of property rights” [91].

Basic Function As a distributed database, a BC allows to execute and record transactions without any intermediary. This makes it a “distributed ledger” that consensually shares and synchronizes information over the network. The preservation of data integrity and transaction order is ensured by so-called consensus mechanisms involving cross-checking and public witness. Therefore, participants in the network collect and validate transactions over a certain period of time and store them in so-called “blocks” after validation by the underlying consensus mechanism (see Sec. 3.3 and A.1). These blocks are strung together like a chain to determine the order of all transactions and to avoid abuse. In [4], the analogy of the BC to an accounting book was drawn, comparing the book itself to the chain, the single pages to the unique blocks, and the accountant to the whole network of participating nodes in the consensus. In addition to the decentralized storage of data, BC technology evolved to execute programs by the introduction of so-called “smart contracts” that enable the automation of (business) processes. This property is essential for a variety of use cases.

The technology’s strengths lie, inter alia, in the transparency of the transaction process, its manipulation security, the possible pseudonymity, and a high degree of availability. Limitations still exist, primarily in scaling, transaction costs, speed, anonymity, interoperability, and energy consumption. Current developments show that many solutions are currently being developed that aim to improve these limitations. The underlying technical details are further described in Sec. 3.3. In addition, the basic functioning of BC technology can be found in [4].

Development History The genesis of the term *“blockchain”* is directly related to the publication of the white paper “Bitcoin: A Peer-to-Peer Electronic Cash System” by the pseudonym Satoshi Nakamoto in 2008 [92]. This paper described the application of a “Proof-of-Work” consensus mechanism (see A.1) that enables a safe and functioning decentralized value transaction system without intermediary for the first time. Based on these developments, the Bitcoin network [93] was launched on January 3, 2009. Since then, the technology has continuously evolved. After several hype phases, primarily resulting from cryptocurrency speculation, the true added value only reveals within the last years. [94] Starting as a pure settlement infrastructure, the BC’s relevance for business and industry applications arose with the evolution towards a *blockchain platform*. This development is closely linked to the introduction of *Ethereum* in 2014 that postulated a “next generation smart contract and decentralized application platform” [95]. Based on this infrastructure, BC technology became usable for industrial applications by automating business processes, including value transactions.

Fields of Application The first and currently most popular use case of BC technology is digital payment ("cryptocurrencies"). However, the technology provides a basis for many use cases in all industries, including the energy sector. The technology's potential applications are diverse related to its value propositions of providing trust without necessary intermediaries, enabling P2P interaction, process automation and optimization, acceleration of data exchange, micro-transactions and billing, or ownership documentation. It further allows potential anonymity or, at least, pseudonymity and security-by-design. Regarding its application in the energy system, BC technology can, e.g., provide time-specific and tamper-resistant documentation. It further provides data integrity and transparency through traceability of processes. Its immutable character enables the setup of revision-safe databases. However, it also brings certain challenges regarding privacy protection and scalability that can be critical in an intended large-scale adoption of energy use cases, depending on the chosen setup and governance scheme. Therefore, different design configurations need to be assessed for the specific use case. [4, pp. 4-11]

1.3 Objectives and Research Questions

The given introduction, including the current state of science and research and ongoing development trends towards a diverse, sustainable, digitalized, and decentralized energy system forms the foundation for the content of this thesis. A particular focus on efficient integration of DER through market- and platform-based CM further provides the framework. As the underlying concept of an LFM is limited to the actual allocation of flexibility offer and supply, the concept of an SMP is introduced within this thesis. The SMP extends the LFM through additional functions to provide an efficient, integrative, and reliable operation. However, this approach offers a variety of conceptual design choices. This thesis aims to identify and evaluate appropriate design variants of an SMP under consideration of blockchain functionalities. The following hypotheses formulate relevant aspects as addressed in the introduction before.

1. LFMs make decentralized flexibility available for grid congestion management. SMPs that realize and extend these LFMs can provide a level playing field to all involved actors. By considering specific requirements from all relevant perspectives, an efficient market design can be achieved.

2. Regionalized energy markets, such as SMPs, demand optimization as an allocation method to consider quality features and constraints within the matching process. Sufficient liquidity is a challenge for sustainable market operation.

3. Platform solutions demand a single point of access. However, this must not lead to a single-point-of-failure. BC offers the basic infrastructure to this and provides tamper-resistant transparency.

4. Technical decentralization can provide added value but does not per se possess inherent value. Therefore, use-case-specific system design is necessary.

In consequence, the following research questions were developed to evaluate the stated hypotheses:

- **RQ1:** What non-functional requirements can be derived for the design of an SMP from relevant perspectives?
- **RQ2:** Which core functions, processes, and interfaces are needed within an efficient SMP design, and how can they be technically implemented according to their functional requirements?
- **RQ3:** Which design options and benefits can decentralization offer, and what value propositions can BC technology bring to the platform?
- **RQ4:** Which of the identified design alternatives offer the greatest added value with regard to the specified requirements?

The research questions motivate the following methodology applied within this work.

2 Methodology

To achieve the research objectives previously described in Sec. 1.3, the method in Fig. 2.1 was developed. It visualizes the relevant work packages within this thesis, including applied methods, intermediary results, and interrelations. It also structures the subsequent chapters as follows.

Background analysis and field of research: By introducing relevant aspects of grid-supportive flexibility use, LFMs, and accessible flexibility potential depending on exploitation schemes, Chapter 3 provides the basics to future CM concepts on the one hand. On the other hand, the foundation to distributed platform applications is provided by a short description of the relevance of platform economics in the energy sector as well as the value propositions and technical details of BC technology.

Non-functional requirements specifications: Relevant requirements for the development of an SMP are presented from different perspectives to answer *RQ1*. These intend to provide a development guideline and, at the same time, an evaluation framework. Therefore, market, stakeholder, technical, and regulatory requirements are evaluated.

Platform design, modeling and simulation: The core of this thesis lies in the actual design, development, and modeling of the SMP as demanded in *RQ2*. Based on a proposed platform layout and process concept, the core functions and interfaces are described and evaluated by applying a scenario-based simulation environment. The necessary functions contain an aggregation and pooling approach to integrate small-scale flexibility. Further, a market monitoring function is introduced to analyze market power tendencies. Finally, the actual allocation of supply and demand, i.e., the matching, based on a constrained optimization is described.

Blockchain-based implementation options: The previously proposed structure and functionalities, including their technical implementation, assume a centralized setup. In a second step, the conception of a decentralized, BC-based implementation of the relevant functions is discussed based on proof-of-concept approaches. Therefore, different BC-based decentralization options are introduced to give answers to *RQ3*. They include distributed data management and storage, proof of data integrity by hashing and Merkle-proofs, and proof of correct data properties and data processing through verifiable computation techniques.

Evaluation of different design options: Based on the presented input, the design alternatives are assessed according to the initially derived non-functional requirements. Additionally, a developed visualization method illustrates the architectural properties. This finally results in a comparative study to evaluate the specific added value of different SMP design options. The results provide answers to *RQ4* and concludes this thesis.

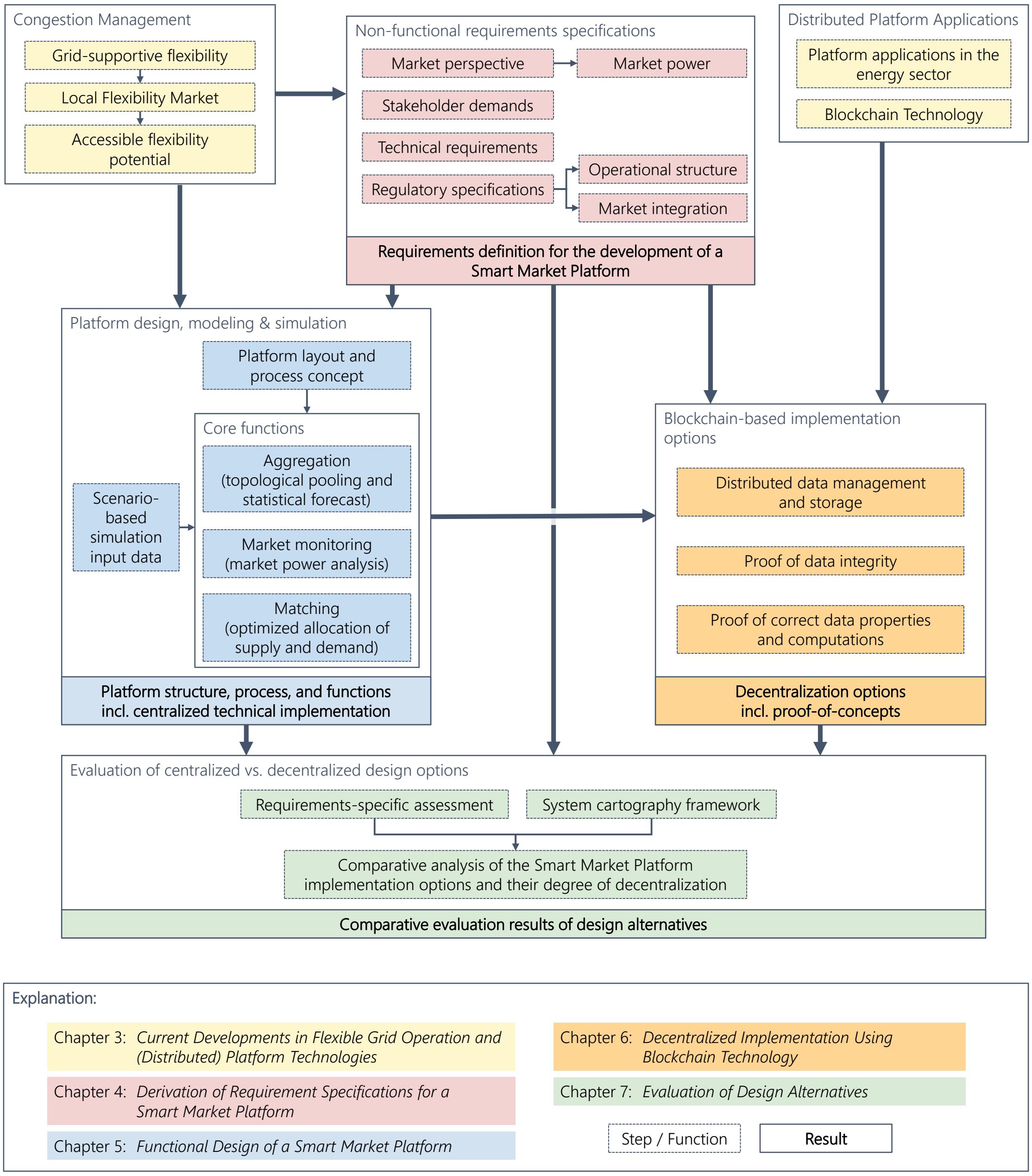

Figure 2.1: Block diagram visualizing the relevant work packages and methods applied in this thesis

From a method theory standpoint, the platform development methodology within this thesis implies a V-Model approach [2, 96]. This systems engineering process model is commonly suggested in "safety-critical system development and infrastructure projects" [97, p. 147] and is based on the steps illustrated in Fig. 2.2. The V-model provides feedback loops and iteration as part of the system development process. It further offers traceability over the entire engineering progress.

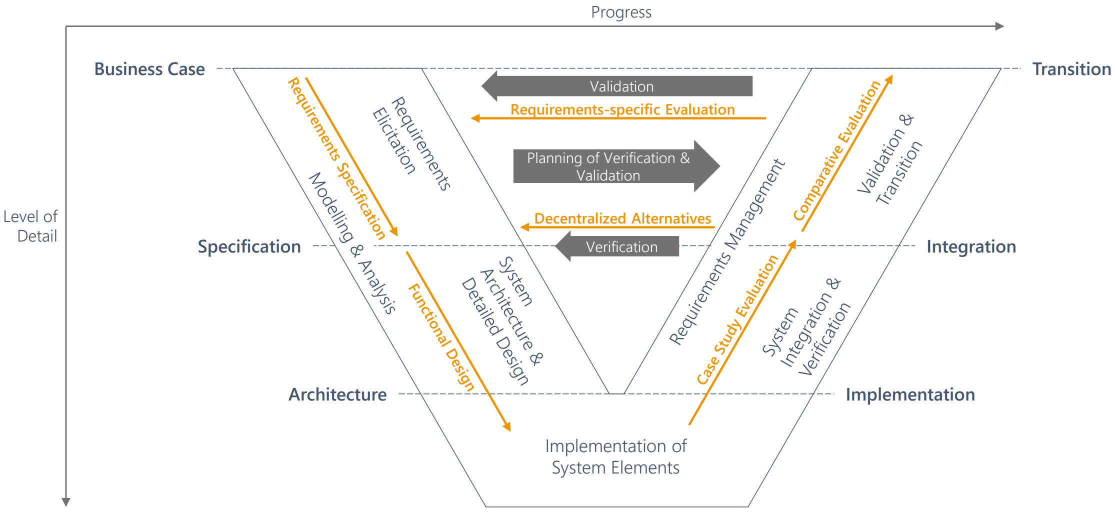

Figure 2.2: Adapted V-model for systems engineering according to VDI 2206:2020 [2] including reference to work packages within this work (orange)

The systems engineering process starts with the introduction of the *business case* of an SMP (Chapter 3). Based on the fundamentals of current and future CM procedures, the relevance of platform-based flexibility-allocation is highlighted. Further, the chances of decentralization through BC technology are introduced.

In the next step, the *requirements elicitation* leads to defined specifications of functional and non-functional requirements. Non-functional requirements describe the qualities of a product, and the expectations of involved stakeholders to the product [98, p. 246]. Therefore, within this thesis, the derivation of these non-functional requirements stands at the beginning of the SMP development process and outlines the demand from four different perspectives according to six dimensions (Chapter 4). In contrast, "functional requirements specify what the product must do—the actions it must perform to satisfy the fundamental reasons for its existence" [98, p. 223]. As the SMP consists of several artifacts, their respective functional requirement definition introduces each of the sections that describe the individual functions, i.e., aggregation (Sec. 5.3.1), market monitoring (Sec. 5.4.1), and matching (Sec. 5.5.1).

The overall system *architecture* and its detailed design, layout, and process concept structure the relevant functions within the platform and their interactions (Chapter 5). The functions are first presented by their intended purpose and then described in detail.

By presenting design proposals and trade-offs between alternative solutions, a preferred solution is then proposed in each section according to the initial functional requirements.

Consequently, the *implementation* of each function is performed and described by its technical fundamentals.

To reach system *integration*, each platform function is applied within a common case study (Sec. 5.2.1). The individual evaluations then allow a consistent review, proof-of-concept, and verification of the complete platform process. With the goal to consider potential decentralization alternatives, as intended in this research, within an iteration loop, blockchain-based design options are being described, prototypically implemented, and evaluated (Chapter 6).

Finally, to prepare the *transition* from the prototype status (opening several design alternatives) to future large-scale realization, a comparative evaluation is conducted (Chapter 7).

3 Current Developments in Flexible Grid Operation and (Distributed) Platform Technologies

The following chapter lays the foundations for the subsequent elaborations regarding the functional design for harnessing grid-supportive flexibility through platform architectures. It includes the basics of CM in a status-quo (Sec. 3.1.1) and current developments towards LFMs due to increasing stress on electricity distribution grids (Sec. 3.1.2). In order to tap the available flexibility potential (Sec. 3.1.3), platform-economic approaches can provide market access to also smaller actors in the energy system and finally create the possibility to exploit available flexibility (Sec. 3.2). BC technology eventually provides a base layer to these platforms by providing common trust through tamper-resistance, transparency, and security-by-design (Sec. 3.3).

3.1 Congestion Management and the Relevance of Flexibility

The energy targets set by the German government essentially lead to the expansion of renewable energies [30]. Electrification further adds new electrical loads with potentially high simultaneity (by global price incentives). Millions of producers, consumers, and storage facilities (see Fig. 1.2) must be integrated in the most efficient way. Due to these developments related to the German energy transition, the demands on the transmission and distribution grids have changed in contrast to their original design principles.

Besides the associated network loads, the mentioned assets also offer relevant potential for grid-supportive flexibility. Until now, however, the Distribution System Operator (DSO) does not have sufficient options to access the available flexibility—apart from emergency measures. In consequence, there is an actual need for new tools in grid operation to handle an increasing number of potential grid congestions. In [99], the current status and related challenges were outlined as described in the following sections.

3.1.1 Status-Quo in Germany

Grid operators must take limited transmission capacities into account in their grid operation planning processes. The delayed progress of grid expansion, combined with the changed generation situation, is currently leading to increased grid bottlenecks [66, pp. 120-136]. While the precondition of uncongested market areas is prevailing, mitigation options to the grid operator are confined. Besides the long-term option of grid expansion, available short term options are limited to grid adjustment and regulated curtailment or contractually ensured power adjustments. The measures available today are defined in § 13 EnWG and § 14 EnWG. § 13 EnWG regulates the possibilities and sequence of applicable congestion management measures for the Transmission System Operator (TSO). According to § 14 EnWG, these regulations apply accordingly to the DSO. Thus, grid-related measures (network topology measures) must be taken before market-related measures (redispatch/countertrading, switchable loads, network-/capacity reserves) and before additional reserves according to § 13 (1) s. 1-2 EnWG. Emergency measures (feed-in management, cascaded system control) in accordance with § 13 (2) EnWG represent the last resort. From this, a general precedence of market mechanisms over emergency measures can be derived. Within the last decade, these measures and the related financial expenses became increasingly relevant (see Sec. 1.2.1 and Fig. 1.1). The increase also led to a discussion about possibilities to increase the efficiency of the network congestion management processes. However, even with grid expansion, from an economic perspective, potential curtailment of renewable energy plants is part of current grid design principles according to [100], i.e., 3% of the annual energy volume of a renewable energy plant may be curtailed. Tab. 3.1 illustrates the currently available measures for congestion management for TSOs and DSOs [6, p. 86].

	TSO	**DSO**
Grid-related measures (§ 13 (1) EnWG)	Network topology measures	
Market-related measures (§§ 13 (1), 14a EnWG, AbLaV)	Redispatch, countertrading	Controllable loads in low voltage level
	Switchable loads (AbLaV)	
	Grid/capacity reserve (national)	
	Grid reserve (international)	
Emergency measures (§ 13 (2) EnWG)	Feed-in management (§ 14 EEG)	
	Cascaded plant control	

Table 3.1: Currently available measures for congestion management [6, p. 86]

Especially with regard to market-related measures, the DSO's intervention possibilities are much more limited compared to the TSO's. The only available measure to the DSO—once all grid-related actions have been exhausted and before emergency measures apply—is to control participating flexible loads in accordance with the preconditions defined in § 14a EnWG[1]. This shortcoming obviously doesn't reflect the relevance of the DG as the "energy transition's backbone" and the conception of an active DSO taking system responsibility [102, 103]. Therefore, several initiatives develop new concepts and tools to strengthen the DSO's possibilities by integration of digitalization, platform applications, and decentralized responsibilities.

3.1.2 Current Development Trends towards Local Flexibility Markets

The long-term option for avoiding grid bottlenecks obviously lies in grid expansion. However, the actual congestion events are mostly restricted to a limited number of time-steps with high network load. Therefore, network reinforcement is not always the most

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[1] In return, the participating units receive a static reduction in network charges [3, 101].

efficient solution to these problems from a system perspective. Several new concepts are discussed, ranging from a quota-based implementation of the network traffic light to aggregator-centric flexibility provision to flexibility trading (see [6, pp. 96-97]).

One initiative already in place since October 2021 is the evolvement of the existing redispatch process ("Redispatch 1.0") towards a *"Redispatch 2.0"* initiated by the "Netzausbaubeschleunigungsgesetz" (NABEG) [33]. Renewable Energy (RE) and CHP plants with more than 100 kW of installed capacity (or < 100 kW if remotely controllable by the grid operator) will therefore be newly integrated in a largely automated redispatch process. However, loads are still excluded and compensation stays cost-based, i.e., generation plants are switched on and off by means of regulated cost compensation. [33]

Smart Grids Traffic Lights Concept Network state can be increasingly well evaluated through grid simulations and measurements. This makes it possible, to determine time and value of a potential congestion in advance and finally brings a new time dimension to the planning process of the network operator. In consequence, a smart grids traffic lights concept has been introduced in [104] and further specified in [105]. Referring to this concept, the three phases of grid status have been described in [7] as follows:

- The *green phase* describes the market phase without any restrictions to the market. Neither critical network conditions nor forecasted congestions exist. The DSO only plays an observing role.
- Within the *amber phase*, a predicted bottleneck demands the grid operator's interaction. In theory, the DSO contracts grid-supportive flexibility to reduce or prevent a potential future congestion.
- The *red phase*, in contrast, demands immediate action as the grid stability is endangered. The grid operator intervenes by directly controlling assets, e.g., through feed-in management measures according to § 13 (2) EnWG and § 14 EEG.

As already indicated, the amber phase only refers to a theoretical concept, as under the current legal framework, there is no mechanism available that would enable a DSO to access flexibility based on congestion forecasts. A specific approach to this is the setup of new systems allowing market-based congestion management in order to efficiently tap and integrate the existing flexibility potential from (small) decentralized units using digitalized infrastructure. LFMs promise such a solution.

Local Flexibility Markets The term "Local Flexibility Market" generally refers to a market for flexibility, involving interfaces for flexibility providers and demanders and the allocation of flexibility bids (i.e., matching). It therefore allows the coordination of decentral flexibility with the goal to be utilized for the grid operator's CM [106]. Fig. 3.1 illustrates the basic setup and high-level interactions of an LFM.

Figure 3.1: Basic setup of a Local Flexibility Market (adapted according to [3, p. 9])

There are several LFM concepts in development, with some of them already operating. The focus of these pilot projects is manifold, with some emphasizing economic requirements or regulatory compliance and others following a greenfield approach by prioritizing technical feasibility. Depending on the application level or its main purpose (i.e., information, coordination, regulatory impact, or examination of market behavior) the market designs differ significantly. Therefore, not all of them provide a distinct allocation method in the sense of directly matching demand and supply on the platform. Comprehensive reviews of European proposals were undertaken in [107] and [108]. Ref. [109] depicts different flexibility market approaches and barriers focusing on market designs, platform types, implementation specifics, and the need of regulatory adaptions. Ref. [11, pp. 6-8] further provides an extensive literature review and meta-study of available LFM concepts, with Tab. 3.2 giving an overview of selected concepts.

Platform	Project and Institutions Involved	Level of Application	Main Purpose	References
Flex4Energy	Storegio e.V. ENTEGA	DSO	Grid congestion management	[110]
Flex2Market	Uni Wuppertal, SPIE SAG GmbH, E-Werk Schweiger OHG	DSO	Grid congestion management, voltage control, curtailment reduction	[111, 112]
EMPOWER	Schneider Electric Norge AS	DSO and TSO	Grid congestion management, local energy community	[113, 114]
iPower	Technical University of Denmark	DSO	Grid congestion management, voltage control	[115, 116, 117]
Total Flex	ForskEL programme, Energinet.dk	DSO	Grid congestion management	[118, 119]
EcoGrid 2.0	Danish Energy Association	TSO and DSO	Grid congestion management, aggregated inclusion of DERs	[120, 121]
Flex-DLM	Universidad Carlos III de Madrid	DSO	Grid congestion management using demand side flexibility	[122]
GOPACS / ETPA	TenneT, Stedin, Liander, Enexis Groep and Westland Infra	TSO and DSO	Grid congestion management, link to ETPA intraday energy market, TSO-DSO coordination	[123, 108]
Altdorfer Flexmarkt (ALF)	C/sells, FfE e.V., Bayernwerk (Germany)	Focus on DSO-level	Grid congestion management	[3, 99, 17]

Table 3.2: Overview of selected Local Flexibility Market concepts (according to [11])

Platform	**Project and Institutions Involved**	**Level of Application**	**Main Purpose**	**References**
ReFlex	C/sells, EnergieNetz Mitte	DSO	Grid congestion management, voltage control	[124, 107, 125]
comax	C/sells, TenneT	DSO and TSO	Grid congestion management	[124, 107, 125]
enera market	enera	DSO and TSO	Grid congestion management, TSO-DSO coordination	[126]
nodes	Nodes AS and Nodes Market Limited	DSO and TSO	Grid congestion management, TSO-DSO coordination, integration of flexibility in intraday market	[127, 128]
ENKO	NEW 4.0	DSO	Grid congestion management, curtailment reduction	[129]
WindNode platform	WindNode	TSO and DSO	Grid congestion management, curtailment reduction	[130, 124]

Table 3.2: Continued: Overview of selected Local Flexibility Market concepts (according to [11])

Although, all of these concepts dealing with the same basic idea of market-based use of grid-supportive flexibility, their technical realization differ depending on the project's focus. This includes product design, addressed asset types, time frame (day-ahead, intraday, or close to real-time), consideration of technical limitations, and applied matching mechanisms (e.g., order book approaches, optimal power flow simulations, or techno-economic optimization). The actual design significantly relies on the addressed voltage level. It can be observed that there is no "one-size-fits-all" solution, but the concept has to be adapted to the scope of its application. [11, p. 8] Focus of this thesis lies in the application within the DG.[2]

Following the definition of [131], an LFM describes a "mechanism that i) aims to relieve congestion in the distribution grid, ii) works through impacting the dispatch of generation, load and/or storage assets, with iii) voluntary participation, and iv) remuneration that is determined based on participants' bids." [131, p. 2] Besides that, there are several other—partly inconsistent—designations and descriptions available. "Market-based Redispatch" or "Redispatch Market" proposes the evolution of the current, cost-based redispatch towards a market-driven approach, mainly focusing on the TG level [132, p. 5]. However, the market approach represents only the allocation method to the grid-supportive use of decentral flexibility. To clarify the distinction from existing concepts, within this thesis, the specification of a *"Smart Market Platform" (SMP)* is introduced. The SMP concept intends to extend the LFM definition through additional functions and features that go beyond the mere allocation of supply and demand.[3]

The term "Smart Market" serves the continuation of the series of "Smart Metering" and "Smart Grid" and holds several interpretation possibilities. As [134, pp. 46-47] em-

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[2] The findings presented in this thesis, referring to the LFM, were inter alia developed within the project C/sells and the field test of the Altdorfer Flexmarkt (ALF) [6].

[3] This is partially in contrast to the definition in [133], where the focus lies more on general flexibility applications and not the functional design of an SMP.

phasizes the coordination aspect that mediates between the market and network spheres considering spatial reference[4], the German regulator Bundesnetzagentur (BNetzA) positions smart markets as "the area outside the grid in which energy volumes or services derived from them are traded among market participants on the basis of the available grid capacity." [135, p. 10]. Aichele and Doleski [136, pp. 13-16] propose a demarcation of "smart grid" and "smart market" based on the addressed spheres of grid and market. At the same time, they introduce a hybrid area in between, which provides the basis for further research as intended in this thesis. In conclusion, a uniform definition of the term "smart market" is not available yet and allows to fill this gap. "Flexibility Platforms" is used in several studies, e.g., within the project C/sells as a description of platform- and market-based network congestion management, with certain overlaps to the presented concept within this work [6, p. 96], [99, 125].

3.1.3 Exploitable Flexibility Potential

As introduced, there are already several flexibility mechanisms in place (see Tab. 3.1 plus "Redispatch 2.0") or in current development (i.e., LFM). Depending on their (voltage) level of application and addressed types of flexible assets, they differ significantly in the flexibility potential that can be tapped. A differentiation of the approximately exploitable flexibility potential under (current and future) mechanisms is illustrated in Fig. 3.2.[5]

The illustrated flexibility potentials refer to different approximation approaches depending on available and sufficiently detailed data to give a rough idea of dimensions. Generation (renewable and conventional) and storage potentials refer to the currently installed capacity in Germany. Installed on-shore wind power is assigned to the category of "100 kW–10 MW". Off-shore wind parks account to the category "> 10 MW". Storage includes HSS in the Low-Voltage (LV) level and larger storage (mainly pumped hydro) in the higher voltage levels. Considered power of flexible loads with less than 100 kW refers to their installed capacity.

Industrial flexibility relates to the practical positive flexibility potential (according to a load reduction) derived in [140]. The underlying assumption distinguish the installed power categories according to economic sectors: Commercial loads are assumed to range between 100 kW and 10 MW and are mainly located in Medium-Voltage (MV) to High-Voltage (HV) levels. Industrial loads (industry processes and cross-sectional technologies) are assigned to the category above 10 MW and are, therefore, predominantly found in HV or Extra High-Voltage (EHV) levels. Commercial load potentials with less than 100 kW of installed capacity are neglected due to missing data.

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[4] This includes an integration into the aforementioned smart grids traffic lights concept according to [104, 105].

[5] References for addressable flexibility potential (Fig. 3.2): RE (2019): [67]; conventional generation and storage > 100 kW: [56]; EV (2020, assumed mean power: 11 kW): [137]; HP (2019, assumed mean power: 2.7 kW): [138]; ESH (2020, assumed mean power: 12.6 kW): [70]; HSS (2017, assumed mean power: 7 kW [139]): [74]; industrial loads (2019): [140]

Redispatch 2.0 already almost triples the potentially accessible flexible power of Redispatch 1.0 from 91 GW to 220 GW. A DSO-platform could reach an exploitable potential of approx. 138 GW. The complete flexibility potential of approximately 273 GW could finally be addressed through an integrated DSO-TSO-platform. Independently of respective potentials, the differentiation regarding voltage level and therefore impact to congested elements is crucial. As introduced, the SMP developed within this thesis is based on a DSO-centric application. The term "SMP" is therefore also chosen to emphasize the underlying structure based on the principles of platform economics.

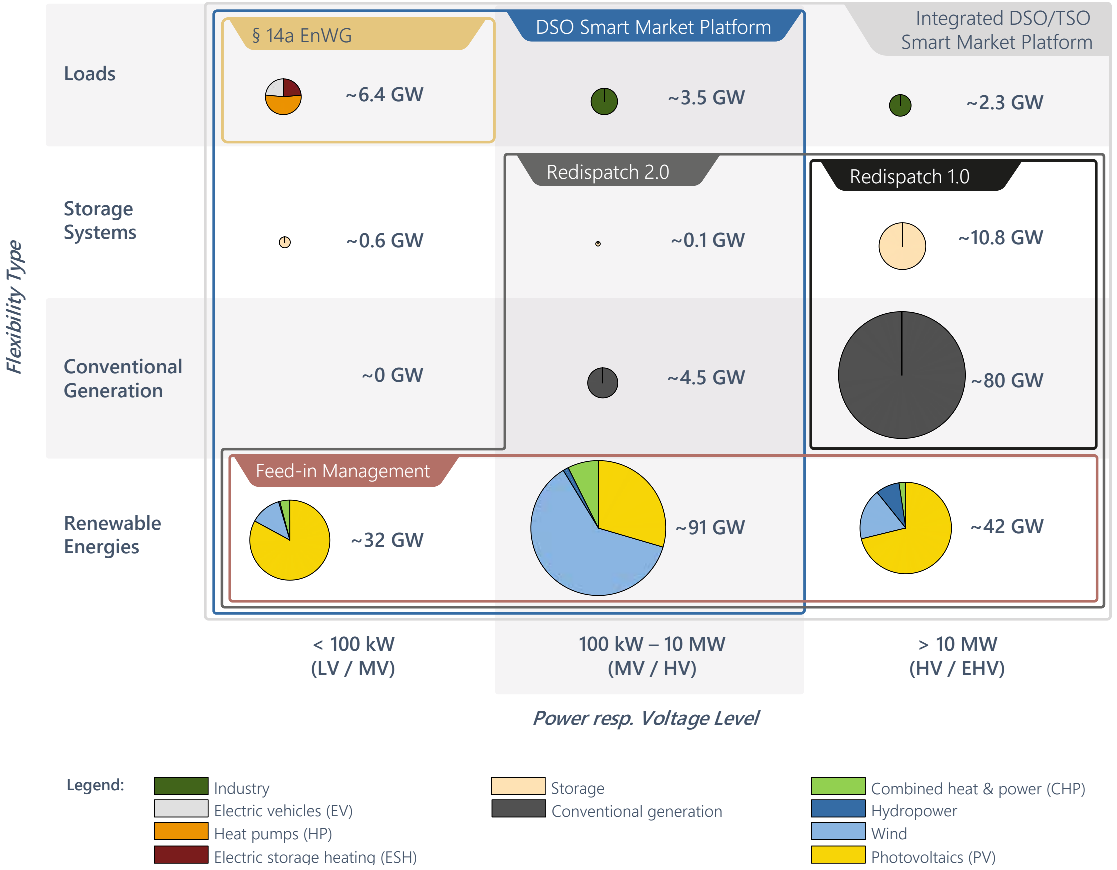

Figure 3.2: Approximation of addressable flexibility potential (status quo) under discussed integration mechanisms (see citations including reference years in footnote)

3.2 Platform Economics and Application in the Energy Sector

While platforms are already widespread and successful in other industries, they are still only found in isolated use cases in the energy industry. Ongoing digitalization and market opening to smaller actors are increasing the potential number of participants for new markets and innovative applications. Therefore, the relevance of platforms will continue to increase in the future. Moreover, lessons can be learned from the experience in other sectors. This provides the opportunity to avoid unwanted developments. In certain industries, however, the downside of the platform economy is already becoming apparent, e.g., through the emergence of monopolies, single-points-of-failure, lock-in effects, intransparency, and persistent dependencies. Therefore, these developments and emerging problems should be prevented within newly developed platforms through both conceptual and technical solutions. [141]

Despite the domination of digital platforms in the last decade, the term "platform" is still lacking a uniform definition. Even though, there have been intentions to clarify this inconsistency, e.g., in [142, 143, 144], available literature is still dominated by two different perspectives:

From an *economic theoretical standpoint*, platforms represent multi-sided markets [145] that help to enable interactions between different groups with mutual interests [146, 147]. In addition to pure "networks", that imply that nodes or users benefit from their interconnection (direct network effects) [148], multi-sided markets also provide indirect network effects that can influence the market participants behaviour [145]. The value of the network to its users is directly related to the number of users with whom they can interact. Network effects and the incentivization of a balanced platform participation and activity do have a direct impact on the success of a platform [146]. [141]

From an *engineering design perspective*, a modular technological architecture describes the essence of a platform [149]. The idea behind this is to efficiently manage the increasing complexity in product development and specifications by re-using common system structures [150]. Robertson and Ulrich describe platforms as a collection of components, processes, knowledge, people and relationships shared by a group of products [151]. Baldwin and Woodward further describe a platform as a system divided into a stable core and variable periphery [142]. Economies of scale apply as the costs for the core infrastructure only increase under-proportionally with the value increase through an extension of the periphery [152]. As software plays the major role in value generation, expenses to additional hardware extensions are almost negligible [153].

Within the energy sector, platforms can reduce incompatibilities of isolated solutions or proprietary systems that require many point-to-point interactions. Clear standards and a common digital infrastructure can foster process efficiency, reduce costs, and provide interoperability between many players. Within [141], several recent platform-based energy projects were analyzed and evaluated regarding their conceptual and architectural approach to these facets. Platform applications in a digitalized energy system are dependent on the contribution of a large number of units and actors in order to be scalable; this means that many—potentially very small—assets and data sources will provide their generated data to other actors in return for services or remuneration. In consequence, new challenges regarding standardized interaction, interoperability, privacy, trust, and responsible data handling arise. The choice of appropriate means of data exchange or the location of data storage is essential. Consequently following the idea of data sovereignty would lead to a decentralized system where each participant would want to keep their data locally and only give access to other parties if necessary. However, this would present a number of hurdles, especially for simple data exchange, data analyses, and the development of collaborative business models. DLT and BC can potentially contribute to these aspects.

3.3 Blockchain and Distributed Ledger Technologies

As a consequence to the specific demands in energy platform architectures, one goal is to establish a common, standardized data management with tamper-proof documentation of data. The BC as the most prominent representative of DLT could be one solution to these demands. By time-discrete consensus on past transactions and their sequence, in addition to the distributed database, it provides unique features [154]. Already announced in Sec. 1.2.3, in the following, technical background to this still young field of technology is provided.

3.3.1 Technical Aspects to Blockchain Technology

BC technology is based on numerous preliminary scientific works and technological innovations, such as various cryptographic achievements, hashing algorithms, or the development of digital currencies and distributed computing approaches. The most important parts are described as follows.

Hash functions are a class of cryptographic functions that translate input values of arbitrary size into a unique checksum (hash value) with predetermined length (also called “digital fingerprint”). The formal definition of the hash function $H : A_1^* \longrightarrow A_2^k$ translates A_1^* with arbitrary size to A_2^k with a defined length k. A change in the input value leads to a different checksum, so that an individual hash can be assigned to each input. [155, 156] Hash functions need to satisfy the following conditions: collision resistance (“uniqueness” for every input value[6]), pre-image resistance (“one-way-function”[7]), second-preimage-resistance[8]. Further, hash functions need to be deterministic as well as computational efficient and fast. [155, 156], [157, p. 321ff], [159, p. 11ff]

Merkle trees—named after Ralph C. Merkle—use a hierarchical arrangement of hash-values to successively combine hash pairs to form a single *Root Hash* [160]. For storing a proof of large amounts of data in a verifiable and secure manner (e.g., on a BC), a Merkle tree significantly reduces the amount of data needed (see Sec. 6.2). Therefore, integrity of individual data objects can be checked without revealing the contents of the other data objects. Instead, certain hash values are sufficient to recalculate the root hash. [92, p. 4]

Asymmetric Encryption provides a method to securely exchange information between several participants without directly exchanging a common secret key, such as

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[6] It is not efficiently possible to find any two distinct input values $M \in A_1^*$ and $M' \in A_1^*$ with identical hash values, i.e., $H(M) \neq H(M')$ [157, p. 322] [158, p. 369].

[7] The hash function $H(M) = h$ and $|h| = k$ at a given input M can be efficiently calculated, whereas the determination of M with $M = H^{-1}(y)$ is computationally infeasible [157, p. 323], [158, p. 367].

[8] For a given hash value, it is not efficiently possible to determine a matching input value which yields the same hash value [157, p. 322], [158, p. 367].

in symmetric encryption. Instead, each participant holds an individual key pair consisting of a public and a private key, whereas the public key is directly derived from the private key through a one-way function [158, pp. 331ff]. To create such a key pair, different cryptographic functions such as "elliptic curve cryptography" or "RSA (Rivest–Shamir–Adleman) systems" can be applied [158, pp. 336ff]. By using asymmetric encryption, data can be encrypted with the foreign public key and can only be decrypted again with the associated private key. In the reverse procedure, data encrypted with a private key can be decrypted with the public key, which forms the basis for digital signatures. Within BC environments, these key pairs are used to secure credentials and to verify ownership of digital assets by digital signatures. The public key is in turn converted into a "public address" and can be used similar to an account number. [4, pp. 21ff]

Digital Signatures can provide a proof of authenticity and origin to a certain information. The sender encrypts the hash value of the initial data with the private key and appends this "signature" to the data. In turn, the recipient can decrypt the signature with the sender's public key and verify that the signature belongs to the data using the hash value. As long as the private key is only in the sender's possession, the origin of the data can thus be proven. [158, p. 380ff] As the authenticity of the public key is critical to this system, Public-Key Infrastructure (PKI) provide a certified relation between identity and public key through a Registration Authority (RA) and a Certification Authority (CA) [158, p. 397ff].

After clarifying relevant cryptographic basics, the following components are indicative for the BC and illustrated in Fig. 3.3. Further technological background and functions of BC technology are presented in detail in [4].

Consensus Mechanism The consensus mechanism represents the core function of a BC. The underlying algorithm ultimately ensures that a transaction is carried out reliably and securely without intermediaries. It prevents double spending of transaction objects (e.g., digital currencies), coordinates agreement on the sequence of changes made in the network, and monitors the rules defined in the protocol. [161, 162] There is a number of different consensus mechanisms in discussion, providing individual advantages and disadvantages directly linked to the used logic. The currently most important concepts are Proof of Work (PoW), Proof of Stake (PoS), and Proof of Authority (PoA) (see Appendix A.1).

Governance Layout The design possibilities of a BC are manifold and concern different options. A central differentiation lies in the accessibility or restrictions regarding participation and type of use. Access to stored data on the BC and its use is determined by a *"public"* or *"private"* setup. The possibilities to participate in the block validation with the consensus mechanism and, therefore, the provision of the network operation can further be restricted (i.e., *"permissioned"*) or open to anyone (i.e., *"permissionless"*). Role and rights management can be defined individually. [163] The different setups and design variants provide certain advantages but also drawbacks depending on the actual usage and stakeholders involved in the ecosystem. As public permissionless BCs provide the highest standards regarding transparency, non-discrimination but also security-by-design and control, they face challenges in data protection and scalability. However, recent advancements with so-called "layer 2" protocols partly dissolved these drawbacks (see Sec. 3.3.2 and Sec. 6.3). Private permissioned setups, on the other hand, potentially provide higher transaction speed, clear legal responsibilities, and a defined group of data recipients. [4, pp. 13-16]

Smart Contracts Smart contracts are automated, executable programs that run decentralized. Based on program code, defined actions can be executed independently, based on fulfilled conditions. Even as the concept of smart contracts was already described independently of BC in 1996 by Nick Szabo [164], the combination of these technologies proposed by Vitalik Buterin and, finally, realized within the Ethereum platform made it possible to securely process program code in a decentralized way without intermediaries. [165, 166] The complexity of a smart contract can range from the simple storage of a hash value to the mapping of complex business processes, e.g., within so-called decentralized autonomous organizations (DAO) [167].

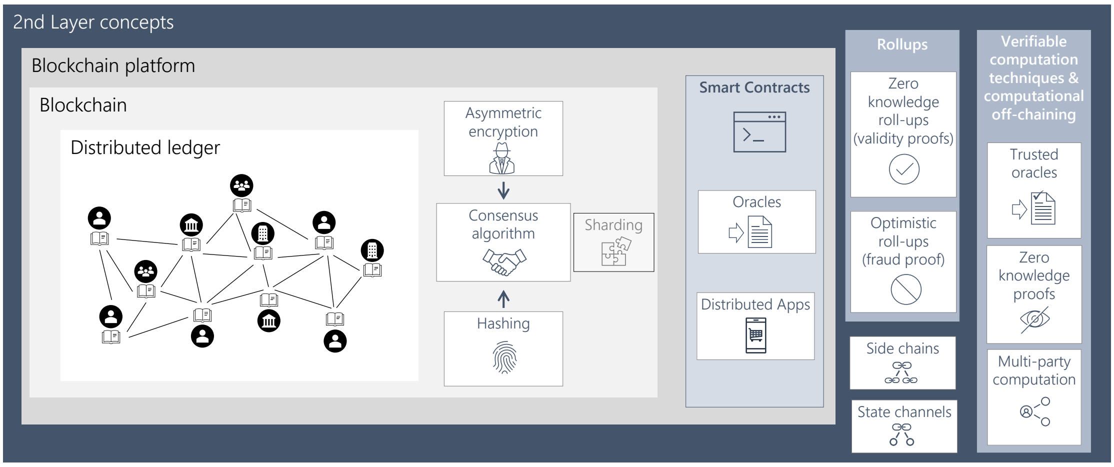

Figure 3.3: Basic components and relevant emerging technologies within a blockchain system (adapted and extended according to [4])

3.3.2 Challenges and Solution Approaches for Industry Application

Besides the chances and value propositions postulated for the application of BC technology, especially its use within existing, historically grown and regulated industries—such as the energy sector—leads to decisive challenges for industry applications. Furthermore, sustainability and scalability requirements make it impossible to use the initial BC system as introduced for Bitcoin. The following aspects are therefore predominant:

Energy Consumption PoW BCs receive their economic reliability from the deployment of hardware resources and applied electrical power for the "mining" process. This leads to a (global) resource consumption of relevant dimensions. The Bitcoin BC alone is assumed to consume approx. 205 TWh of electrical energy per year (as of January 2022) according to [168].

Scalability Besides the energy spent for the consensus mechanism, current public BCs are also limited regarding their computational power. Looking at the transaction rate (e.g., approx. 7 tx/s with Bitcoin and approx. 20 tx/s with Ethereum [169, p. 43]), a widespread application for commercial use cases seems infeasible.

Privacy BC's value proposition is often linked to anonymity or at least pseudonymity. This may be correct when it comes to direct identification of participants. But, within commercial application, the provision of potentially sensitive information (e.g., GDPR-relevant) may be necessary. If directly written on a BC, and therefore publicly accessible, it will inevitably lead to privacy issues.

The named drawbacks are already being discussed for several years and represent the main motivation for further system development. The following technologies represent a selection of these advancements, divided into so-called *layer 1* and *layer 2* approaches related to the respective stack level as discussed within the example of Ethereum [170].

Layer 1 concepts intend to further develop the core protocol of the BC (see *ETH 2.0* in Ethereum), i.e., the consensus mechanism and the data distribution. *Alternative consensus mechanisms* are the most studied development perspective. By moving away from existing PoW algorithms towards the already introduced PoS is therefore the preferred action for public BCs. As this transition provides a reliable solution to the excessive energy consumption, it still lacks significant increases in transaction speed towards an industry level. [161] *Sharding* represents a currently discussed upgrade of the core protocol that intends to horizontally split the database and spread it across parallel chains, defined as "shards". Within each shard, state updates are propagated as usual, but communication between shards is limited to a simple synchronization mechanism. This way, shard data can be processed in parallel, significantly increasing the number of transactions per second. [1, p. 4] [15, p. 2]

Layer 2 concepts, on the other hand, are developed "on top" of the base protocol and propose an additional layer to the basic BC. Research focus shifted towards these technologies as they promise to provide solutions to all challenges named before. *Off-chaining data* implies the storage of only a trust anchor on the BC, e.g., in form of a hash reference proving its existence by date, form, and content. *Side chains* and *state channels* outsource transactions to respective supplementary BCs or functions and only write the final outcome back to the main BC [15, p. 2]. *Roll-ups* also externalize transactions, but use cryptographic functions to provide a proof of the correct execution to the initial BC. In general, there are optimistic or zero-knowledge roll-ups. The former preliminary assume correct execution and only demand proof in case of a challenge ("fraud proof"). The latter already submits a "validity proof" within the settlement. [171]

While the named approaches focus on mere scalability in terms of transaction speed, the issue of conducting complex computation in BC environments is only partly addressed by the proposed solutions. Also, considerably fewer solutions address the problem of privacy preservation. As prevailing cryptographic techniques like asymmetric encryption or hashing are limited to secure private data, they cannot provide proof of correct computation. Within industrial BC environments, this often leads to private permissioned BC setups with restricted access to sensitive data. While this is a valid approach, the initial security model of a BC and open participation is partly diminished. Motivated by addressing these drawbacks, recent research advancements try to combine both performance and privacy by outsourcing sensitive data and extensive computational effort. Summarized by the term *Verifiable Computation (VC)*, (complex) computations will be executed offline by external nodes.[9] An added verification scheme provides the ability to verify the correctness of the returned results. Thus, VC promises to merge the security of BC to the various sensitive and demanding use cases of the energy sector by providing added value through increased transparency. [1, p. 5] [15, pp. 2-3] Fig. 3.4 gives an overview and a basic functional description of the following VC representatives.

- *(Trusted) Oracles*—as a special form of smart contracts—can check the correctness of external data before it is sent to the BC [172]. Oracle services execute computations off-chain. The result is checked and published on-chain via the oracle's smart contract. Two major approaches can therefore be distinguished, *Incentive-driven Off-chain Computation (IOC)* and *Software Guard Extensions (SGX)*. The former is based on game theoretical incentives between a number of participating oracle nodes executing the same computation. The latter is based on a secured hardware *Trusted Exection Environment (TEE)*, i.e., a cryptographic co-processor developed and introduced by Intel. [1, p. 6] [15, pp. 9-10]

- *Zero Knowledge Proof (ZKP)* is a cryptographic technology that provides "a way to prove the correct execution of a defined computation, without disclosing the values used when performing that very computation" [173]. There are different implementations of ZKP with *zk-SNARK* (Zero-Knowledge Succinct Non-interactive ARgument of Knowledge) being the most commonly applied in the BC context. [1, pp. 6-7] [15, pp. 30-32]

- *Multi-Party Computation (MPC)* describes security protocols processing secret inputs that are jointly executed by multiple nodes without being revealed. Only the result of the computation is finally made public including cryptographic artifacts that enable a verification of correct execution. *Linear Secret Sharing* represents one prominent example for MPC. [1, p. 7] [15, p. 46]

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[9] This marks the contrast to the mere aggregation of transactions as proposed within the mentioned layer 2 concepts.

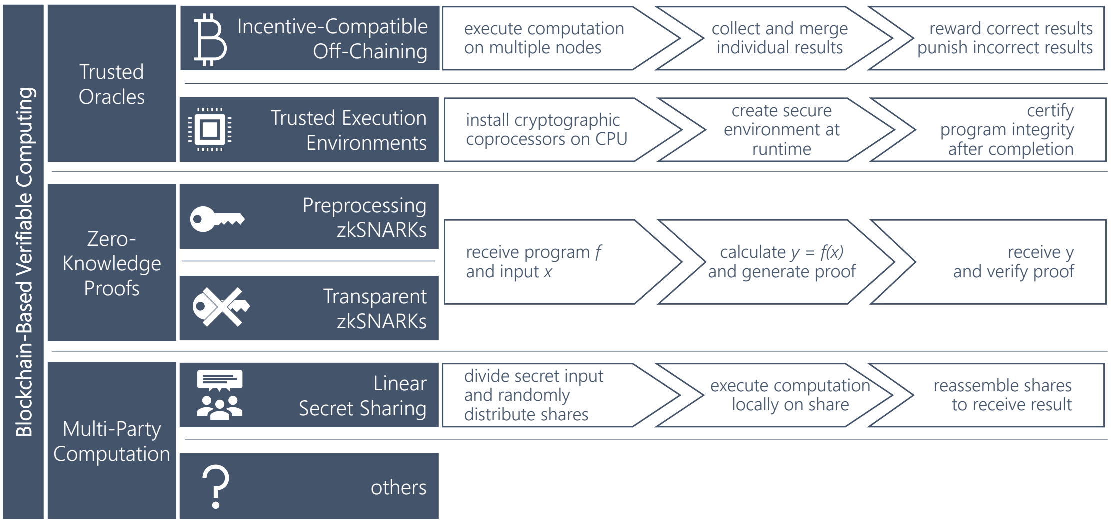

Figure 3.4: Overview and function of considered verifiable computation techniques [1, p. 5]

4 Derivation of Requirement Specifications for a Smart Market Platform

To reach the goal of this work, the development and analysis of an appropriate market design for an SMP, initial requirement elicitation by definition of the research scope is necessary. Therefore, the framework methodology of this study is based on the traceable fulfillment of specified requirements.

Non-functional Requirement Specifications For the definition of requirements, relevant stakeholders and overarching goals need to be addressed. Tab. 4.1 depicts a requirements matrix revealing the demands from a market, platform participants', technological, as well as energy economic and regulatory perspective.

		A **Market perspective**		**B** **Platform participants' perspective**		**C** **Technological perspective**		**D** **Regulatory perspective**	
1	**Practicality/ accessibility**	**A1**	High market liquidity	**B1**	Asset-specific products	**C1**	Standardized market access, defined interfaces	**D1**	Non-discriminatory access
2	**Market potential/ scalability**	**A2**	Sufficient performance	**B2**	Inclusion of all types of potential market participants	**C2**	Little technical restrictions	**D2**	Large-scale application
3	**Efficiency/ market quality**	**A3**	Optimal market results, avoidance of market manipulation	**B3**	Demand side: reliable delivery Supply side: maximum revenue	**C3**	Consideration of technical constraints	**D3**	System-optimal results, avoidance of market inconsistencies
4	**Costs**	**A4**	Minimal operational costs	**B4**	Minimal costs for participation	**C4**	Minimal extra costs through additional functions	**D4**	Minimized system costs
5	**Security**	**A5**	Reliable, robust market operation	**B5**	Reliable interaction and access	**C5**	High availability and reliable interaction	**D5**	Defined responsibilities, reduction of single-points-of-failure
6	**Transparency/ data protection**	**A6**	Maximum transparency	**B6**	Data privacy to protect sensitive data	**C6**	Protected communication and data storage	**D6**	Transparency to review market operations

Table 4.1: Requirements matrix specifying the demands for a Smart Market Platform from relevant perspectives

The identification of these non-functional requirements is based on extensive literature study as depicted in the following sections and stakeholder input from several project workshops including grid operators, aggregators, researchers, and representatives of regulatory bodies [6, 35, 54]. The addressed dimensions include practicality of the platform implementation and operation plus aspects of accessibility and usability. Market potential and scalability of the market design, efficiency, and quality of the market approach represent further aspects. In addition, security features combined with transparency and data protection need to be considered within the platform design. Finally, the ratio of expenses to revenues should be positive.

As a wide range of design variants is conceivable, the methodology is intended to model and evaluate the fulfilment of the requirements in a reliable and comprehensive way. The following sections further define the requirements that set the ground for the evaluation of the design variants in Chapter 7.

4.1 Market Requirements

An efficient market (Tab. 4.1, column A) requires sufficient liquidity and operational performance. The allocation scheme needs to be proven to achieve optimal market results, and market manipulation or market power tendencies need to be avoided. The reliable, robust market operation, combined with maximum transparency, finally leads to trust in the market. Minimal operational costs are further desired.

Finding consistent and general requirements or functions that need to be fulfilled to create an efficient market is challenging. Starting with a general definition of the term "market", the Encyclopædia Britannica states that market is "a means by which the exchange of goods and services takes place as a result of buyers and sellers being in contact with one another, either directly or through mediating agents or institutions." [174] Nevertheless, there are certain market principles and elementary functions that were defined by representatives of the market process theory summarized under the term "Modern Austrian Economics" (see, e.g., [175, pp.14-47] and [176, pp. 5-10]). In [177, p. 2], Grossekettler defined the following market functions:

1. **Market clearing** includes the coordination of demand and supply of goods. Price formation leads to efficient allocation and distribution of goods in type and quantity and provides the regulating effect of market prices based on the (transparent) provision of information.

2. Increased efficiency results from competitive pressure and a **rate of return normalization**.

3. Power limitation is given through competition and, therefore, **erosion of market power**.

4. Efficiency increase and **innovation promotion** is provided through incentives for **product optimization** and **technological progress**.

"The ideal state would be achieved when all these functions are fulfilled permanently and simultaneously on a market.", Grossekettler stated in [177, p. 3], followed by the statement that "this cannot be expected in reality." This fact is further exacerbated as the market structures dealt with in this work can not be understood as a homogeneous market with perfect competition but rather an optimized combination of specific, constrained product requirements from both, demand and supply side. Based on the theory developed by Alvin Roth, who was awarded the Nobel Prize in Economics in 2012, these market types can be described as "matching markets" [178, 179]. Matching markets consider more specific quality aspects of a product and demand more complex ways of allocation than, e.g., conventional approaches merely based on merit order lists (as applied in most energy markets).

However, the market functions defined before should apply to all types of markets. So, having the chance to set up completely new market structures for future market-based congestion management systems, these basic principles can serve as a guideline. The following requirements were consequently derived for an efficient smart market design:

1. Transparent allocation and price formation is essential (Tab. 4.1, A6). As additional external constraints need to be considered, this leads to increased complexity in the coordination mechanism. Market clearing should therefore be comprehensible, reliable, verifiable, and replicable (Tab. 4.1, A5).

2. Non-discriminatory, technology-neutral, and open access should be provided by the market platform to increase liquidity and raise competition (Tab. 4.1, A1). This includes integrating existing flexibility potentials through low entry barriers and a high degree of automation but also by providing "open" products that incentivize an optimized operation on both sides—demand and supply.

3. To reach an efficient allocation scheme, minimized operational costs (Tab. 4.1, A4) and sufficient performance of the market structure (Tab. 4.1, A2) are prerequisites.

4. Increased liquidity and competition combined with monitoring schemes ensure the limitation of market manipulation, e.g., through market power tendencies (Tab. 4.1, A3) as defined in the following.

Market Power Market power is the ability of a market participant to profitably alter prices away from competitive levels [180, 181]. Beyond this basic definition, it is useful to differentiate between potential market power and exercised market power. Potential or structural market power exists when the size of a market participant or the market conditions of the relevant time period result in this participant gaining the ability to profitably alter the price [182]. Possessing structural market power is not necessarily illegal itself, depending on jurisdiction. In Germany or Texas for instance, a violation of competition law has only occurred after this market power has been exercised in order to alter the price [182, 183]. Nevertheless, in order to provide a functioning and efficient market, structural market power should be avoided or at least monitored. Electricity markets exhibit several features that set them apart from other commodity markets and make them particularly vulnerable to the abuse of market power [155, 180, 182].

The intended regional design of an SMP, the character of future market participants (e.g., aggregators), and the location-specific nature of congestion could combine to make these markets yet more susceptible to the abuse of market power. A regional market limits the number of market participants based on geography (i.e., grid structure), potentially decreasing competition compared to a national market. Minor players in the larger market may suddenly find themselves in a dominant position within the regional market, so-called local market power [184]. Limited available flexibility can result from low market participation. Whether few flexible units are present in an area or participation is not adequately incentivized, a market for flexibility with low participation will be of limited usefulness and susceptible to the emergence of structural market power. However, even a market with satisfactory participation does not guarantee adequate available flexibility. Especially with flexibilities on the household level, unit availability also depends on the weather, owner's comfort restrictions or patterns of use, and technical restrictions, any of which can reduce the flexibility available at a given time [185]. Concentration of available flexibility can take the form of large single units representing a significant proportion of available flexibility, or through the aggregation of more numerous smaller flexible units. Regardless of the form it takes, concentration of ownership can quickly lead to a dominant supplier that is able to raise market prices at lower levels of demand than any other market player. The direction of congestion and the location of the congested element determine which flexible units can help relieve the congestion, further limiting the number of participants [186]. These conditions can each be exacerbated by instances of high demand for flexibility. Potential measures to identify and reduce market power include transparency, regulatory obligations, or market monitoring approaches. [77, 187]

4.2 Platform Participants' Requirements

Platform participants refer to flexibility providers and demanders (Tab. 4.1, column B), although in this thesis, focus is put on flexibility provision. Defined products provide the basis to an intended inclusion of all types of potential market participants and assets. Market actors strive for maximum revenue, implying minimal costs for participation. Reliability through a reduction of points-of-failure combined with data privacy is a prerequisite.

Flexibility Provider Flexibility providers represent owners, operators, and marketers of a Flexibility Option (FO) that offer their flexibility on the SMP. FOs are generation, consumption, and storage facilities that can adjust their generation or load capacity [99]. The operators can significantly differ in their professionalism—ranging from simple homeowners to highly automated aggregators. To incorporate as many FOs as possible in the market, diversified product options are required, including variable energy pricing and compensations (see [124]). From an asset operator's perspective who intends to participate in the market, products need to cover specific technical requirements (Tab. 4.1, B1) [188, p. 5]. Therefore, product types differentiation depends on the professionalism of potential providers. The procedural and technical integration of smaller flexible units operated within a household, e.g., HP, small Photovoltaics (PV), or ESH, is challenging but necessary to exploit the flexibility potential in the lower grid levels (Tab. 4.1, B2). Besides that, financial incentive is a crucial aspect for participation in the trading platform, as economic benefit is mostly considered the primary motivation for participation in local markets (Tab. 4.1, B3) [189, p. 58920]. In consequence, this includes minimal costs for participation (Tab. 4.1, B4). A low access threshold combined with a suitable and reliable communication technology is an additional requirement for broad participation (Tab. 4.1, B5) [188, p. 5]. Finally, protection of privacy (also regarding GDPR [52]) or commercial secrecy includes non-disclosure of market actions [190, p. 3]. The more data is shared and stored with the platform or other participants, the greater the concerns about misuse of the data (Tab. 4.1, B6) [191, p. 5].

Flexibility Demander Grid operators act as flexibility demanders, intending to solve their predicted grid bottlenecks. They can utilize SMPs as an operational planning tool to contract flexibility in response to predicted grid congestions in addition to the established CM measures. Their intention is to reduce dependency upon emergency measures for CM. If the grid operator determines a need for flexibility within its day-ahead load flow and network safety calculations, the determined flexibility demand includes the time and amount of predicted overload on a specific grid location. From a grid operator's perspective—representing the demand side—contracted flexibility provision needs to fulfill technical and trading requirements depending on the actual purpose of use (e.g., congestion management, voltage control, redundancy support, or a combination of these [188, p. 11]). To provide high planning security, the reliability of contraction is essential (Tab. 4.1, B3). As grid operators act in the sphere of critical infrastructure, information regarding grid topology and network assets need to be kept within the responsibility of the grid operator (Tab. 4.1, B6). This aspect also includes the need for reliability and a reduction of potential single-points-of-failure.

4.3 Technical Requirements

The technological aspects (Tab. 4.1, column C) focus on an efficient access to available flexibility potential, demanding asset-specific products combined with defined interfaces. Standardized market access with limited technical restrictions increase the accessible flexibility potential. Technical added value needs to be achieved under the premise of little extra costs for required additional features to participate. High availability and secured communication need to fulfill industry standards.

Provided access to the market needs to meet two opposing requirements. On the one hand, interfaces should be as generic as possible to provide enough freedom for optimization at the edge of the grid, i.e., energy management systems optimizing internal objectives (e.g., maximum self-consumption) and only providing excess flexibility to the grid, energy system, or market. This requires a data exchange model that is as general as possible but provides sufficient setting options to consider potential technical constraints (Tab. 4.1, C3). [188, p. 12] On the other hand, certain assets demand interfaces with low entrance barriers (Tab. 4.1, C1). This mainly applies to already existing units without energy management or optimization capabilities (e.g., heat pumps or electrical storage heating). Therefore, little technical restrictions (Tab. 4.1, C2) should apply, and marketing procedures should be outsourced to market functions. Consequently, extra costs for potentially needed additional features to participate should also be minimized (Tab. 4.1, C4). iMSys infrastructure promises to provide standardized access to the energy system and to tap small-scale flexibility with high reliability. It should therefore be considered as the preferred means of communication (Tab. 4.1, C5) [192]. Using this infrastructure leads to protected exchange and storage of information (Tab. 4.1, C6).

4.4 Energy-economic and Regulatory Requirements

Energy economic and regulatory demands (Tab. 4.1, column D) include an evolutionary integration into the existing market environment. Further, technology neutrality and intended large-scale adoption shall provide scalability. From a macro-economic point-of-view, system-optimal market results at minimized system costs need to avoid preferential treatment of individual actors or technologies. Market inconsistencies should be minimized. From a regulator's perspective, defined responsibilities are important. Further, single-points-of-failure should be reduced. External review of market activities represents a core responsibility of the regulator.

Basic principles regularly stated by political and regulatory bodies set the baseline for new market developments. With reference to balancing markets regulation, the European regulation *2019/943* on the internal market for electricity demands that "services are defined in a transparent and technologically neutral manner and are procured in a transparent, market-based manner" [193, Art. 6 (1b)] (Tab. 4.1, D6). Further they should "ensure non-discriminatory access to all market participants" [193, Art. 6 (1b)] (Tab. 4.1, D1). Scalability and large-scale application should lead to standardization an avoid isolated solutions as requested within relevant research initiatives, e.g., the SINTEG program [35] (Tab. 4.1, D2). The main goal of introducing these new types of markets and platforms lies in the efficiency increase and, therefore, reduction of system costs related to congestion management measures, as described in Sec. 3.1.1 (Tab. 4.1, D4).

Integration into Existing Market and Congestion Management Processes The German energy system is a historically grown and complex web of defined responsibilities and regulations. Therefore, structural evolvements need to integrate into the existing system and market inconsistencies should be avoided (Tab. 4.1, D3). Already introduced in Sec. 3.1.2, the SMP operates in the amber traffic lights phase. As there are already several other mechanisms in place, such a new concept needs to be fitted into existing procedures regarding temporal and structural interference. This includes the timing of the platform processes in relation to existing market and coordination processes (see Fig. 5.3). The exact time of flexibility contraction influences both the determination of the demand and the available supply, as follows [7]:

- The earlier a demand is covered and, consequently, flexibility is contracted, the more planning security is given to the DSO to manage the limited network capacities. On the flip-side, early contracting increases uncertainty to supply availability forecasts and demand prediction. Accordingly, a correspondingly higher degree of security would have to be taken into account when contracting early, or the risk of a red light phase would have to be consciously accepted.
- Supply liquidity is highest at a contracting time relatively close to the time of performance (see [194]), i.e., late contraction potentially allows more flexibility to be accessed and reflects in lower prices. A disadvantage is the uncertainty in the operational planning of grid operators and thus a higher risk of having to resort to red light measures.

In addition, market inconsistencies can open the space to market manipulation. Susceptibility to potential (increase-decrease or “INC-DEC”) gaming depends, inter alia, on the existence of competing secondary markets. A detailed discussion to this can be found in [132, pp. 14-22] and [195, p. 13].

Market Operation The energy system is based on defined roles that must assume certain responsibilities and meet defined requirements that are preliminary defined (e.g., by ENTSO-E in [196] or by the German BDEW in [197]). The platform operator is responsible for the functioning, maintenance, and further development of the SMP. This includes the provision of server infrastructure, support service, and personnel. However, the role of an SMP operator and its regulatory obligations have not yet been officially defined but demand a new market role (Tab. 4.1, D5).

Different constellations for market operation are conceivable as examined in [5]. These include the grid operator, a consortium of grid operators, (commercial) external third parties, power exchanges (e.g, by introducing new products with a regional component), or even the Federal Network Agency. Fig. 4.1 gives an overview of potential operation schemes, differentiated by centralized and decentralized platform structures. In consequence, requirements to a platform operator are significantly related to this general setup and its degree of decentralization. In a centralized implementation, platform operation is usually carried out by a single intermediary. This can be either a regulated or a for-profit player that must ensure reliable operation. Decentralized setups could reduce single points-of-failure as only applied in a confined area of application. A blockchain-based operation is understood as a centralized platform, as the platform structure only refers to the regional and not technological setup.

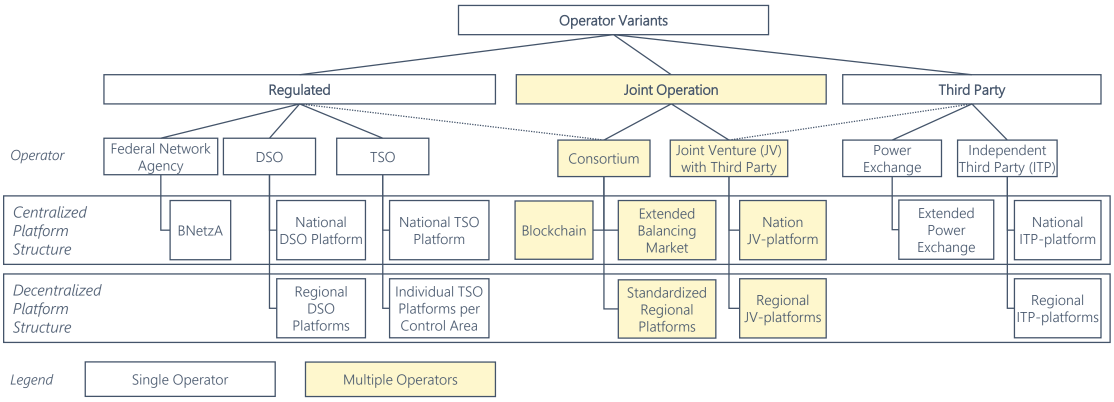

Figure 4.1: Potential Smart Market Platform operation structures including different platform layouts and operators in their energy-economic role (adapted according to [5, p. 28])

5 Functional Design of a Smart Market Platform

Within the following section, the actual design of an SMP, including the fundamental layout, process, and main functions, is developed and tested according to functional specifications derived from the non-functional requirements introduced beforehand.

5.1 Smart Market Layout and Process Concept

The SMP layout results from the interaction and functional needs of the involved stakeholders. Fig. 5.1 illustrates the basic structure and key features. It further highlights the increased complexity in contrast to a plain LFM as illustrated in Fig. 3.1. The platform generally serves as the intersection between flexibility providers and demanders and orchestrates their needs based on defined functions. Involved actors are factored in, according to their responsibilities, provided information (i.e., flexibility demand, offers, and products), and their integration in the platform process.

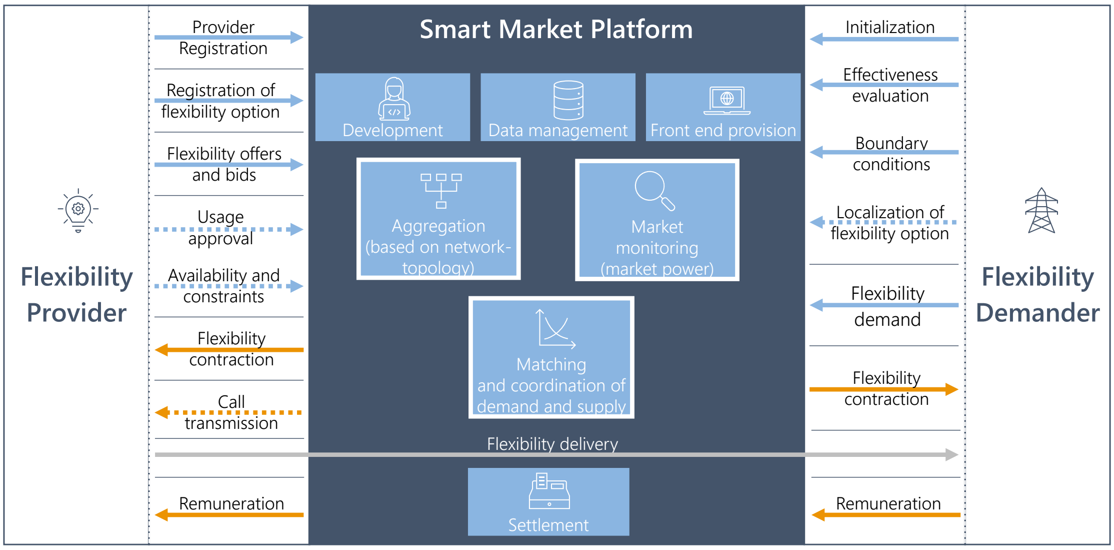

Figure 5.1: Structural setup of a Smart Market Platform featuring the presented key functions *aggregation*, *market monitoring*, and *matching*

Flexibility Demand The grid operator submits its flexibility demand to the platform in order to resolve predicted grid congestions. A thermal overload results in a current problem with a corresponding flexibility demand in ampere at the identified grid component for a specific future time step. Over- or undercutting of voltage band limits at grid points will lead to a voltage problem. In consequence, the provided data contains all affected grid components in terms of current and/or voltage problems. Both congestion types need to be provided in 15-minutes intervals resulting in 96 time steps per day. Within this thesis, as in most other LFM projects (see Tab. 3.2), focus lies on current problem demands, even though voltage demands could be conceptually included. This is due to the fact that efficient and cost-effective alternative measures for voltage control are already available with an existing potential far from being exhausted (esp. by applying reactive power management) [53].

Flexibility Offers and Products Unlike flexibility demand, flexibility offers differ in several aspects depending on the marketing type and the properties of the FO. Therefore, a differentiation between flexibility providers who are able to actively place flexibility offers on the platform and providers who lack this capability is necessary. The two options are reflected in the proposal for two flexibility products, i.e., schedule offers and long-term contraction (see Fig. 5.2).

Schedule offers define the standard product, providing professional marketers with the possibility to actively place offer bids on the platform. Actively marketed FOs have pre-planned working points, the so-called baseline. These are required for electricity trading, supply contracts, or balancing group management, for example. The schedule offer bid contains a day-ahead time series in 15-minutes steps, including available positive and negative flexible power, energy, and price, respectively. In addition, potential call boundary conditions can be considered (see Sec. 5.5.3). Existing data standards, as defined within the KWEP[1]-process, provide orientation for the development of the bid format [198].

Long-term contraction defines an alternative for including small flexibility units in the marketing process. In contrast to schedule offers, this does not require frequent interaction with the platform by uploading new bids. Instead, this option only needs a single-time authorization and includes an automated marketing service. In this case, no periodic (e.g., daily) marketing decisions have to be made by updated offer bids. This encourages participation through a minimal market entry barrier and targets assets without the ability of active marketing, such as small PV plants, HPs, or ESHs. This way, the platform is granted access to control the FOs within defined boundaries. In addition, depending on the type of FO, an aggregation process will subsequently pool similar available units in topological (i.e., regional) proximity to each other (see Sec. 5.3).

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[1] "Kraftwerkseinsatzpläne", German for "power plant deployment plans" for the standardized communication with the TSO

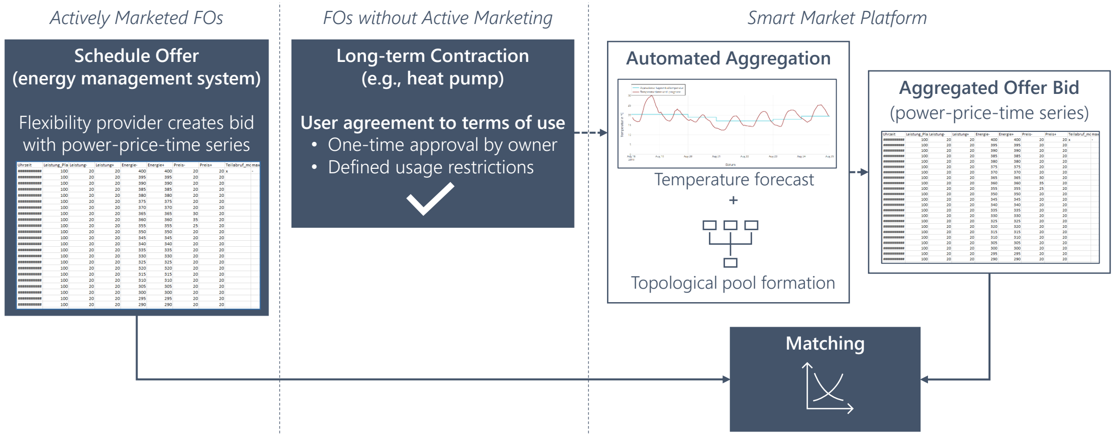

Figure 5.2: Differentiation between schedule offers and long-term contraction (adapted according to [6, p. 130])

Temporal Sequence As already presented in [7], the timing of new market processes is crucial to an appropriate integration into a complex energy system dealing with legacy issues. Besides that, the operational demands of the involved stakeholders need to be considered. A grid operator workshop within the project C/sells lead to the insight, that a day-ahead process for the procurement of grid-supportive flexibility in the amber traffic lights phase is preferred by the involved DSOs [6, p. 103]. The main argumentation was a better integration into the existing operational planing process [7]. Potential uncertainties through longer lead time within the forecasts could be taken into account accordingly by a security surcharge. After all, emergency measures in the red phase still persist (Sec. 3.1.2). After determination of a predicted congestion, the grid operator identifies its flexibility demand and submits it to the SMP. Fig. 5.3 illustrates the temporal integration of SMP processes into the current congestion management processes in Germany.

On the supply side, alternative marketing options are particularly important for the available flexibility. The timing will consequently affect market liquidity in terms of available flexibility offers. Thus, the offer price is also determined by the revenue opportunities on other market places that are known or accepted at the time the offer is made. Therefore, relevant points in time of different market processes were taken into account when designing the timing of the platform processes. This relates in particular to day-ahead (DA) spot market trading, which is concluded by 12:00 the previous day, and the intraday (ID) trading, whose opening auction takes place daily at 15:00; continuous ID trading starts from 16:00. [199] The coordination with existing processes of balancing power procurement plays only a minor role at the distribution grid level.

At 16:00 day-ahead, the SMP's matching between flexibility offer and demand is conducted. The flexibility options are contracted, and all parties are notified of the successful matching. The day-ahead process is herewith concluded. On the day of provision, an update may be made by the grid operator to make a final decision on the call-off at the time of the contracted provision. Finally, the call-off will be carried out in accordance with the conditions agreed upon the day before. [7]

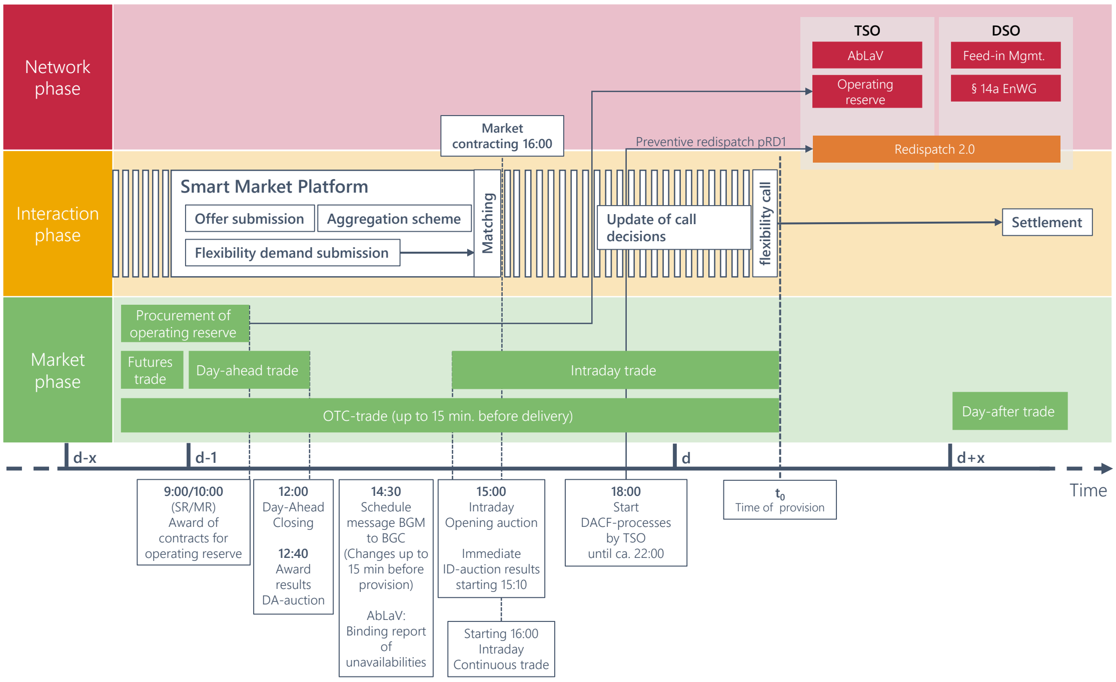

Figure 5.3: Integration of a Smart Market Platform into the time schedule of current congestion management and energy market processes [7]

Platform Process The detailed platform process concept is illustrated in the UML[2] sequence diagram in Fig. A.1 [17, p. 21]. The actual platform process starts after an initialization procedure, providing a specific set of rules for each network group, processed grid data, and defined limitations. The first platform step then consists of transferring all necessary master data to register the providers and their respective FOs. The latter are further assigned to their corresponding network connection point by the Access Network Operator (ANO)[3]. [99] After completion of the registration process, offer bids can be placed by the flexibility provider individually, depending on system availability. As described, this can be conducted by a single authorization for long-term contraction or on a daily basis with schedule offers, involving preprocessing activities by the flexibility provider (Fig. 5.2). On the demand side, demand bids are submitted by the network operators in an automated day-ahead process. They use grid condition forecasts and sensitivity analyses to determine flexibility demands and transfer these to the platform for coordination. The subsequent matching of supply and demand, under consideration of all relevant constraints and boundary conditions, defines the market's core. Ex-post

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[2] Unified Modeling Language

[3] The ANO represents the responsible network operator in whose grid the FO is connected.

to the allocation and contracting process, the flexibility calls are transferred to the FOs. Depending on the type of technical unit, this can be executed automatically using iMSys infrastructure or handed over to the responsibility of the asset operator. Finally, the settlement process sets the final step including a proof of provision of the requested flexibility and documentation.

The SMP is divided into a back-end, containing all internal platform processes and functions, and a front-end, providing interfaces for interaction, data provision, and visualization to the involved actors [99]. A detailed description of the platform concept can be found in [3].

5.2 Modeling and Simulation Inputs

Before moving on to the functional design, the following section describes the modeling environment and input data for the simulations applied in the case studies. To prove the functionality of the relevant SMP functions, defined in Fig. 5.1, and, especially, to draw an exemplary picture of the application of the proposed market design, the functions are modeled using an example network layout and corresponding asset penetration. The model setup relies on an actual network topology from a medium voltage grid. In addition, scenario-based input data provide different sensitivities regarding flexibility demand, supply, and market participation.

5.2.1 Modeling Environment and Process

The modeling environment is inspired by preliminary works within the project C/sells [6] and is further enriched with specific features applied within this thesis. Fig. 5.4 shows the general modeling environment, input dependencies, and respective simulation process. The setup is based on input data resulting from external sources (e.g., provided or defined by the involved DSO[4]), preliminary works (i.e., cited from relevant literature resources), and assumptions, defining the experiment outline for the particular platform functions under review. Further, these input data relate to grid specifications, market properties, and auxiliary data. 2013 was chosen as the sample year for providing meteorological input data. The actual input to the functions is diverse. In addition, there are some dependencies between the functions that demand input from other functions according to the platform process (see Sec. 5.1).

The *aggregation* function, derived in Sec. 5.3, demands input regarding available FOs in the market area (i.e., flexibility potential), combined with grid topology data to generate relevant aggregation pools. In a next step, aggregated offer bids are generated based on these pools. By integrating external prognosis data (e.g., temperature forecast) and a preprocessed lookup table containing simultaneity factors (Sec. 5.3.2), the aggregated offers are created under consideration of predefined call restrictions.

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[4] The field test within the project C/sells was conducted in collaboration with Bayernwerk Netz GmbH as the responsible local grid operator for the respective grid area.

The *market monitoring* function (Sec. 5.4) considers available offer bids (schedule offers and aggregated pools, see Fig. 5.2) and weighting them according to their effectiveness on the flexibility demand. Then, key indicators describing market power tendencies (Sec. 5.4.3) are calculated, considering the given ownership structure of the available FOs in the market area.

Finally, the *matching* function (Sec. 5.5) allocates all available offers (schedule and aggregated) to the given flexibility demand under consideration of the effectiveness values and technical restrictions included in the offer bids.

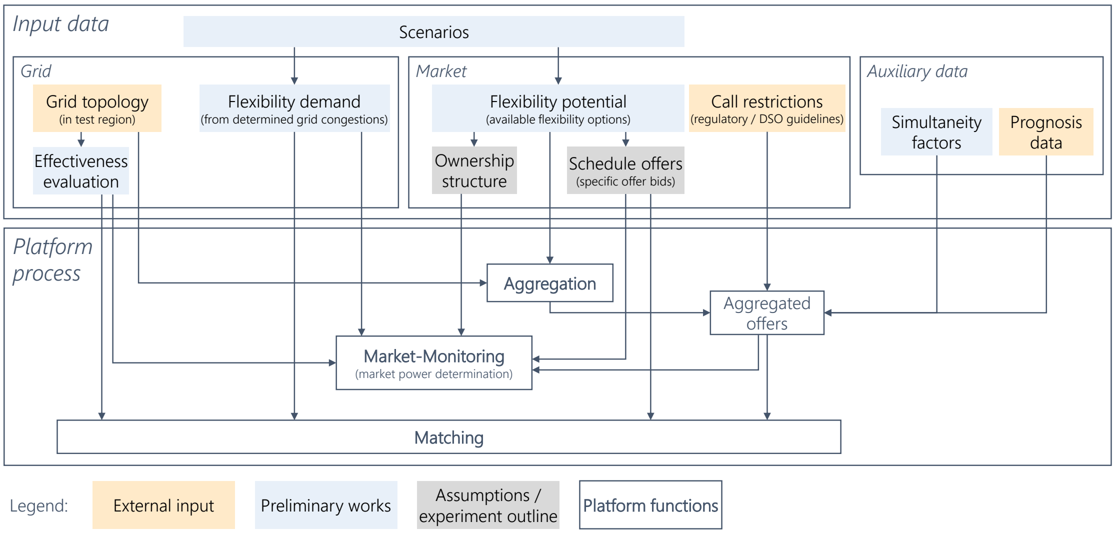

Figure 5.4: Modeling environment and simulation process

In the following, the modeling parameters and simulation data used within the case studies of the next sections are defined and referenced.

5.2.2 Simulation Input Data

To achieve robust results within the case studies, input data based on available network and market conditions were used from preliminary works. The definition of power direction for flexibility provision is equal to the specification of balancing power[5] [78].

Scenarios As a result of a bottom-up scenario process during the project C/sells, four different scenarios set the foundation regarding available loads and generation units within the network [200]. These scenarios evolve from the status quo representing the current grid state and asset penetration. They are characterized by different penetration ratios, asset composition, and load behavior that finally result in a specific flexibility

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[5] Positive flexibility: increased feed-in power/reduced consumption; negative flexibility: reduced feed-in power/increased consumption; in consequence, positive demand requires positive, and negative requires negative flexibility provision, respectively.

demand combined with the respective flexibility potential (see [6, p. 148 ff.]). The scenarios are outlined as follows:

- *Evaluation Scenario "Solar Producer" (SP)* is defined by a high addition of ground-mounted PV and rooftop systems with a reduced electrical consumption compared to the baseline (i.e., HP penetration remains unchanged, no EV is considered, and currently existing ESH are reduced by 50%). With a penetration of 100%, each rooftop PV system is assigned a HSS. Further, the existing capacity of ground-mounted PV is increased. [6, p. 149]

- *Evaluation Scenario "Electrified Consumer" (EC)* is characterized by a significant increase of electrical consumers, combined with little additional renewable energy units. Thus, the penetrations of EV (11 kW charging power) is 50% of all residential units. HPs are attached to 50% of all house connections. The number of ESH remains unchanged. All three types of loads are controlled based on market prices within the scenario. Rooftop PV remains at a low share of the project region's existing potential. Further, 50% of the rooftop PV systems are equipped with HSS [6, p. 149].

- *Evaluation Scenario "Autonomous Prosumer" (AP)* combines the preceding scenarios. HP and EV have a penetration of 50% and existing ESH remain in operation. Available PV potential is being exploited to a high degree, with 100% of rooftop PV being supplemented with HSS. Installed capacity of the ground-mounted PV is also increased. The charging control lies in the hand of the individual actor, i.e., acting with a focus to increase the individual autonomy of the prosumer [6, p. 150].

- *Evaluation Scenario "Market-oriented Prosumer" (PM)* shows identical penetration characteristics as AP. In contrast to AP, the load components charge according to market prices [6, p. 150].

The underlying grid penetration within the developed scenarios is illustrated in the following graphs in Fig. 5.5.

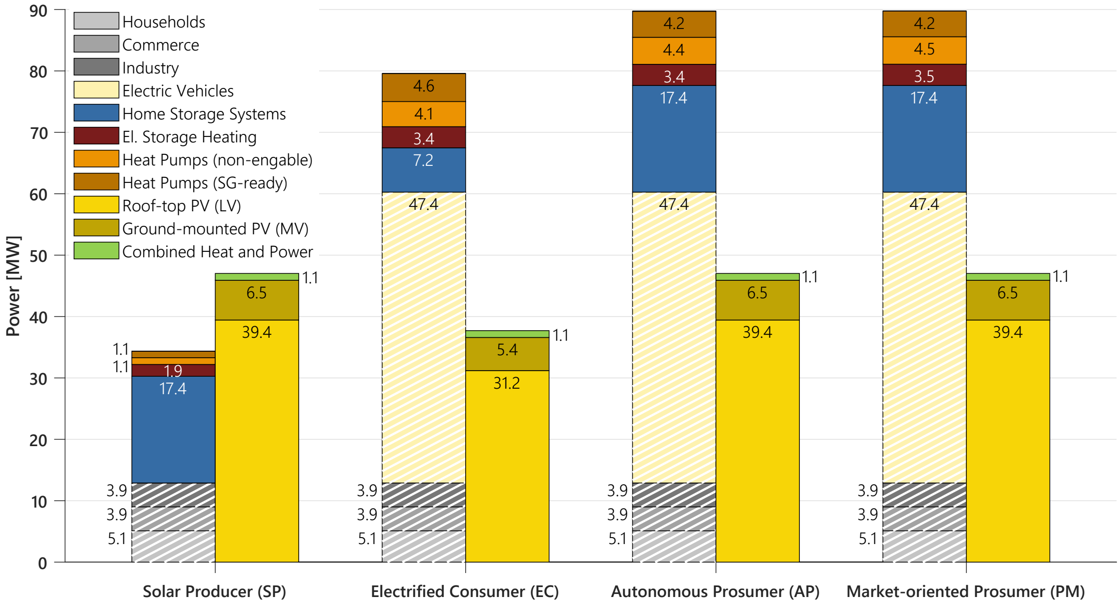

Figure 5.5: Installed capacity of relevant components in the four scenarios (hatched lines describe components that are not considered as flexibility options), based on [6, pp. 154-155]

Grid Data The network's underlying structure is defined by its topology and installed equipment. The input data was therefore provided by Bayernwerk Netz GmbH within the project C/sells. The project region is located in Lower Bavaria around the municipality of Altdorf. Further, available information regarding connection point specific energy consumption as well as installed RE capacities served as input data. [6, pp. 144ff].

Grid Topology and Effectiveness Evaluation The analyzed MV network is characterized by four urban and four rural branches that are supplied via two HV/MV transformers. 173 LV networks are connected to the MV network via local network transformers. In addition, five larger PV plants are directly connected to the MV grid. Fig. 5.6 illustrates the grid topology and configuration of the considered MV grid.

In order to determine the actual impact of an activated FO to the specific topological location of the congested network element, an *effectiveness evaluation* was conducted and presented in [186]. The impact of a power adjustment at all relevant grid connection points is therefore evaluated through the corresponding change in current or voltage at all relevant grid components, depending on the grid's circuitry and impedance factors. By linearizing the resulting changes, effectiveness (i.e., sensitivity) factors were derived. Applied regression analyses proved generalizability within certain boundaries. This resulted in an effectiveness matrix containing factors between an addressed grid component and the considered FO in A/kW or V/kW, respectively. This allows to approximate and evaluate the effect of flexibility without the need for continuous load flow simulations. No detailed and sensitive grid data must be provided to the SMP. [11, pp. 11-12]

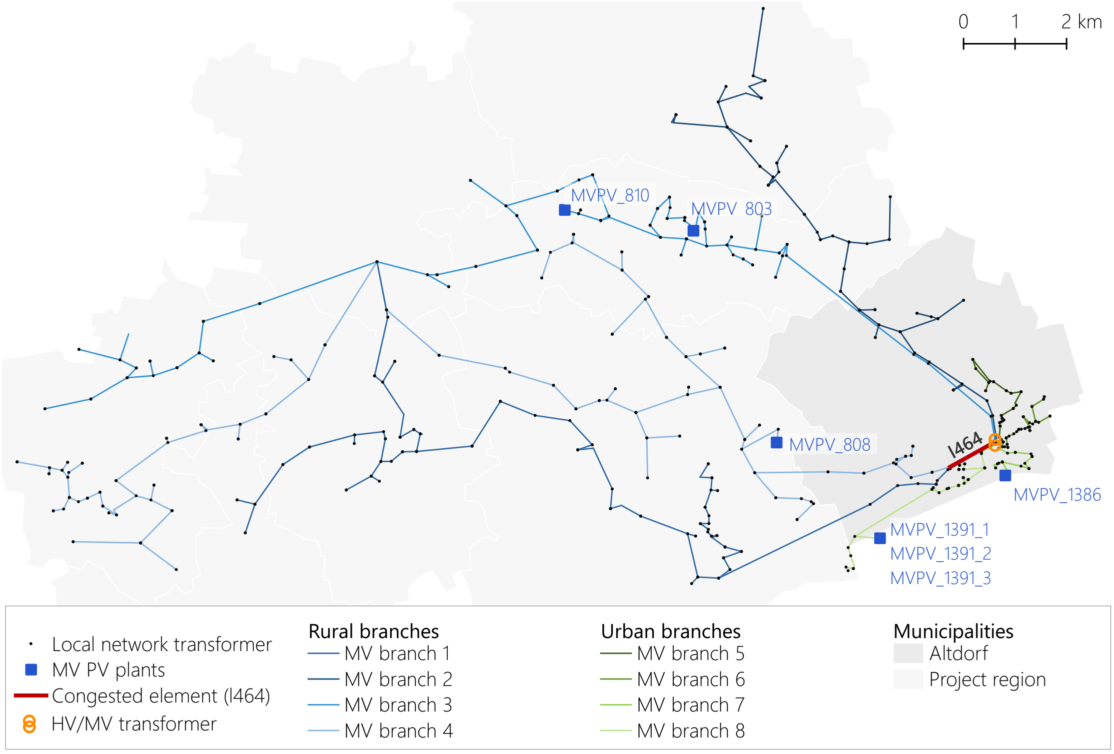

Figure 5.6: Considered medium-voltage grid including relevant components within the project region (adapted according to [6, p. 145])

Flexibility Demand As the focus of this thesis lies on the SMP layout and interactions with relevant stakeholders, the horizon of consideration towards DSO processes ends with the provided interface to supply flexibility demands to the platform. Nevertheless, the determination of relevant flexibility demand within the evaluation period was extensively investigated in corresponding research (see [6, pp. 155-184]). For this reason, demand bids to the platform are considered as external input from preliminary works based on the same initial input parameters to guarantee consistency. Tab. 5.1 provides key parameters of occurring grid congestions within the modeled sample year. The grid component *l464* (see Fig. 5.6) shows the highest number of congestions. The demand distribution can be seen in Appendix Fig. A.2.

	Positive demand					**Negative demand**				
Scenario	**Number of cong.**	**Mean** [*A*]	**Median** [*A*]	**Max** [*A*]	**Most cong. component (count)**	**Number of cong.**	**Mean** [*A*]	**Median** [*A*]	**Max** [*A*]	**Most cong. component (count)**
SP	0	0	0	0	-	3,313	-32.1	-27.8	-149.9	*l464* (1,839)
EC	593	33.0	24.0	228.3	*l464* (352)	651	-11.7	-9.3	-58.0	*l464* (575)
AB	29	3.2	2.5	10.7	*l464* (29)	1,931	-24.8	-22.3	-95.5	*l464* (1421)
PM	457	31.8	22.8	218.2	*l464* (283)	2,054	-25.4	-22.4	-99.7	*l464* (1,456)

Table 5.1: Key parameters of flexibility demand resulting from congestions in the four scenarios

Market Data Available offers to the SMP are dependent on the actual flexibility potential of existing FOs including their provided products, i.e., schedule offers or aggregated offers in long-term contraction (see Fig. 5.2). The latter option is further depending on defined call restriction according to regulatory and DSO guidelines (see Tab. A.1 referring to § 14a EnWG) [8, 101].

Available Flexibility Options The local flexibility potential is directly linked to the defined scenarios. Considered FOs include HSS, CHP, ESH, HP and PV. Households, commercial and industrial loads are not considered as flexibility options due to little potential or lacking data. Furthermore, electric vehicles are excluded as their marketing options are complex and not a specific part of this study. As several ongoing projects (e.g., *unIT-e²* or *BDL*[6]) focus on aggregating, forecasting, and efficiently marketing electric mobility services, this thesis will only give reference to the potential relevance of these flexibility options, but will not focus on their exploitation.

Fig. 5.5 (non-hatched graphs) and Fig. A.3 give an overview of the FO's distribution within the considered MV grid.

Schedule Offer Parameters Within the defined experimental setup, only HSS and CHP plants are considered as actively marketed flexibility options (compare Sec. 5.1) and subsequently provide schedule offers. With the aim to provide realistic market availability and reduce complexity to be able to interpret the results, the parameters in Tab. A.1 were chosen. With the intention to leave sufficient capacity for normal operation (i.e., optimized local consumption), only ± 50% of HSS power is offered as potential grid-supportive flexibility. To meet the energy constraints, a 2 h off-time interval is considered sufficient to "balance" the previous flexibility call with maximum 2 h of call duration or to prepare for the next one. CHPs are considered to offer ± 20% of their installed power, as efficiency losses emerge in partial load below 80% according to [201, pp. 17-18]. Furthermore, as calls are announced day-ahead, they can be included in the internal planning process.

Long-term Contraction Parameters and Call Restrictions PV plants receive an individual prognosis according to their orientation and tilt based on reference meteorological data of the sample year 2013. HP and ESH use the same meteorological input (i.e., temperature) and are aggregated according to the process described in Sec. 5.3. Tab. A.1 provides further details on the chosen assumptions.

Additional Data Besides the described data, further external information or assumptions are used within the specific analyses in the following case study sections. For the aggregation function (Sec. 5.3.4), these include *prognosis data* based on the applied meteorological year (2013), and *simultaneity factors* (derived in Sec. 5.3.2). Within the market monitoring function (Sec. 5.4.4), assumptions regarding a potential *ownership structure* were made.

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[6] www.ffe.de/bdl, www.ffe.de/unit-e

5.3 Function: Aggregation

As already introduced in Section 5.1, the SMP considers two different types of products, i.e., schedule offers and long-term contraction. The latter intends to provide access to small-scale FOs that currently do not have the opportunity to provide sufficient information to predict their available flexibility or place a corresponding offer bid. The considered solution approach contains an automated marketing service that includes predictions under a certain minimum reliability. Applied to renewable energy resources, several commercial providers already offer prognosis services generating individual generation forecasts. Small-scale loads, e.g., heat pumps or electrical storage heaters, still lack such services. This is for a reason, as their power consumption is, on the one hand, driven by external parameters (e.g., temperature) and, on the other hand, relies on individual user behavior that can hardly be specifically predicted. Nevertheless, these small-scale assets can provide relevant flexibility potential, especially in the lower voltage levels (see Fig. 3.2) [202]. Inspired by the methods applied to assess standard load profiles of household consumption [203], an aggregation scheme can also be applied to stochastically determine the available flexibility of a pool of FOs. Within [8], the approach was already presented, describing the integration process, the determination of available aggregated flexibility, and, finally, the respective options for pool formation to market aggregated offer bids on an SMP.

5.3.1 Functional Requirements of an Aggregation and Pooling Scheme

The defined goal is to generate valid and reliable flexibility offers for pooled FOs that need to be made available to the central matching process in a defined format (i.e., arrays of available power for a defined grid-location in steps of 15 minutes). The prediction methodology should therefore rely on aggregating them into different pools and calculating the simultaneity factor based on historical data. The forecast method should also take into account confidence intervals (i.e., Level of Security (LoS)) to assess the reliability of the process. Once the prediction has been conducted, the next step is to create an aggregated flexibility offer at the SMP, which considers system type and the locality of the pool. This locality is needed to apply the effectiveness evaluation as proposed in [186]. Finally, generated pools should be as big as possible but as small as necessary to consider homogeneous effectiveness values within the pool [8].

Another challenge is the technical restrictions of each system that need to be considered. The flexible capacity, for example, is dependent on the size of the warm water tank of the HP. However, as there is already an existing process defined by § 14a EnWG for accessing current flexibility through the DSO (even if limited in its effectiveness), these preconditions can be used as a common basis [8]. In practice, this means that there are already technical requirements legally defined that controllable loads need to fulfill to offer their flexibility [101]. The challenge to providing an accurate forecast is the lack of information to predict the specific technical behavior of each system, as these are operated under the influence of stochastic parameters (i.e., user behavior). Nevertheless, external factors influence the behavior on an aggregated level (i.e., day of the week, season, temperature level, etc.). [204, 205, 206]

The proposed aggregation scheme should eventually consider HPs and ESHs. HPs can be engageable and/or disengageable. Disengageable HPs are the standard case and already in application through existing usage agreements with the DSO according to the named § 14a EnWG (see Sec. 3.1.1). Engageable types are currently specified by a "Smart Grid (SG)-Ready" label that verifies that these can be forced to heat [207]. ESHs currently provide the highest negative flexibility potential compared to other decentralized loads [202]. Nevertheless, tapping their flexibility is constrained by several boundary conditions, as described in [208]. Their realistic potential is significantly reduced, starting with the use of old technology, integrated into an existing system of defined nocturnal release times (usually between 10 PM and 6 AM), and a subdivision into forward and backward controlled systems. And still, relevant effort needs to be undertaken to provide reliable function. [208] EVs are a very prospective type of (future) decentralized flexibility potential and could potentially also be pooled and eventually marketed with the given approach. Nevertheless, an aggregated use, based on a stochastic evaluation, cannot adequately represent the complexity of the actual usage and therefore availability of EVs. Combined with extensive research effort that is currently going on to develop an optimized way of considering both, individual usage behavior and a minimal loss of comfort, a stochastic aggregation can only be a first step. For these reasons, in the following, the aggregation method is exemplarily exercised to HPs only (both, engageable and disengageable) as derived in [8]. Nevertheless, within the case study in Sec. 5.3.4, ESHs are also included under the given restrictions. EVs are deliberately neglected within the case study due to the named shortcomings.

5.3.2 Statistical Simultaneity Factors and Available Flexibility

To derive the available flexibility, within a first step, relevant impact factors have to be determined. In the case of HPs, time t, (equivalent daily mean) temperature[7] $T_{m,eq}$ and number of systems n under a defined minimal reliability (i.e., LoS) do have the biggest impact. Additional parameters, like the day of the week, season, or household sizes, are neglected as these already influence the chosen values or lack input data. By cause of missing measured data in the needed resolution, generic heat pump load profiles with 15 minutes time resolution for a whole year were used. These varied based on assumed numbers of persons per household, heat pump sizes, location, and building age [8, 9].

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[7] The equivalent daily mean temperature $T_{m,eq}$ serves as an indicator of the heating demand, taking into account the thermal inertia of the building. It is calculated from the average daily temperatures T_m of the last three days and the considered day d to:
$T_{m,eq} = 0.5 \cdot T_m(d) + 0.3 \cdot T_m(d-1) + 0.15 \cdot T_m(d-2) + 0.05 \cdot T_m(d-3)$

The determination process of the simultaneity factors was finally conducted in the following steps:

1. Generation of a data sample with several thousands of heat pump load profiles for the same year with identical meteorological conditions
2. Resampling process (applied 1,000 times without replacement)
    a) Random selection of a defined number of profiles n
    b) Calculation of the simultaneity factor depending on n and sample for each 15 minutes and grouping by $T_{m,eq}$
3. Determination of quantiles reflecting the probability of specific simultaneity factors
4. Export of lookup table for the defined degree of security

Based on the derived values, a prediction of available and running heat pumps can be derived for each 15 minutes time step of the day, number of aggregated units, and outside temperature. Fig. 5.7 illustrates the simultaneity factor $g = f(t, T_{m,eq}, n)$ over one day with $T_{m,eq} = 3$ °C.

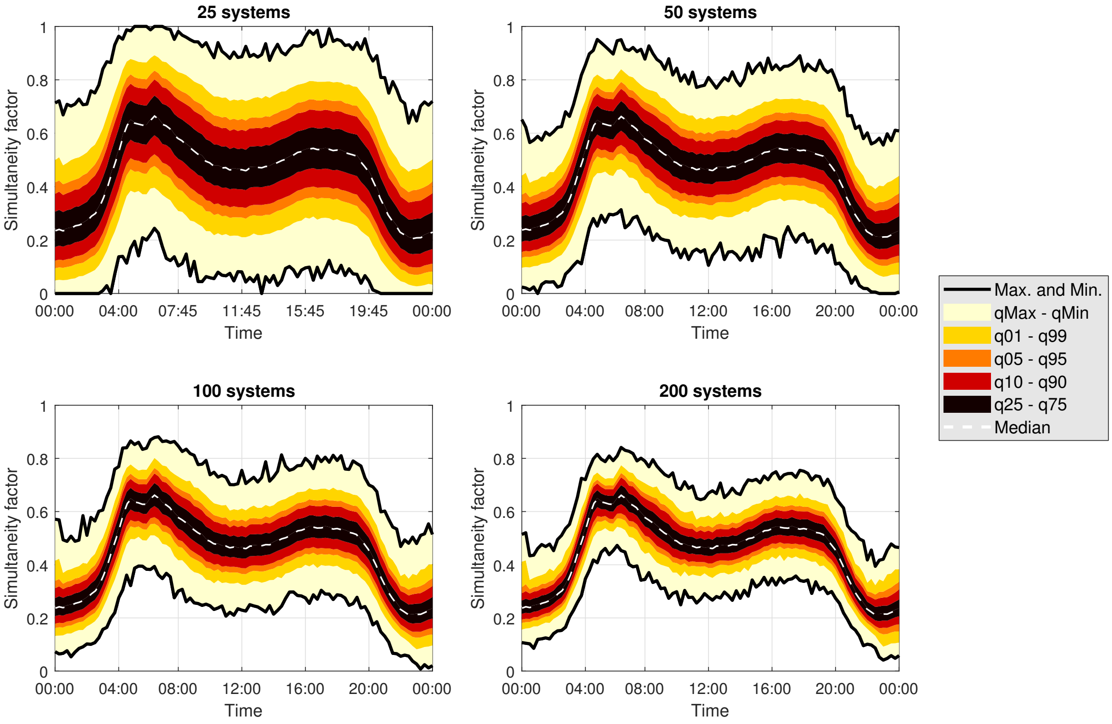


Figure 5.7: Quantiles of the simultaneity factors depending on number of systems and time of the day at an equivalent mean temperature of 3 °C (adapted according to [8, p. 3] and [9, p. 34])

Fig. 5.8 further depicts the simultaneity factors against the number of pooled systems in different temperature scenarios.

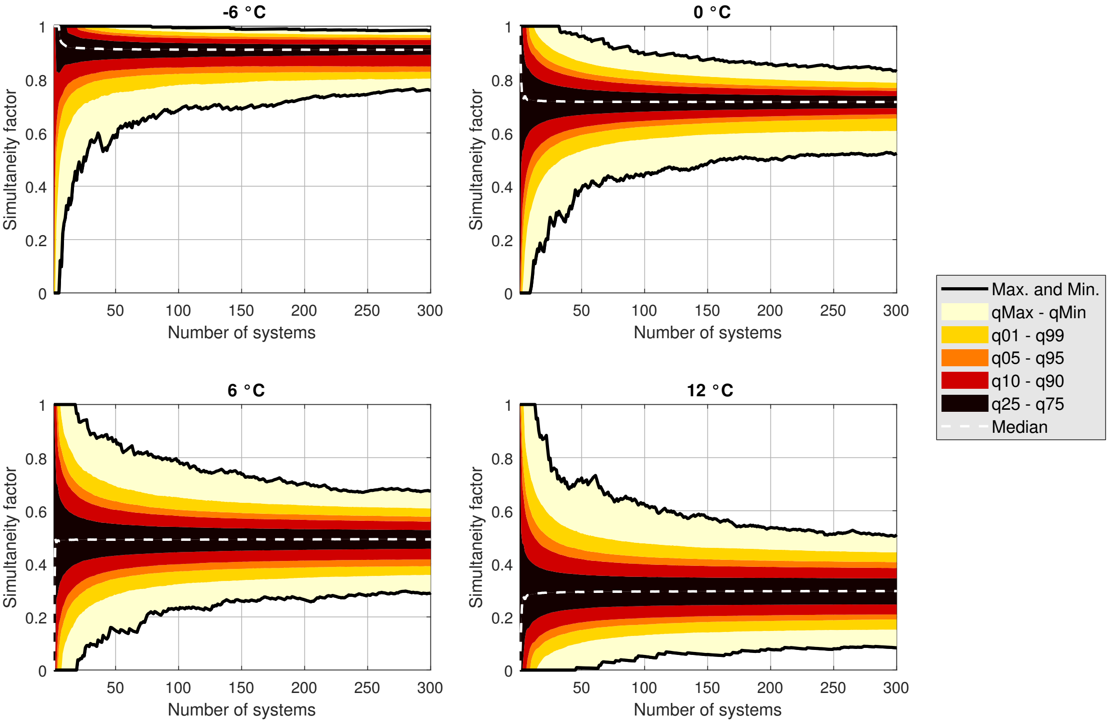


Figure 5.8: Quantiles of the simultaneity factors for different temperatures and numbers of systems at 7:30 AM (adapted according to [8, p. 3] and [9, p. 33])

The LoS of these predictions finally relies on the chosen quantile q and describes, in how many cases these simultaneity factors are undercut. For example, the 10% quantile ($q10$) describes that in 90% of the samples, the simultaneity factors lies above the determined value. Subsequently, only 10% of the values are below this boundary. The choice of an appropriate LoS depends on various considerations. As—in contrast to balancing power provision—grid-supportive flexibility use, as intended here, provides certain planning uncertainties. A 90% LoS is chosen for the following evaluations and the case study in Sec. 5.3.4. Finally, based on these values, a simultaneity factor matrix in form of a three-dimensional look-up table (value dependent on time of the day, mean temperature, and number of pooled units) can be derived.

As the previous figures describe the quantiles of simultaneous heat pump operation, the disengageable, as well as the engageable power reflecting positive and negative flexibility can be derived from these values. Positive available flexibility (disengageable power) can then be calculated via Equation 5.1 and negative flexibility (engageable power) via Equation 5.2.

$$P_{av}^{+} = g_{q10} \cdot P_{mean} \cdot n \tag{5.1}$$

$$P_{av}^{-} = (1 - g_{q90}) \cdot P_{mean} \cdot n \tag{5.2}$$

where

$P_{av}^{+/-}$	Available disengageable / engageable power in kW
g_{q10}	10% Quantile of simultaneity factor, depending on $t, T_{m,eq}, n$ (corresponding to a chosen LoS of 90%)
g_{q90}	90% Quantile of simultaneity factor, depending on $t, T_{m,eq}, n$ (corresponding to a chosen LoS of 90%)
P_{mean}	Mean power of all the systems in kW
n	Number of systems

Fig. 5.9 illustrates the simultaneity factor g at the chosen LoS of 90% at different time and temperature combinations (left) and the respective resulting available positive power P_{av}^{+} (right) with $P_{mean} = 2.87$ kW.

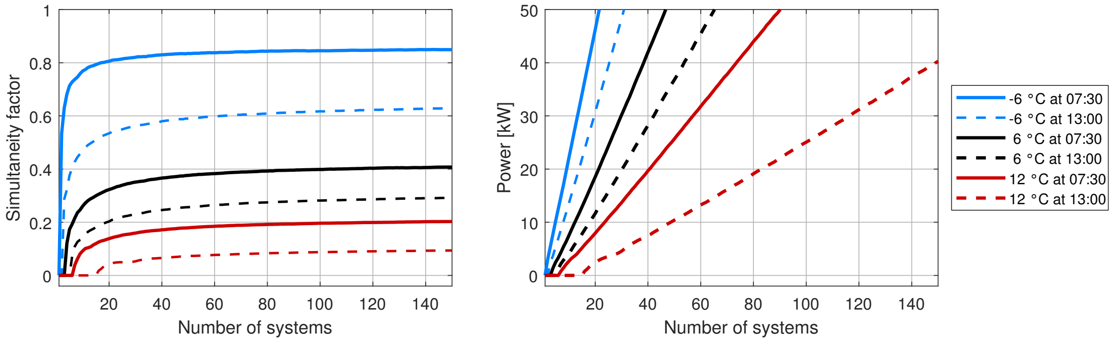


Figure 5.9: Simultaneity factor (left) and respective positive flexible power (right) at different temperatures and times of the day at a Level of Security of 90% and $P_{mean} = 2.87$ kW (adapted according to [8, p. 4] and [9, p. 48])

By supplying the determined look-up table to the SMP, containing all relevant data to calculate the available flexibility based on temperature prognosis and the time of the grid congestion, the aggregated offer bids are determined based on the number of aggregated units. To determine this number, different methods are available to choose an appropriate pool size.

5.3.3 Pool Formation and Aggregation

By using the values in the respective lookup table, it is now possible to statistically determine available flexible power of a pool of systems of the same type at a certain LoS depending on the relevant external factors [8]. The next step is the integration of this information for use in the SMP process, i.e., defining the pool formation and, therefore, the appropriate level of aggregation from a grid perspective.

To define the level of aggregation, it is necessary to consider the following requirements and correlations:

1. Increasing the pool size reduces statistical uncertainties.
2. The systems in the pool should have homogeneous effectiveness factors.
3. The aggregation process should be comprehensible and traceable.

This finally leads to a conflict of interests, as in general, the larger the pool, the higher the simultaneity, but the more inconsistent the effectiveness factors of the pool due to wider topological dispersion. Another upcoming question is whether a partial call of the pool is necessary. There are two possibilities:

1. Always calling the entire pool provides the advantage that there is no minimum number of systems necessary per pool. On the other hand, it poses the risk of too much power for large pools in relation to the demand. Therefore, the pools should not be too big. For the calculation process, the simultaneity factor can simply be called from the lookup table as a function of the number of systems (n), temperature ($T_{m,eq}$) and time of the day (t).
2. Providing a partial call of the pool allows more precise matching. In case that only a part of the power that is available by the pool is demanded, only part of the systems in the pool will be addressed. On the other hand, it demands a fixed simultaneity factor based on a minimum number of systems as the simultaneity factor itself is dependant on the number of systems. This finally leads to a linearization of the available power graph, illustrated in Equation 5.3. Due to this, the fixed simultaneity factor is usually underestimating the available capacity. However, the methodology also works with large pools, since the simultaneity is converging to the median power with increasing numbers of systems.

$$P_{av} = g_{const} \cdot P_{mean} \cdot n_{partial} \tag{5.3}$$

where

P_{av}	Available power in kW
g_{const}	Constant simultaneity factor depending on $(t, T_{m,eq}, n_{min}, LoS)$
P_{mean}	Mean power of all the systems in kW
$n_{partial}$	Number of systems called in the range of $[n_{min}; n_{Pool}]$
n_{min}	Minimum number of necessary systems depending on $(t, T_{m,eq})$
n_{Pool}	Total number of systems in the pool

Linearization demands a minimum pool size n_{min} for each t and $T_{m,eq}$. To determine this number, different approaches are possible as described in [9]. In practical means, the necessity of a partial call is finally dependent on the pool size or the available power of the pool, respectively. This leads to an appropriate determination of the level of aggregation. The following different methods have been determined, all providing advantages but also certain requirements and drawbacks:

1. *Aggregation based on grid topology:*
    a) Static aggregation at the local grid transformer level represents a simple and comprehensive method. The number of systems per pool tends to be low which then can lead to high uncertainties. A partial call is less necessary due to little available power per pool.
    b) Static aggregation at defined points in the grid topology (switches, strings, load areas, etc.) can be restricted to a minimum number of systems. Subsequently, the addressable spots of congestion move up hierarchically, depending on the number of available systems.

    These two approaches do not require information regarding congestion but only of the grid structure. The level of aggregation determines the pool's effectiveness factor.

2. *Aggregation based on effectiveness evaluation:*
    a) Dynamic formation of groups of low voltage grids with similar effectiveness evaluation could be done until a minimum number of systems per pool is reached. Partial call-off is therefore possible.
    b) Arbitrary pooling of systems with similar effectiveness evaluation would also be feasible. The chosen pool effectiveness can be uniform for the entire pool (e.g., minimum or average effectiveness of the pool is used for the whole pool). This can lead to a significant underestimation of the pool's effectiveness.

    Approaches based on effectiveness evaluation only work for individual demands and, therefore, need information regarding the congestion.

Tab. 5.2 shows the differentiation of the given methods in a qualitative manner.

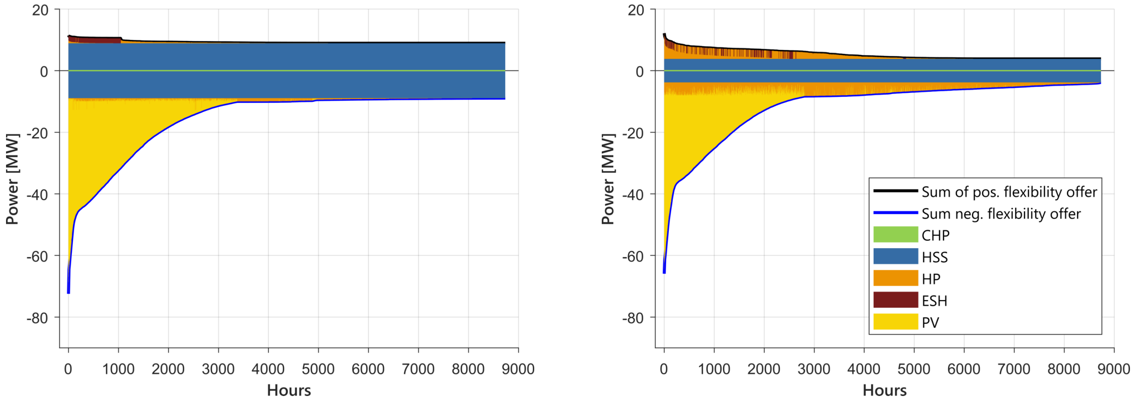
Aggregation method	**1a.**	**1b.**	**2a.**	**2b.**
Information on congestion necessary	*no*	*no*	*yes*	*yes*
Pool size	*tends to be little*	*sufficient*	*sufficient*	*sufficient*
Minimum pool size	*not necessary*	*yes*	*yes*	*yes*
Effectiveness	*homogenous*	*possibly heterogenous*	*rather homogenous*	*rather homogenous*
Partial call	*no*	*no*	*yes*	*yes*
Accuracy of intended power	*low for small pools*	*ok, increases with pool size*	*tends to underestimate*	*tends to underestimate*
Complexity	*low*	*medium*	*high*	*high*

Table 5.2: Qualitative overview of suggested aggregation methods' properties [8, p. 5]

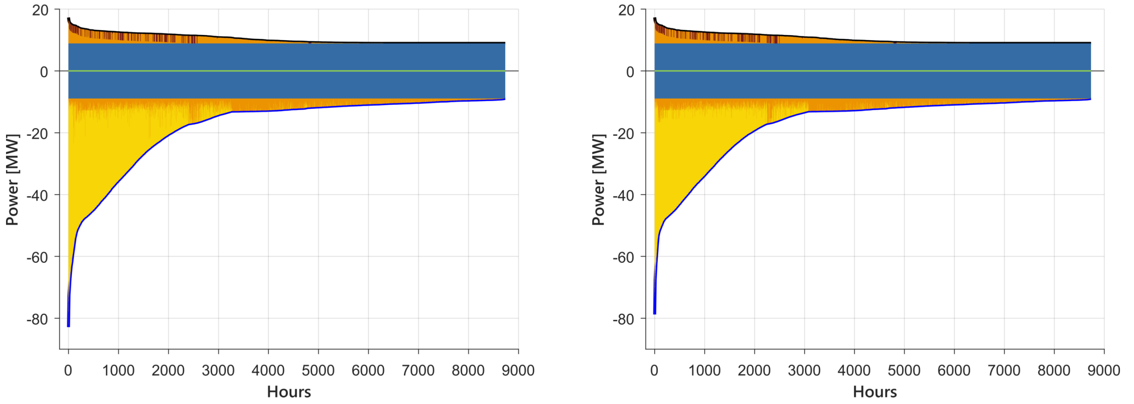
5.3.4 Case Study

In the following case study, aggregation method 1 a) in Tab. 5.2, based on topological aggregation at the MV/LV-transformer, has been applied to HP and ESH within the network setup described in Sec. 5.2.2 and Fig. 5.6 in the respective scenarios[8].

The following figures illustrate the resulting *total flexibility offers* (including all FOs) considering all available FOs over the year. Fig 5.10 depicts the duration curves of the positive and negative flexibility offers sorted by the total positive/negative flexibility[5] in distinct time steps over the year.



(a) “Solar Producer” (SP) **(b)** “Electrified Consumer” (EC)



(c) “Autonomous Prosumer” (AP) **(d)** “Market-oriented Prosumer” (PM)

Figure 5.10: Duration curve of positive and negative flexibility offers by flexibility types over the considered year in the four scenarios (legend in (b) applies to all figures)

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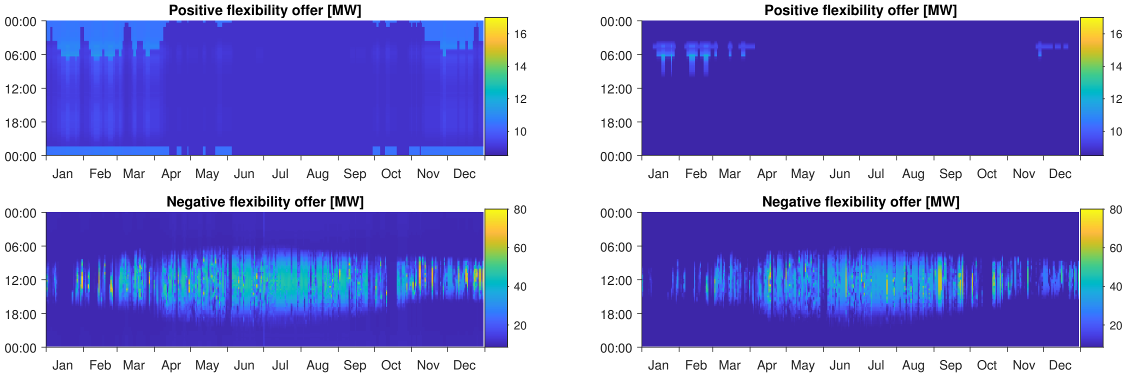
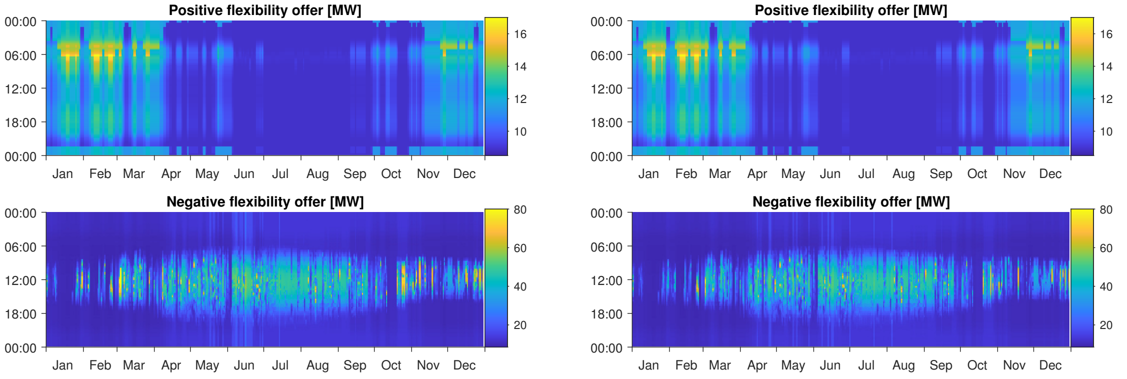
[8] Depending on the scenario, the number of pools with at least 10 units are composed as follows: *disengageable HPs*: 56 pools in scenarios EC, AP, PM (with max. 78 units), 4 in scenario SP (with max. 23 units); *engageable HPs*: 30 pools in scenarios EC, AP, PM (with max. 40 units), 1 pool in scenario SP (with 13 units); for *disengageable ESH*, the pool sizes remain the same in all four scenarios: 9 pools with more than 10 units and a maximum number of 37 units in the largest pool.

In most time steps, negative flexibility offer—dominated by potential curtailment of PV—exceeds the positive offer. A baseline of flexibility in both directions is provided by CHP and HSS, although differing in amount. In positive direction, disengageable HPs and ESHs make their contribution. Negative flexibility (besides PV) is also provided by engageable HPs. Fig 5.11 transfers these parameters to the dates and hours of the chosen year.



(a) “Solar Producer” (SP)

(b) “Electrified Consumer” (EC)



(c) “Autonomous Prosumer” (AP)

(d) “Market-oriented Prosumer” (PM)

Figure 5.11: Flexibility offer by date and hour of the day over the chosen year in the four scenarios

The charts allow several conclusions to be drawn that are directly linked to the chosen scenarios and the initial modeling setup (see Sec. 5.2.2, Fig. 5.5, and Tab. A.1): As ESH is only disengageable during release time (10 PM until 6 AM) and only limited to forward controlled units (50%) that start charging at 10 PM, accessible flexibility potential is quite limited. Fig. 5.11 a) shows mainly ESH as positive aggregated flexibility offer. Fig. 5.11 c)–d) represent similar positive potential, resulting from available disengageable HPs. These are specifically dominant in the morning hours in winter.

5.3.5 Conclusion and Critical Review

The described approach to tap the flexibility potential of decentralized controllable loads through aggregation shows a method to forecast the flexible power of pooled small-scale FOs. However, there are some challenges on the way. The shown prediction method is based on synthetic data due to a lack of available, measured historical values. This may result in the risk of having too similar profiles. Applying measured data in the simultaneity factor determination could increase its reliability. In addition, until now, it is not possible to challenge the forecast method with measured values. The suggested approach only works in normal, temperature-driven operating modes. If the plants are actively marketed or operated based on other signals, such as excess PV, the presented methodology is not directly applicable.

The pooling approach is crucial for the whole method. In contrast to system balancing services, similar effectiveness factors within the pool are required in a local market environment, such as an SMP. Therefore, pool sizes are limited which results in lower simultaneity factors.

Finally, the presented method is comprehensive and applicable. It provides an efficient way of integrating HPs and ESHs as the prevailing legacy systems into an SMP environment and allows to access their available flexibility potential.

5.4 Function: Market Monitoring

Market monitoring serves to control market power and manipulative behaviour. Past events show that market manipulation can become a relevant problem in electricity markets. One example is the California Energy Crisis in the years 1998 to 2002 where—after a fundamental market deregulation—market manipulation was exercised extensively. Market prices increased up to tenfold, finally leading to an estimated economic impact of \$40 to \$45 billion over two years [209, p. 4]. Market power played a major role in this. [187, p. 3]

In limited market environments, as is the case in regionalized markets such as market-based congestion management (i.e., SMP), limited liquidity may further encourage the exploitation of market power. As this can lead to significant inefficiencies, identification for potential penalties is necessary.

5.4.1 Functional Requirements of a Market Monitoring Scheme

Not least as a consequence of the events of the California Energy Crisis, several methods have been developed to detect and measure market power. A distinction must be made between the analysis of markets for their potential vulnerability to the abuse of market power and the examination of market outcomes for evidence of the exercise of market power [187, p. 26]. In [184, p. 10], different market power detection techniques are listed, divided into ex-ante or ex-post, and long-term or short-term analysis.

Within this work, focus lies on a possibility to identify structural market power (see Sec. 4.1). As the SMP concept is still a new development, the real market behavior of participating actors is difficult to map. Therefore, based on the available data, an a priori and platform-integrated assessment process should give insights into structural market power tendencies. The use of comprehensible metrics within a comprehensive approach shall provide a better understanding and insight into the possible compositions of market participants.

In consequence, exercised market power is not in focus as it demands bidding behavior. Same applies to potential mitigation of (INC-DEC) gaming, as this requires monitoring of parallel market structures within an external function. However, this still leaves room for future research approaches.

5.4.2 Measuring Structural Market Power

The presence of structural market power can be measured by applying a variety of instruments [181]. The following sections rely on [77], where the presented descriptions and methods have already been published.

The Concentration Ratio (CR) (Equation 5.4) and the Herfindahl-Hirschman Index (HHI) (Equation 5.5) are two common indicators used to measure structural market power [210].

$$\mathrm{CR}_n = (\sum_{i=1}^{n} S_i) \tag{5.4}$$

$$\mathrm{HHI} = (\sum_{i=1}^{N} S_i^2) \tag{5.5}$$

where

n	Number of the largest suppliers within the market
S_i	Market share of firm i in %
N	Total number of suppliers within the market

The CR simply adds the market shares of the n largest suppliers to measure their degree of control to the chosen industry. The higher the CR, the more likely one or more of these n firms can exercise market power. Different sources consider different concentration ratios as the threshold for structural market power for different numbers of firms (see [184]). [187, p. 27] While the concentration ratio measures only the market share of the n largest firms in a given market, the HHI considers all firms in the market. As can be seen in Equation 5.5, the market share of each supplier in the market is squared, and these values are then summed to produce the HHI value. More highly concentrated markets are represented by increasing values, up to a value of 10,000 (equal to $(100\%)^2$), representing a complete monopoly [184]. [77]

Both of these indicators are generalized tools that only consider the supply side of the market [211, 212]. Prior to deregulation of the California energy markets in the late 1990's, metrics including the CR and HHI indicated a competitive market. In reality, the widespread abuse of market power was a contributing factor to the crisis [212, 213]. After the crisis, the Residual Supply Index (RSI) was developed by the California Independent System Operator (CAISO) specifically for use in energy markets, where fluctuating demand can lead to small firms being able to exercise market power [210, 212]. The equation used to calculate the RSI can be seen in Equation 5.6.

$$\mathrm{RSI}_x = \frac{\sum_i^N C_i - C_x}{L} \tag{5.6}$$

where

C_i	Generation of a market participant i
C_x	Generation of the participant x being examined for market power
L	Load to be met
N	Total number of suppliers within the market

A pair of threshold values are of particular interest. An RSI value below 1 indicates that demand cannot be met without the generation controlled by the participant in question. This participant is then described as pivotal and possesses structural market power [214]. An RSI value of 1.2 is the second threshold of interest. Statistically significant evidence was found linking an RSI value of the largest participant of 1.2 or larger with market results functionally equivalent to a competitive baseline result [215]. Values between 1 and 1.2 indicate situations in which the owner in question can likely exert some influence on price, but not to the same extent as when pivotal [184]. The German competition authorities consider an RSI value of 1.1 or lower in over 5% of hours in a year indicative of structural market power in wholesale markets [211].

5.4.3 Application of the RSI to Local Flexibility Markets

Several properties specific to an SMP require an adaption of the initial RSI calculation. This includes the fact of a limited market area. Further, the effectiveness of flexibility supply bids to a demand needs to be considered. Besides that, market actors are inhomogeneous based on their technical abilities. These are also reflected in the product specifications and directly linked to the typical distribution of bid-sizes (including limitation to, e.g., call levels). Pools with large numbers of units marketed by a single aggregator or big individual plants can have a dominant role in the market relative to competing market participants. While application of the RSI to electricity markets can be performed using rated power, additional steps must be taken in an SMP. The ability to influence congestion of a specific network element is determined in part by the unit's location relative to the congestion and the underlying grid topology. Therefore, the effective flexibility of the individual FO on a chosen congestion can be determined by including the effectiveness factor (see Sec. 5.2.2) and the rated power. All individual values can then be summed to obtain the total available effective flexibility. Once the effective flexibilities for all FOs can be calculated, ownership of each unit must be determined to calculate the RSI of individual market actors. A final adjustment to the original RSI formula concerns demand [212]. In a market for flexibility, a (localized) demand is represented by the change in power required to return the current flowing over the congested element to safe operating levels[9]. With these alterations, the adjusted formula for the calculation of the RSI in an SMP is given in Equation 5.7.

$$RSI_{xl} = \frac{\sum_{i=1}^{N}(\Delta P_i \cdot e_{il}) - \Delta P_x \cdot e_{xl}}{\Delta I_l} \tag{5.7}$$

where

ΔP_i	Flexible power adaption ΔP provided by FO i in kW
e_{il}	Effectiveness factor of FO i to grid component l in $\frac{\text{A}}{\text{kW}}$
ΔP_x	Flexible power adaption ΔP provided by examined FO x in kW
e_{xl}	Effectiveness factor of examined FO x to grid component l in $\frac{\text{A}}{\text{kW}}$
ΔI_l	Demanded Flexibility at grid component l in A

5.4.4 Case Study

Based on these adjustments to the RSI formula, the case study presented below will apply the RSI to the MV network described in Sec. 5.2.2 as a demonstration of its potential for market monitoring. The following analyses include both a static approach to market power evaluation based on installed capacities (see Fig. 5.5), as well as an application of the method to individual time-steps within the year-long simulation based upon the available effective flexibilities. To conduct an exemplary evaluation for all four scenarios, line *l464* in *MV branch 4* (see Fig. 5.6, Tab. 5.1, and Fig. A.2) was chosen, as it represents the most congested grid component in all four scenarios (for positive and negative flexibility demands[5]).

Exemplary RSI-Evaluation in a Single Time Step Starting with a static evaluation of potential market power tendencies, the installed capacities serve as the evaluation basis according to [77] and [187]. Within Fig. 5.12, the RSI values of available asset and different aggregation[10] options are depicted as a function of potential flexibility demand (x-axis) in one time step within the four scenarios. In addition, limited competition scenarios are modeled. To assess different market constellations within the evaluation, the following marketing option are distinguished (see legend in Fig. 5.12 (a)).

1. *Asset with largest impact* (effective power) on the congested element (*l464*) for positive/negative flexibility demand (i.e., pos.: *HSS_507*, neg.: *MVPV_808*)
2. *Aggregation of positive flexibility offers*, i.e., *all HP units* or *all HSS units* respectively pooled by a single marketer
3. *Aggregation of negative flexibility offers*, i.e., *all LV PV power plants* or *all HSS units* respectively pooled by a single marketer

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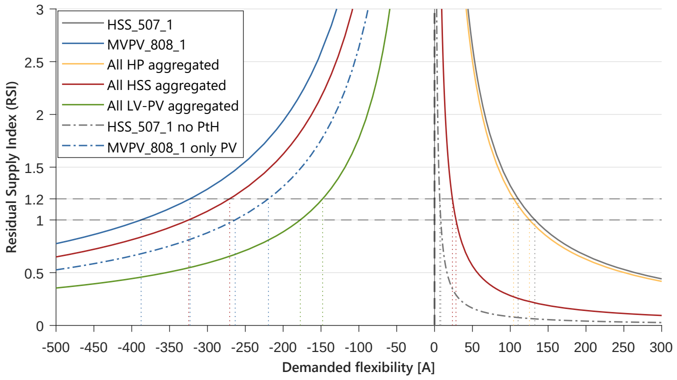
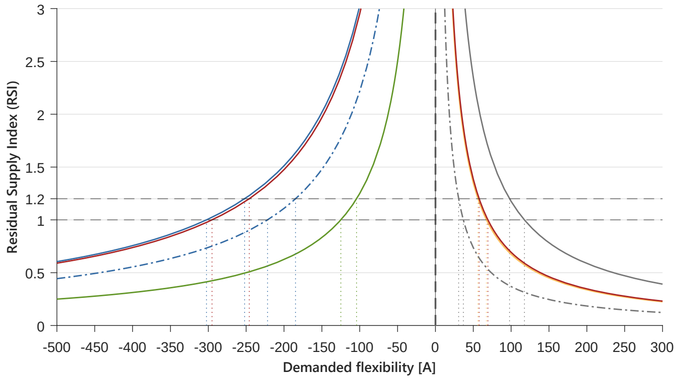
[9] The consideration of voltage band violations is neglected here. However, a corresponding adjustment would be possible by modifying the effectiveness values.

[10] This aggregation refers to the joint marketing of the respective FOs by one single entity/marketer and is not to be mistaken for the aggregation mechanism in Sec. 5.3.

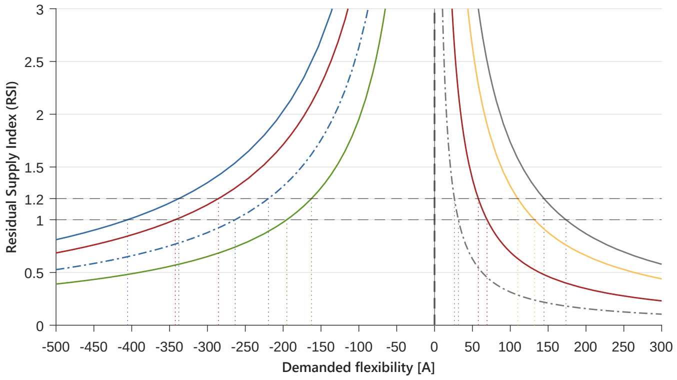
4. *Restricted available flexibility supply*, reflecting reduced market competition, i.e., in positive direction: *no availability of Power-to-Heat (PtH) units* (i.e., no offers of HPs and ESHs) and in negative direction: *only competing PV offers available*



(a) “Solar Producer” (SP)



(b) “Electrified Consumer” (EC)



(c) “Auton. Prosumer” (AP) / “Market-or. Prosumer” (PM)

Figure 5.12: Residual Supply Index (RSI) as a function of flexibility demand at congested grid element *l464* for different offer compositions in the four scenarios (legend in (a) applies to all three figures)

As the assessments are purely dependent on installed capacities, the differences between scenarios AP and PM are marginal and, in consequence, produce similar results. The results are jointly displayed in Fig. 5.12 (c). The depicted results allow several conclusions regarding the potential market power of the assets with the highest effective power or jointly marketed pools under different circumstances. In consequence of Equation 5.7, the RSI and, therefore, the undercutting of the “critical values” of $RSI = 1.2$ and $RSI = 1.0$ depend on the installed capacity of the examined asset x and the summarized capacity of all available assets i. The changing composition of FOs in the different scenarios has significant impact on market power tendencies.

In the positive direction, *HSS_507* (as the single FO with highest effective impact) already becomes pivotal with RSI values below 1.0 at flexibility demands that are in the range of realistic circumstances[11] (as described in 5.1 or depicted in Fig. A.2). For negative demand, the critical demand range is significantly higher due to the higher competition of PV plants.

Depending on the types of pooled assets, joint marketing shows significant risks of structural market power. In both demand directions, aggregation of decentralized FOs like HPs, HSS, or LV PV shows lower RSI-values than the largest single FO unit. In particular, aggregated and jointly marketed HSS lead to significantly lower RSI values in the positive direction and, finally, become pivotal in the two-digit ampere range[12]. In the negative direction, pooling all LV PV shows relevant impact, leading to lowest limits of pivotal potential of all examined options.

Limited supply in application to the assets with biggest impact (i.e., “*HSS_507 no PtH*” and “*MVPV_808 only PtH*”) results in substantially reduced RSI values in all scenario variations. In the positive direction, the non-consideration of flexibility supply by PtH units leads to the lowest values of all examined variations. In the negative direction, the impact of neglecting all FOs except PV is not that critical, as PV units mark the majority of negative flexibility potential.

However, the absolute RSI values should be used with caution, as in this static review, they only reflect a hypothetical maximum availability of all FOs that is very unlikely in a real market environment. To further evaluate these aspects, within the following year-long simulation, the real availability and demand structure come into consideration.

Evaluation Over One Year Within the Modeling Environment The respective analysis of the simulation results of the modeling environment for the whole year focus on two metrics: 1) an assessment of demand situations (time steps) with low RSI values and therefore potential market power of individual assets, and 2) evaluation of single FOs that regularly show market power tendencies reflected in an $RSI \leq 1.1$ in more than 5% of the time steps with flexibility demand, in reference to [211] (see Sec. 5.4.2).

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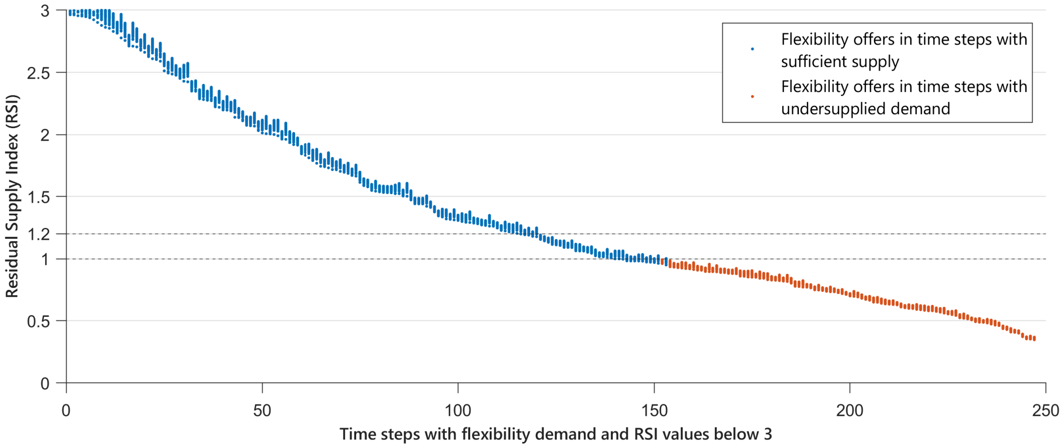
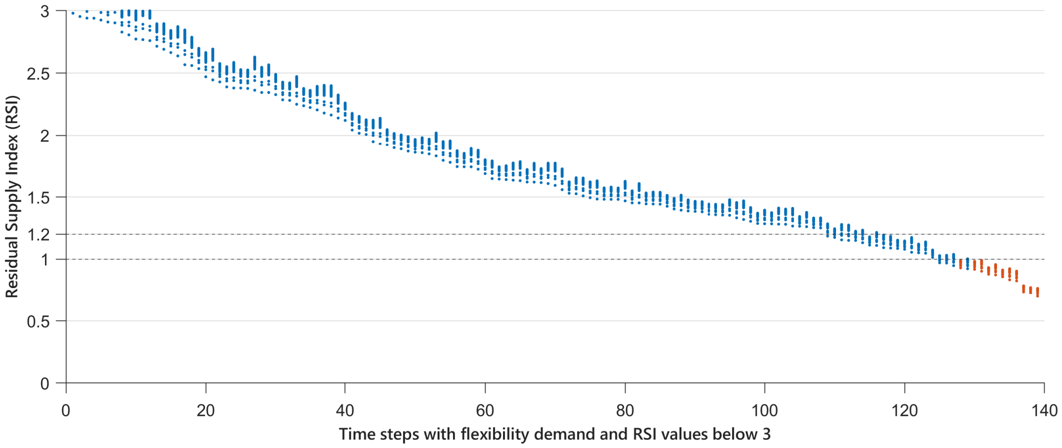
[11] 132.4 A in scenario SP, 117.5 A in EC, and 173.5 A in AP/PM

[12] 28.3 A in scenario SP and 69.3 A in EC, AP, and PM

1) Fig. 5.13 illustrates all time steps with low RSI values (≤ 3) over the examined year for flexibility demands at grid component *l464*. These situations only occur for positive demands in scenarios EC and PM. Each dot reflects the RSI value of an offer bid in the time step. Further, a distinction is made regarding a sufficient supply of flexibility offers to potentially cover the whole flexibility demand in the respective time step. Undersupplied demand eventually always leads to potential market power, i.e., an $RSI < 1.0$ (red dots in Fig. 5.13).



(a) “Electrified Consumer” (EC)



(b) “Market-oriented Prosumer” (PM)

Figure 5.13: Market power evaluation over one year at the congested grid element *l464* within scenarios that show potential market power (legend in (a) applies to both figures)

The first fact to be noted is the general occurrence of time steps with low RSI values of individual flexibility offers in the respective scenarios. As no scenario shows RSI values below 3.0 for negative demand, only scenarios EC and PM exhibit these for positive demands. Again, within these two scenarios, the number of time steps indicating low RSI values is different. As all dots (representing individual offer bids) are superimposed close to each other in Fig. 5.13, it becomes apparent that the deviation of RSI values is quite low in each time step. This reflects the similar capacity dimensions of available FOs (see Fig. A.3). The fact that only these two scenarios show market power tendencies is due to different aspects. In scenario EC this is, on the one hand, due to the lower generation output that could compensate for local demand. On the other hand, it stems from the uncontrolled load behaviour. In case of scenario PM, the difference to scenario AP becomes particularly clear. The most significant influence here is the self-optimized mode of operation in scenario AP which significantly reduces the amount of flexibility required.

2) The FO-specific analysis, on the other hand, examines each offer bid by all individual FOs and counts the number of occurrences with $RSI \leq 1.1$. According to [211], critical market dominance is given at a share of more than 5% in the respective time steps. In conclusion, no individual FO reached a significant share $\geq 5\%$ in the examined scenarios and time steps with flexibility demand at grid component *l464*. Consistent to Fig. 5.13 and Fig. 5.12, *HSS_507_1* represents the most dominant FO in the two relevant scenarios EC and PM for positive demand. The respective share of time steps with demand and an $RSI \leq 1.1$ is 0.24% in scenario EC and 0.05% in scenario PM and, therefore, well below the critical threshold of 5%.

5.4.5 Conclusion and Critical Review

In summary, the derived and demonstrated adaptation of the RSI to assess structural market power within an SMP proved its applicability and usefulness. Its strengths include the ability to reflect changes in the supply of and demand for flexibility and different ownership/marketing constellations. The easy-to-interpret output values support comparison with clearly defined threshold values. Furthermore, this method requires no additional data beyond that required for market operation.

The primary result of the case study is the successful demonstration of the derived method for the monitoring of potential market power in SMPs. Key results of market power tendencies applied to the two selected case study variations are as follows:

1. Static RSI evaluation considering installed capacities
    - The risk of potential market power is generally given for the largest units available in the given setup. Structural market power is, therefore, proportional to the effective flexible power of each unit.
    - The aggregation of single unit types to bigger pools marketed by a single entity shows significant impact and can lead to relevant market dominance.
    - Limited available flexibility has a decisive influence on the market power of larger market participants.
    - High levels of demand extend structural market power even to small market participants

2. Dynamic, year-long RSI evaluation within the modeling environment
    - Potential market power could be identified for a limited number of time steps with positive flexibility demand in two of the four scenarios.
    - In several time steps of these two scenarios, the flexibility demand remains undersupplied, which, in consequence, always results in structural market power of all offer bids. Therefore, the possibility of exploiting market power is potentially given in these time steps. This further underlines the significant relevance of reaching as much available flexibility as possible by appropriate measures.
    - However, no single FO could be identified to possess a significant share of structural market power throughout the modeling time series. However, the applied 5% limit is only an estimate by the regulatory authority [211]. Adjustments may be necessary for the application within an SMP after further empirical studies.

Evaluations in hypothetical grid situations were also conducted in [77] and [187]. Within this thesis, the examinations are extended to the modeling environment considering a whole year in four scenarios to get deeper insight into long-term effects. Nevertheless, potential for further research is given by examining real-time operation including different marketing constellations.

However, the introduced method also has limitations. The most essential point is that with the RSI as applied here, only structural and therefore potential market power can be identified. This explicitly excludes conclusions concerning exercised market power. As described, this was not in the scope of this study, even though there are several approaches available and described in literature (see [184] and [212]). Furthermore, the approach can neither provide information regarding strategic bidding or gaming tendencies nor collusion. This also excludes increase-decrease (INC-DEC) gaming as it is mainly a result of market inconsistencies and independent of market power tendencies [132]. Mitigation options to this are further presented and discussed in [195].

Several approaches for mitigating market power are proposed and discussed in the literature [182, 184, 212, 216, 217]. These include reducing barriers to market entry, regulatory incentives, dynamic price caps, or sanctioning regimes. The foundation of some of the most promising are already discussed in this thesis: A market monitoring system based on the proposed RSI evaluation could dynamically assess the offer-demand structure and alert in case of potential market power situations. In the next step potentially applied market power can be further examined in detail. Alternatively, identified market power could result in regulated maximum prices or automated bid mitigation [182, 184]. In addition, long-term contraction, as introduced in Fig. 5.2 and Sec. 5.3, provides another promising option to reduce market power tendencies [216, 212].

5.5 Function: Matching

The allocation or trading logic, called matching, reflects the core of the SMP. Since several technical restrictions and location-dependent effectiveness on the bottleneck need to be considered, and a day-ahead process was chosen (Sec. 5.1), the allocation of supply and demand requires an optimization logic to find the solution with minimal cost respecting existing constraints. To reach an optimized solution, effectiveness-weighted supply bids are allocated to demand bids over the whole considered time period (the next day). Therefore, costs need to be minimized with simultaneous penalization of non-fulfillment. As the impact of flexible power adjustment is evaluated for all network connection points in advance, the effectiveness matrix needs to be part of the optimization logic. The initial sensitivity evaluation is used as input data for the optimization itself in the form of linearized effectiveness functions, as described in [186]. To find a global optimum of the results, deterministic linear optimization is used, as described by the objective function. [10]

The following section describes all relevant aspects of the given approach and was partly already published in [11]. Within Fig. 5.14, the basic optimization process, including all relevant input data is depicted [10, p. 14].

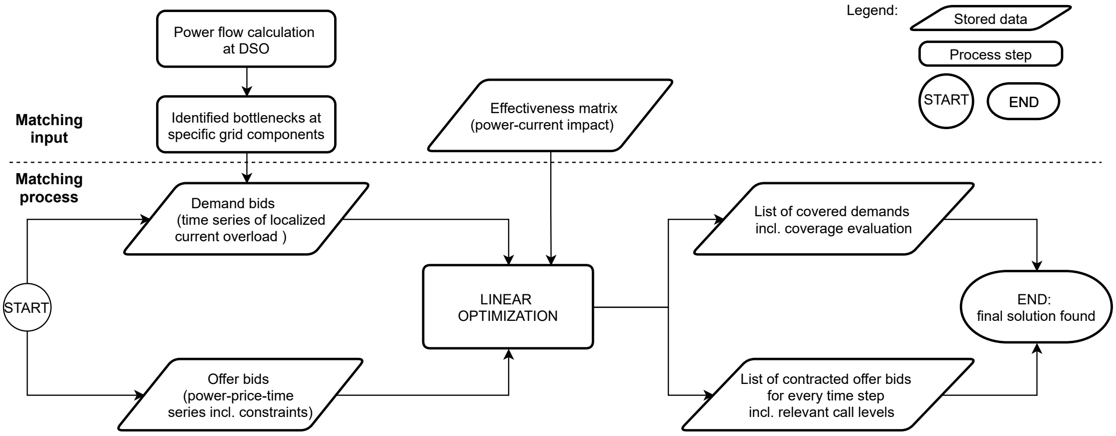


Figure 5.14: Process description of the constrained optimization matching process under consideration of effectiveness, including relevant input data [10, p. 14]

5.5.1 Functional Requirements for Flexibility Allocation

To determine an appropriate allocation logic, the intended behavior needs to be derived first. In most existing energy markets, i.e., the intraday or day-ahead spot markets, price is the only considered allocation parameter. Due to the following reasons, this is not applicable within SMPs:

1. The topological grid location of available flexibility is relevant to solving specific congestions and has to be integrated in the matching.

2. Flexibility offers can be associated with boundary conditions (e.g., defined call levels or call restrictions).
3. A trade-off between planning security and practicality has to be reached, as the achievable LoS of performance from the supply side is not comparable to, e.g., balancing power.

Applied to SMPs, the allocation method includes the consideration of several aspects on both sides (congestion and the available flexibility in the grid) as follows:

1. Offered price for flexibility can be individually specified by the flexibility providers for each time step in schedule offers (see Sec. 5.1).
2. Available power is provided by the active marketers for every 15 minutes slot of the contraction period (i.e., the next day) or determined by the aggregation algorithm for long-term contracted asset pools (see Sec. 5.1).
3. Constraints and boundary conditions regarding power and call restrictions can be further voluntarily indicated for schedule offers, or are predefined as a condition of participation for long-term contraction (see Sec. 5.5.3).
4. Effectiveness of flexibility offered to the congestion is defined as the impact of power adaption to the overloaded grid component by the resulting change in current (or voltage). An approach to determine a linearized relation between the congestion and flexible assets without the need for continuous load flow calculations and grid data is described in [186] (see Sec. 5.5.3).

One possibility for an SMP is the regional order book, which is, for example, used in the enera flex market (see [126] and shown in Tab. 3.2). A regional order book adapts the processes from wholesale markets to regional markets. A considerable advantage of this procedure is the easy implementation by the use of well-known mechanisms: the enera flex market basically uses the processes of the day-ahead market of the EPEX Spot SE.

Based on the analysis in Sec. 5.1 and the defined requirements, in this thesis, a different approach is necessary for the considered SMP due to several reasons:

1. A regional order book assumes a constant effectiveness of all FOs on the congestion. According to [186], the effectiveness in a mid-voltage grid varies significantly and has to be integrated in the matching process.
2. In a regional order book, the traded flexibility is the deviation from a baseline. In this case, it is not possible to consider restrictions of the supply side.
3. From a system perspective, an optimal matching solution on the SMP must be found not for a specific point in time, but for a time period (i.e., the entire day of contraction with 96 time steps of 15 minutes each in a day-ahead market process), while considering the restrictions of flexibility offers and demands. Therefore, an iterative determination of the optimum combinations of flexibility offers is necessary to efficiently meet the demand.

A detailed meta study regarding allocation approaches in existing market setups can be found in [11, pp. 6-8]. The next section provides an overview of the relevant auction design basics that are found in the literature.

5.5.2 Auction Design Basics

A market can generally be defined as a place where supply and demand for a good are matched in price and quantity [86]. In the case of an SMP, however, further aspects need to be considered in the matching process. Roth [178] described this type of market that considers more specific quality aspects of a product as a matching market (see Sec. 4.1). The concept developed in the following is based on several preliminary works as well as joint workshops with DSOs, aggregators, and potential flexibility providers that led to the identification of the requirements stated above.

Following the classification in [90], an auction-theory-based approach best meets the aforementioned needs. Auctions define a rule-based market mechanism through which resource allocation and prices are determined on the base of bids from auction participants. Regionalized SMPs can be modeled as a double-sided multi-attribute combinatorial reverse auction [218]. The following list elaborates the term's constituents to confirm the suitability of that specific modeling approach.

1. Reverse auctions are characterized by the inverse roles of sellers and buyers compared to a traditional auction. Here, the sellers constitute the bidders, while a buyer wants to acquire a resource for the lowest possible cost.

2. Combinatorial auctions allow bids for combinations of heterogeneous goods. This is necessary, as flexibility is considered a heterogeneous product due to its multiple attributes [218, 219].

3. Multi-attribute auctions are required, because in addition to the price, flexibility bids are characterized by the aforementioned constraints, i.e., effectiveness, available power, and boundary conditions.

4. Double-sided auctions typically feature multiple buyers and sellers. Concerning regionalized SMPs, the buyer side could potentially involve several DSOs demanding flexibility for congestion management.

As a flexibility demand can be fulfilled by multiple FOs, it is necessary to consider a price-clearing mechanism for paying bidders with different bid prices. Two common approaches are pay-as-bid and uniform pricing [218]. Due to the non-homogeneous nature and fragmentation of flexibility products, for which uniform pricing cannot account, the pay-as-bid price is considered superior for modeling SMPs [220, 219].

Based on the auction model, the optimization problem lies in determining the winner of the auction, i.e., identifying the allocation of resources by bidders while reaching a predefined optimization objective. This problem is commonly referred to as the combinatorial auction problem (CAP) and can be formulated as a mixed integer problem (MIP).

In particular, the aspects presented in the previous sections, including inhomogeneous effectiveness values, differing price offers, and available power, necessitate constrained optimization in order to find a techno-economic optimal solution for the defined time period. The subsequent sections discuss the optimization objective and relevant boundary conditions to formulate the optimization problem.

5.5.3 Constrained Optimization Setup

As part of the formalized optimization problem, all identified goals need to be reflected in the objective function. The constraints of the problem need to address all limitations. Furthermore, the effectiveness parameters need to be considered. The objective function seeks the optimal solution in order to achieve the following two goals:

1. *Minimize operating costs:* The goal is to minimize the cost for relieving congestions. This is represented by the objective function where the sum of all operational costs is minimized, while

2. *Simultaneously meeting as much of the demand for flexibility as possible:* By only minimizing costs, it is impossible to reach a satisfying market result, as the cheapest option would always be not contracting anything at all, resulting in costs equal to zero. However, attempting to always exactly match flexibility demand might result in disproportionately high costs. Therefore, demand fulfillment is not formulated as an equality constraint but instead incorporated into the objective function via a penalty factor. This approach is valid as flexibility demand includes a certain degree of elasticity. In the case of critical network conditions, DSOs have other contingency measures for resolving grid congestion available to them, which are independent of the flexibility offers. Accordingly, they are not forced to draw disproportionately expensive FOs.

The following describes relevant input, i.e., boundary conditions and restrictions, from both sides, demand and supply based on the initial product definition in Sec. 5.1.

Boundary conditions The boundary conditions determine the constraints of the optimization problem and result from different FO properties, which are discussed in the following.

Technical Boundary Conditions of Flexibility Options FOs can be called at different levels depending on the plant type. For the considered setup, three different plant types are considered regarding their available call levels, as shown in Figure 5.15.

Binary controlled (0/1) plants only have the two operating states *On* or *Off*. An example of this would be an aggregated pool of heat pumps, where the availabilities can only be determined stochastically (see Sec. 5.3) [8]. All systems that were installed as a result of the German Renewable Energy Sources Act (EEG) of 2000 belong to the second system type (e.g., PV-plants or wind turbines). These renewable energy plants have four potential production levels (0%, 30%, 60%, and 100%). Lastly, some plants have no discrete production levels and can increase or decrease their power output progressively according to a schedule. Limitations apply only to the minimum and maximum power output or intake, respectively. Power restrictions can take the form of both negative and positive values. Examples for scheduled plants are HSS and CHP. All different call levels of these plant types are considered as constraints in the optimization problem.

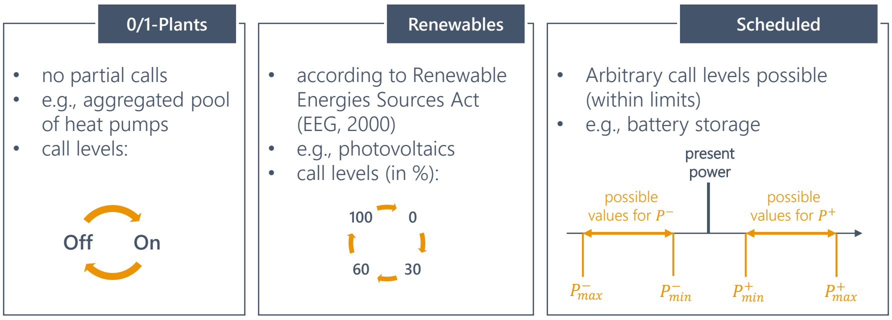


Figure 5.15: Available call levels depending on plant type [11]

Call Restrictions of Flexibility Offers Boundary conditions for the optimization problem can also be derived from technical limitations of the FOs. This particularly applies to aggregated offers resulting from pooling long-term contracted FOs. In addition to the power restrictions, limitations on the duration of a call, the minimum time between two calls, the total call duration during a day, plus the total number of calls per day exist. The call restrictions can be seen in Fig. 5.16.

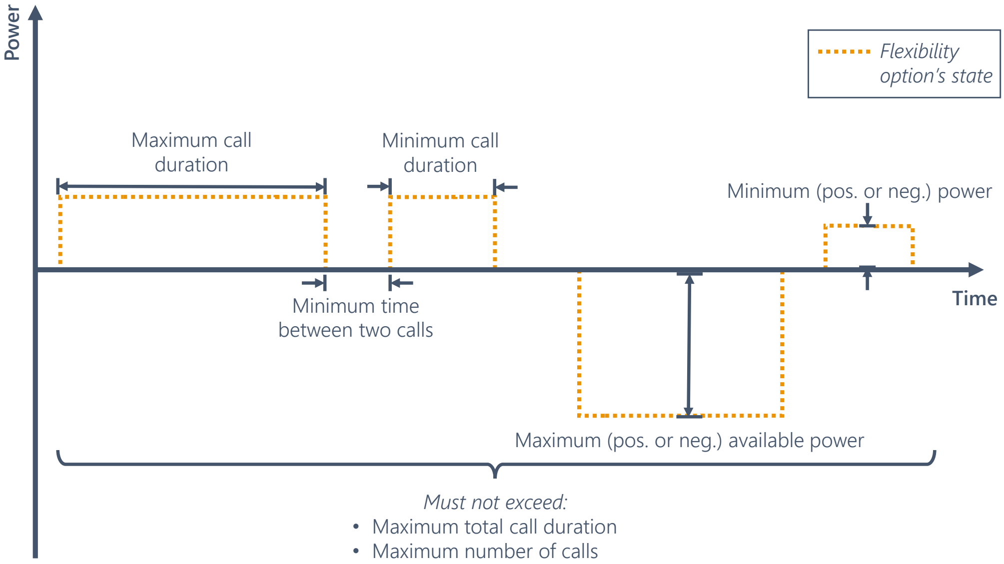


Figure 5.16: Potential call restrictions of flexibility options [11]

Consideration of Localities via Effectiveness Values Another aspect to SMP matching in the proposed allocation scheme is the deliberate independence of platform operation from the need to possess detailed grid structure information. This has several advantages regarding the independent role of the platform operator or even potential joint platform operation (see Sec. 4.4). Since the actual impact delivered to the flexibility demand after activating an FO can vary depending on the grid structure, sensitivity is determined in advance (see Sec. 5.2.2). Therefore, the generated effectiveness factors need to be considered as weighting factors of the flexibility offer bids in respect to present demands (i.e., congestions).

Definition of the Optimization Problem After defining relevant input data, the next step in developing the matching process is the mathematical formulation of the optimization problem, including the optimization goal, boundary conditions, and decision variables. Decision variables cover the contracted power call P_{ij} for every available FO. As the call levels for certain plant types cannot be continuously adapted, the corresponding variables are restricted to being integers. Therefore, the optimization problem, containing both real-number and integer variables, falls within the domain of mixed-integer programming.

By nature, it is necessary to compensate for positive and negative power calls from FOs. However, considering this via absolute values results in a non-linear problem. Again, non-linearities pose several challenges that impact the efficiency of market processes, mainly reflected in increased solving times and lower-quality results compared to linear problems [221, 222]. To avoid these pitfalls and maintain linearity, decision and auxiliary variables are introduced that differentiate between positive and negative values. The objective function of the optimization can then be described according to Formula 5.8. Note that the demand fulfillment constraint from Section 5.5.3 is incorporated into the objective function via an additional penalty term.

$$\underset{P_{ij}^{+},P_{ij}^{-}}{min} \sum_{j=1}^{96} \sum_{i=1}^{n} \left(C_{ij}^{+} \cdot P_{ij}^{+} + C_{ij}^{-} \cdot P_{ij}^{-} \right) + \sum_{l=1}^{o} G_{lj} \left(d_{jl}^{+} + d_{jl}^{-} \right) \tag{5.8}$$

where

$C_{ij}^{+} \geq 0$	Costs for positive flexibility of FO i at time period j
$C_{ij}^{-} \geq 0$	Costs for negative flexibility of FO i at time period j
$P_{ij}^{+} \geq 0$	Contracted power increase for FO i at time period j
$P_{ij}^{-} \geq 0$	Contracted power reduction for FO i at time period j
$G_{lj} \geq 0$	Penalty costs for non-fulfilment of the demand l
$d_{jl}^{+}, d_{jl}^{-} \in \mathbb{R}^{+}$	Auxiliary variables described in Equation 5.9

The simulation of non-fulfillment of demand l at time period j and the inclusion of the effectiveness parameters e_{il} is covered through Equation 5.9.

$$d_{jl}^{+} - d_{jl}^{-} = \delta_{lj}(D_{lj} - \sum_{i=1}^{n} e_{il}\cdot(P_{ij}^{+} + P_{ij}^{-})) \qquad (5.9)$$
$$(\forall j \in J,\ l \in L)$$

with

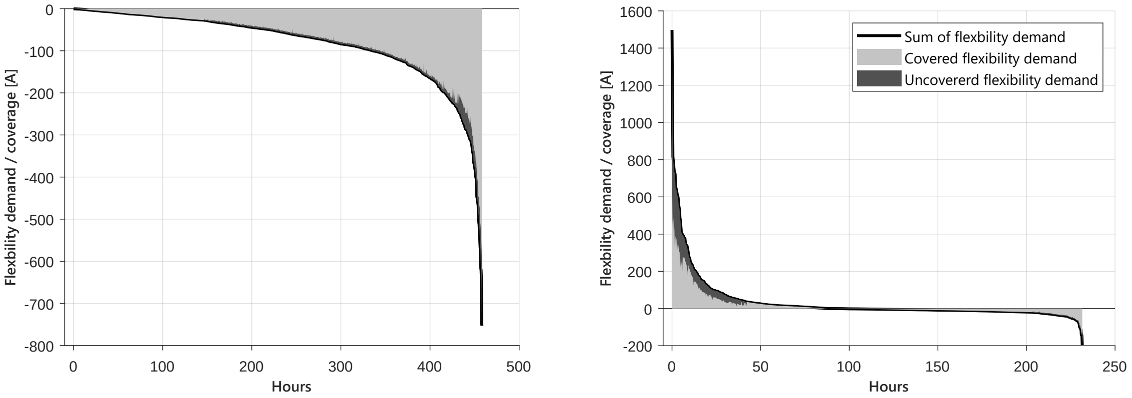
$\delta_{lj} = \begin{cases} 1, & \text{if } D_{lj} \neq 0 \\ 0, & \text{else} \end{cases}$	Indicator for zero demand for a flexibility demand l at time period j
$D_{lj} \geq 0$	Flexibility demand l at time period j
$e_{il} \geq 0$	Effectiveness factor of FO i to demand l

This way, over- and under-fulfillment of the flexibility demand D_{lj} is not prohibited, but causes additional costs in the optimization. Furthermore, the effectiveness evaluation, converting the offered flexibility in kW at the point of supply into a change of current in A (or voltage in V respectively) at the congestion, is considered. However, this formulation does not lead to an unconstrained problem, as more dependencies need to be considered. The matching process further takes into account all other constraints as depicted in Fig. 5.16 and Fig. 5.15. The mathematical formulation of the additional constraints can be found in Annex A.4 or [11, pp. 12-14], accordingly.

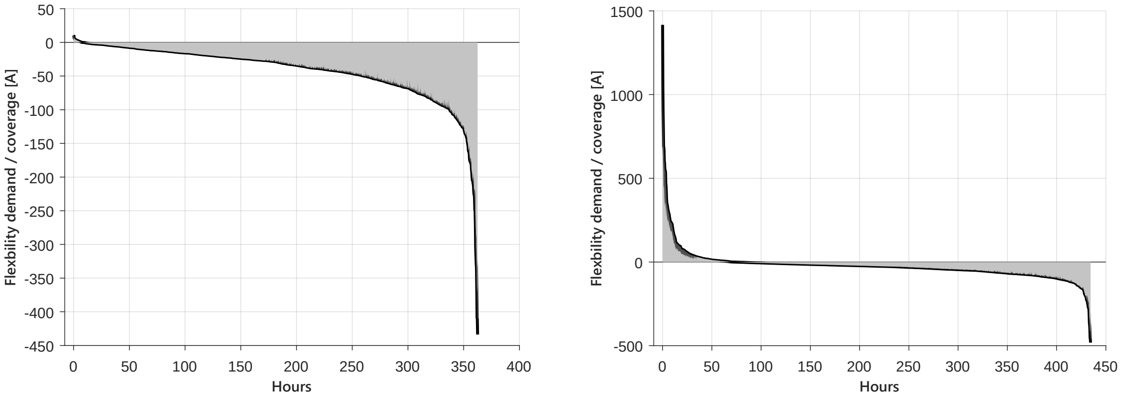
5.5.4 Case Study

Based on the modeling input parameters regarding flexibility demand (Tab. 5.1) and flexibility offer (Fig. 5.10 and Fig. 5.11), the matching process is conducted for the whole year in the four presented scenarios within the case study[5]. It must be noted that the following evaluation is not primarily intended to draw distinct energy-economic conclusions as the results are mainly dependent on the initial assumptions made in Sec. 5.2.2. Instead, they illustrate the functioning of the algorithm including associated strengths and potential shortcomings.

Demand Coverage Fig 5.17 illustrates the demand coverage for all congestion events within the four scenarios.



(a) "Solar Producer" (SP) **(b)** "Electrified Consumer" (EC)

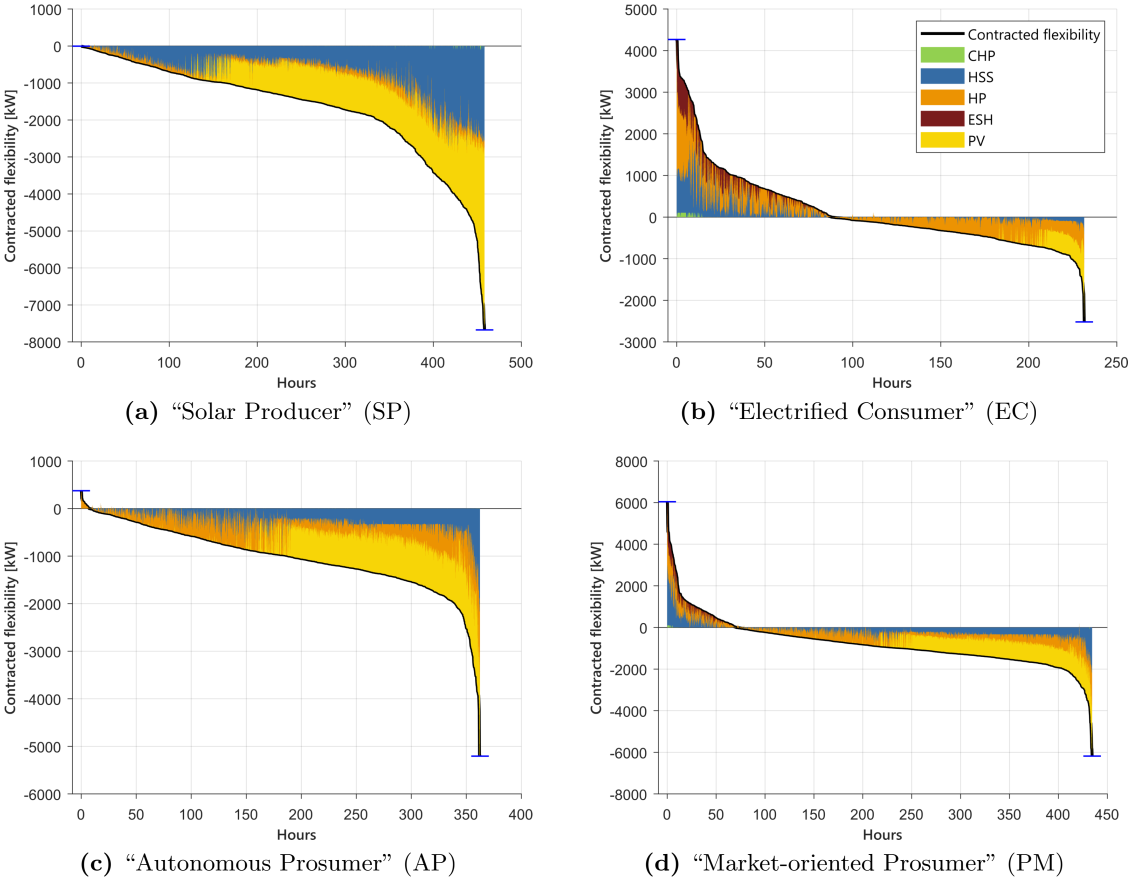


(c) "Autonomous Prosumer" (AP) **(d)** "Market-oriented Prosumer" (PM)

Figure 5.17: Demand coverage within the four scenarios after matching

First of all, different demand structures in direction and value become apparent within the four scenarios. Scenarios SP and AP mainly result in negative flexibility demand from time steps with high generation. In contrast, scenarios EC and PM also pose negative demand, especially due to load simultaneities. Nevertheless, demand is covered in most time steps. However, depending on the scenario, in some time steps demands remain uncovered, resulting from a) insufficient flexibility offer (e.g., positive demand in scenario EC, Fig. 5.17 (b)) or b) due to additional costs through potential over-fulfillment. The latter particularly stems from the discrete increments within the available call levels (see Fig. 5.15) that eventually lead to over-fulfillment of the demand. As excess coverage is further penalized through additional costs of the FO contraction (in addition to the applying penalty factor G_{lj}, see Formula 5.8), the algorithm decides for under-fulfillment. The following overview of the contracted offers further illustrates these interpretation.

Contracted Offers Fig 5.18 only considers the covered share of Fig. 5.17 and differentiates between the contribution of different types of FOs.



(a) "Solar Producer" (SP) **(b)** "Electrified Consumer" (EC)

(c) "Autonomous Prosumer" (AP) **(d)** "Market-oriented Prosumer" (PM)

Figure 5.18: Contracted offers within the four scenarios after matching

The contribution of different FO-types is determined by their direction of flexibility supply. Negative offers can be provided from curtailing generation units or by increasing load power. Therefore, PVs, HSS, and engageable HPs provide the major share of negative contracted flexibility. CHP plants are also considered, but only with a minor contribution due to smaller installed capacities. Positive flexibility offers are contracted from HSS, CHP, disengageable HPs, and ESH.

Overall, it can be concluded that all flexibility options make their valuable contribution to market based congestion management. As initially stated, the simulation results are mainly dependent on the underlying assumptions, i.e., asset penetration within the grid, share of available flexibility, and cost structures (see Fig. 5.5 and Tab. A.1). Further, the choice of considered FOs is decisive. In this case study, the charging behavior of EVs contributed to a relevant part of the problem. Still, EVs are not considered part of the solution in terms of flexibility provision. However, this modeling choice had different reasons as stated in the description of the simulation setup (i.e., additional complexity and development of more efficient marketing strategies in ongoing research projects).

Finally, the optimization approach proved its function as intended and provides an efficient way of matching within an SMP.

5.5.5 Comparison to Alternative Matching Algorithms

As introduced, the provided matching approach is one way of implementation, specifically tailored to the initial functional and non-functional requirement specifications of an SMP. However, alternative methods exist. Within [10], two other options, i.e., heuristic algorithms, were compared to the presented constrained optimization.

The alternative options use either a merit order list or a weighted merit order list in combination with a hill climbing approach to solve all problems by calculating the network status at different settings of flexibility dispatch. Detailed descriptions of these can be found in [10, pp. 8-12]. The qualitative comparison considered the following topics: ensured demand coverage, data minimization, computational effort, and the transferability of the algorithms regarding network issues and different flexibility mechanisms. Quantitative analysis has been conducted in an exemplary network part of the grid depicted in Fig. 5.6. The resulting metrics included the sum of the used flexible energy, specific energy cost, and the total cost of the flexibility supply as combination of these both values.

Tab. 5.3 summarizes a part of the comparison results, rating the algorithms in the mentioned categories with the following measure: “+” = advantages, “-“ = disadvantages and “0” = neutral. [10, p. 22]

	Specific cost	Flexible energy	Ensured demand coverage	Data minimization	Computational effort
Linear optimization	0	+	-	+	+
Merit Order List (MOL)	+	0	+	-	0
Weighted Merit Order List (wMOL)	+	0	+	-	-

Table 5.3: Qualitative comparison of the three analyzed matching approaches in [10, p. 22]

As a short summary, within the two parameters *specific cost* and sum of contracted *flexible energy*, combined, no single algorithm tends to perform better or worse than the others. Still, because they use the least expensive bids first, the heuristic approaches MOL and wMOL obtain lower specific costs than the linear optimization. The linear optimization approach can counterbalance this by providing a smaller amount of flexible energy. [10, p. 21-22]

Regarding the *ensured demand coverage*, differences in the initial setup become apparent. Unlike the other two approaches, the linear optimization approach allows a deficit in the demand of flexibility. Optimization includes all congestions within the considered time period. Even if a penalty term in the optimization equation forces contracting close to demand, a deficit may occur under certain circumstances (see Sec. 5.5.4). In this case, the level of demand varies among the grid components. Since bids affect several congestions, there are sometimes high excess demands in individual grid components, which in turn are subject to the penalty term. Thus, cost-optimal solutions can occur that do not completely cover all congestions. Including a penalty term for the deficit but not for the excess coverage could be a remedy.

One intention to realize the optimization approach was the reduction of necessary grid information within the matching. [10, p. 22] This resulted in the better performance at *data minimization.* In contrast, the wMOL and MOL approaches include the repeated execution of load flow calculations, so a complete network model must be available. [10, p. 22]

The main factors that determine *computational effort* are the necessity and quantity of network calculations. While the linear optimization technique only uses network calculations initially, the MOL and wMOL algorithms calculate the network status several times per optimization. The wMOL in particular runs one network calculation for every flexibility provider as a preprocessing step before conducting the optimization itself. Therefore, the operation of the heuristic approaches has a high computational effort that grows with added flexibility suppliers and more complex networks. However, the complexity of the linear optimization also depends on these factors. Another aspect of the computational effort is the number of bids. These can be significantly reduced by aggregation schemes as proposed in Sec. 5.3. [10, p. 23]

5.5.6 Conclusion and Critical Review

The presented optimization-based allocation method of flexibility demand and supply proved its function and efficiency in several laboratory and field tests. Regarding the actual market design of the SMP, the proposed allocation method represents one solution for matching grid-supportive flexibility with demands. It further proved its application in realistic network environments as illustrated within the case study in Sec. 5.5.4. [11, pp. 16-17] However, there is still room for improvement and further research. From a technical standpoint, the following selected issues were identified:

- The matching algorithm currently neglects the energy component of the flexibility offers. Although this aspect is intercepted via additional boundary conditions, energy constraints may offer added value, especially for storage facilities.

- Penalization of demand over- and under-fulfillment is still defined by a uniform penalty factor. In order to adapt to realistic market and demand behavior, a differentiation between allowed over-fulfillment and avoidable under-fulfillment may be beneficial.

- Furthermore, a limitation on maximum costs has not yet been implemented. Limiting maximum costs to avoid exorbitant costs may be realized by an additional constraint, setting a cap on the costs of the activated power of all FOs per time step and demand. This cap can prevent price gouging by a supplier possessing market power due to a lack of alternative solutions to a given congestion (see Sec. 5.4).

In summary, the proposed concept offers an efficient method of considering all necessary requirements defined in Sections 5.1 and 5.5.1.

6 Decentralized Implementation Using Blockchain Technology

After introducing the needs, considerations, and evaluations to a proposed setup of an SMP, an iteration loop intends to discuss the chances of decentralization options (see procedure defined in the underlying V-model in Fig. 2.2). Therefore, the following chapter analyzes potential added values and existing challenges to provide input for a final comparison.

The increasingly decentralized character in the development of the energy system shows direct impact on the design of an SMP. It involves, both, the rising number of actors but also influences the local component of flexibility demand and provision on an SMP. In consequence, it also raises the question of decentralizing the corresponding platform architecture. Taking a closer look reveals three different dimensions of potential platform decentralization (Fig. 6.1) [13].

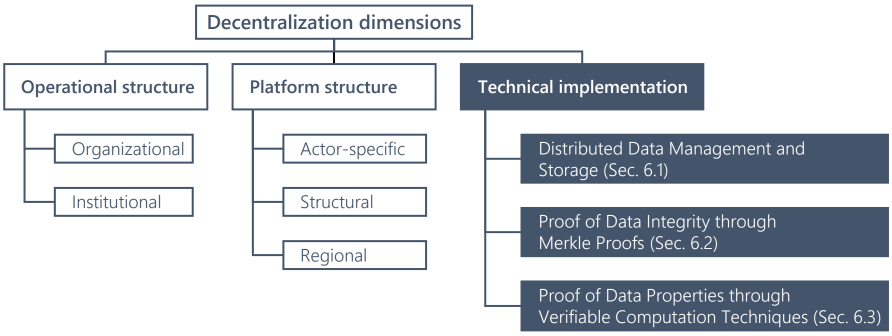


Figure 6.1: Dimensions of decentralization within the Smart Market Platform design

Operational Structure Operational decentralization refers to the organizational and institutional operation alternatives of the platform. This includes the provision of the necessary soft- and hardware and the allocation of responsibilities within the network. In general, different organizational forms can be realized, i.e., centralized operation (by individual actors) or joint operation in a consortium. The latter can further be divided into different forms of consortia operation: collaborative operation, founding a joint venture, or joint commissioning of a third-party institution (see Sec. 4.4) [5].

Platform Structure Structural decentralization addresses the platform and consequently market structure, which is designed, for example, according to regional effectiveness, limited or defined reach, or target groups. A variety of SMPs is conceivable according to different boundary conditions, which could also partly overlap. These could be institutional boundaries (e.g., related to DSO or TSO grid area), network or energy system structure (e.g., related to control area or grid congestion areas), or regional aspects in terms of geographical or administrative boundaries. [13]

Technical Implementation Technical decentralization is aimed at the actual deployment and realization of the platform itself or of its individual functions. As there is not per se an inherent value in technical decentralization, it is necessary to take a closer look at potential added value provided to relevant functions, processes and finally stakeholders' needs. [13] Within the following sections, the most relevant aspects of distributed technical operation using DLT or BC technology are addressed and evaluated on behalf of their added value towards the proposed SMP architecture in Sec. 5. One heading hypothesis describing the motivation introduced in Sec. 1.3, is therefore: *"A single-point-of-access doesn't have to lead to a single-point-of-failure."*. The single-point-of-access needs to be provided by standardized structures. But still, the back-end does not necessarily have to be dominated by a centralized intermediary. As part of decentralized applications, DLT in general, or BC technology in specific aims to replace or at least support traditional, centralized databases, promising transparency, tamper-resistance, and a high degree of availability [223, 95]. Regarding an SMP, this could finally lead to increasing credibility and therefore be a competitive advantage compared to alternative platforms. [13] As *"security and trust are the Achilles' heel (of digitalization)"* [224, p. 38], providing system-inherent trust and reliability—independent of the actual platform operator—supports transparency in an increasingly complex market environment of an SMP. This, on the one hand, concerns the general setup of a distributed platform environment based on BC technology and, on the other hand, the design of individual functions. By designing the technical layout, it is essential to note that different functions demand different solutions adapted to their specifications. As introduced in Sec. 3.3.1, the design choices for the underlying BC infrastructure is specifically determined by the applied governance layout. Private permissioned BCs show certain advantages due to defined access. However, they certainly undermine the initial idea of a transparent and open platform. And still, scalability is limited and privacy issues cannot be resolved completely, e.g., based on the fact of irreversibility. Therefore, in the following evaluations, a *public permissionless BC* setup is assumed. This is also due to the fact that this demands the highest requirements regarding data privacy and platform-independent extensibility. To address the distributed design options of the individual SMP functions, three aspects are examined in the following sections: 1) data and identity management and storage in Sec. 6.1, 2) trusted and traceable data provision in Sec. 6.2, and 3) verifiable data processing and computation in Sec. 6.3.

6.1 Distributed Data Management and Storage

Participation at the SMP generally demands a certain process of initialization (see Fig. 5.1). On the flexibility provider's side, this includes the registration of the provider itself and respective FOs including the provision of technical specifications. On the demander's side, basic information regarding grid-specific effectiveness evaluation and boundary conditions need to be provided. In a centralized setup (as suggested in Chapter 5), these information are directly transmitted to the platform operator. Technical decentralization offers alternative ways for distributed data management and storage that promise sovereignty over data and defined and documented access to it.

6.1.1 Identity Management through Self Sovereign Identity

Self Sovereign Identity (SSI) describes a transformation of the previously centralized identity management systems, controlled by a service provider, to a user-centric system. In general, a digital identity allows direct provision of certified master data. Identity can therefore contain all specifications to an entity that makes it distinguishable from others. With SSI, institutions can further assign and certify properties and attributes to identities. The user retains control over these credentials and does not have to disclose more data than necessary for a specific use case. The basic principle of SSI can be applied to natural or legal persons, but also to technical entities (assets). Particularly in complex systems like the energy sector, where different applications and use cases can be adopted by an asset, providing consistency and reliability by certification and validation of specific properties of the participating asset is crucial. SSI can thus represent a sensible extension or even alternative to existing master data systems (e.g., the "Marktstammdatenregister" in Germany) [225, p. 15]. In the case of an SMP, master data could include information regarding location and type of the asset as well as technical specifics. [226] Fig. 6.2 illustrates the basic setup of an SSI architecture.

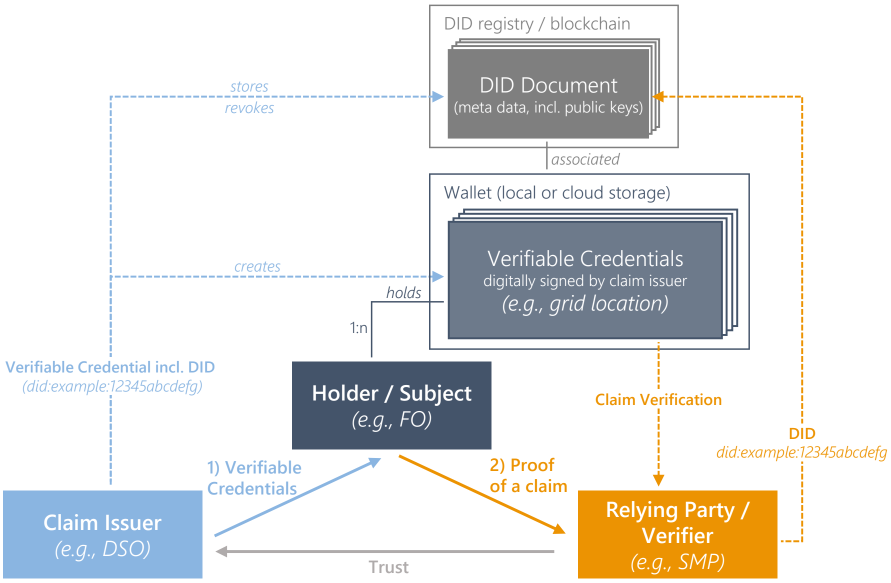


Figure 6.2: Basic architecture of a Self Sovereign Identity framework (based on [12, p. 17])

Involved parties (roles) in the SSI architecture generally include the actual *holder* (subject), the *claim issuer* (trusted authority), and the *verifier* (relying party). [12, p. 14] The components of SSI contain an identifier, i.e., *Decentralized Identifier (DID)*, and *verifiable credentials* to exhibit and proof a certain claim. DIDs are standardized, self-certified identifiers that can either point to a *DID document* in a registry or BC, or allow to setup encrypted end-to-end communication. Their core properties are described by persistent or permanent identification, providing resolvability (i.e., the DID can be resolved to associated meta data), cryptographic verifiability (i.e., the ownership of a DID can be verified), and decentralization (i.e., no central authority is required for registration). [227] The BC can serve as a trusted database that holds appropriate certificates or attestations and enables verification of the authenticity of these credentials. Verifiable Credentials are digitally signed collections of attributes that can be stored in a *digital wallet.* A *verifiable presentation* further expresses and potentially aggregates data from one or more verifiable credentials. This allows to present only a certain part of credentials in a traceable and verifiable way without compromising privacy. [228] The associated identification processes can be split into the provision of a verifiable credential from a claim issuer to the holder (Fig. 6.2, step 1), and the proof of this claim from the holder to the verifier (Fig. 6.2, step 2), as described in the following.

1) A characteristic (e.g., topological location of a FO) is assigned by an issuer (e.g., DSO or ANO) and provides a newly created, digitally signed verifiable credential to the holder. In addition, the issuer stores a DID document on the BC that is linked to the corresponding certificate.[1] The combination of the two data sets (individual certificate and public key in the BC) allows to verify the validity and signature at any time.

2) The holder proofs a claim to a relying party by providing its verifiable presentation. This relying party resolves the provided DID and verifies the correctness of the presentation by checking the authenticity of the related verifiable credentials combined with the information in the DID document. [229]

Finally, SSI allows the verification of presented master data based on end-to-end communication. Within an SMP, an extensive external master data infrastructure based on SSI that allows to transparently verify attributes of an asset could significantly reduce the need for data provision. In consequence, this could increase data sovereignty and reduce redundant storage capacity. However, this aspect is rather independent of the actual SMP design but implies a fundamental change of the existing master data registry architecture. As standardization is inevitable, there are already research projects addressing these aspects (see, e.g., [230]).

6.1.2 Distributed Data Provision

In addition to the verifiable provision of master data, data storage itself can also be realized in a decentralized database. One prominent example is the InterPlanetary File System (IPFS) [231, 232]. The IPFS protocol enables distributed P2P storage and allows increased availability of data. Unlike DLTs, IPFS does not document transactions and

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[1] In the event that the certificate later becomes invalid, has to be adapted, or expires, its revocation must also be possible [12, p. 24].

therefore does not have a consensus mechanism. Instead, IPFS prevents manipulation by addressing data based on content via a hash value (as the content identifier). Distributed hash tables are used to document which user owns which data so that data remains discoverable. [231]

Thus, IPFS can be used for applications such as file sharing, collaboration tools without a central instance, or as a cloud storage alternative. [16, p. 4] The main advantages of IPFS are reduced storage costs, e.g., compared to storage on a BC, with high availability. Data protection can be achieved via access controls, although the advantages of decentralization are limited here depending on the implementation. However, the technology is still in an early development stage [233]. Regarding its application in an SMP, distributed data storage would only affect externally hosted data and would therefore not directly impact the platform design. [14, pp. 16-17], [234, pp. 77-82]

6.2 Proof of Data Integrity

The following passage is based on [13], where a detailed concept description of a "tamper-proof documentation of flexibility market processes" including a hands-on implementation proposal is presented.

Providing trust and transparency towards correct data provision within an SMP could address the following user stories of potential parties involved:

1. *Flexibility providers* want to ensure that their flexibility offers are considered correctly on the SMP. Their demand bids should be documented immutably and time-discrete to avoid conflicts. The flexibility provider should only be able to see their own offers and, if applicable, corresponding contraction.

2. The *grid operator* places flexibility demands and, as such, wants to ensure that its demand bids are considered correctly on the market platform. The demand bids should be documented immutably and time discrete to avoid conflicts. The grid operator should only see his own demand bids and (anonymized) allocated flexibility offers.

3. The *platform operator* receives flexibility demand and offers and conducts the matching algorithm. It wants to provide transparency to users by proving the correctness of registered demand and offers as well as to eventually fulfill its reporting duties to relevant authorities.

4. In addition, the *regulatory authority* supervising electricity market (i.e., federal network agency or BNetzA in Germany) needs to ensure the correct function of the market [235]. Eventually, it wants to check that all flexibility offers are considered without discrimination. Thus, it needs to be able to inspect all in- and output data (in pseudonymized form), as well as results and version of the matching algorithm provided by the platform operator to spot-check on request.

On top of these stakeholder perspectives, there are external requirements evolving from legal and regulatory frameworks. Besides safe, efficient, and trusted operation, one very relevant aspect is the compliance with GDPR-related data privacy.

6.2.1 Concepts for Documentation of Relevant Processes

In order to cover the identified needs for transparency and data security, there is another challenge regarding an initial proof of correct data input. Data can be stored very securely on a BC but there is no impact to the correct provision of data. Especially (but not only) in the energy sector, this so-called “oracle problem” shows a fundamental challenge in realizing feasible end-to-end use cases [236]. Input sources can be manifold including:

- Measurement gear that need to provide trustable sensor data (e.g, by iMSys infrastructure, see Sec. 1.2.2).
- User interaction, i.e., data input coming from a user interface (e.g., by providing an offer bid to an SMP)
- External data sources, like information from third parties (e.g., weather prognosis data to the SMP)
- Computational results, i.e., solving complex problems (e.g., the allocation result of an SMP considering a high number of bids including constraints, see Sec. 6.3)

Nevertheless, there are already different approaches available to address the challenge of trusted data provision. The most obvious approach is to regulate technical connections and the data providers themselves by a central authority. In the energy sector, available standardized and secure iMSys infrastructure, including trusted metering point operators, regulated by the Federal Network Agency (BNetzA) and the Federal Cyber Security Authority (BSI), provides an advantage and immanent trust compared to other sectors [237]. A second one is to provide the possibility of checking the validity by each single user, e.g., by applying BC technology and its value propositions of irreversibility and transparency. This can be done by redundant offline storage of user-specific data and ex-post verification. The approach will be further evaluated in the following chapter. [233] A third option is to enable different, redundant pathways to the BC and using consensus oracle operations as well as verifiable multi-party computation to validate the correctness of data provision (see Sec. 6.3) [238]. Finally, the correct application of these approaches needs to be decided on a use-case-specific point of view.

Applied to the SMP, an appropriate validation process could be considered in the following platform steps (cf. Fig. A.1):

1. Provision of basic operational platform data (e.g., grid topology, boundary conditions, market area)
2. Provision of flexibility demand (by the DSO)

3. Provision of flexibility offers (by operators of FOs)
4. Optimization and provision of allocation results (through the platform-operator), see Sec. 6.3
5. Proof of flexibility provision (through measurement data from iMSys)
6. Settlement information (provision of billing and payment information)
7. Revision-safe documentation

6.2.2 Evaluation of Data Storage and Validation Options

BC platforms like Ethereum provide the possibility of storing any type of data through the use of smart contracts [95]. As illustrated in Fig. 6.3 a), data can be stored openly as "plain text" within a smart contract transaction. Storing all application data on a BC comes with limitations, mainly regarding scalability and data privacy. In general, scalability of BCs is limited in terms of storage capacity and throughput. Furthermore, the cost of storage is high. Current developments such as alternative consensus mechanisms, sharding, or state channels aim to solve the scalability issue, but still have significant overhead compared to traditional databases (see Sec. 3.3).

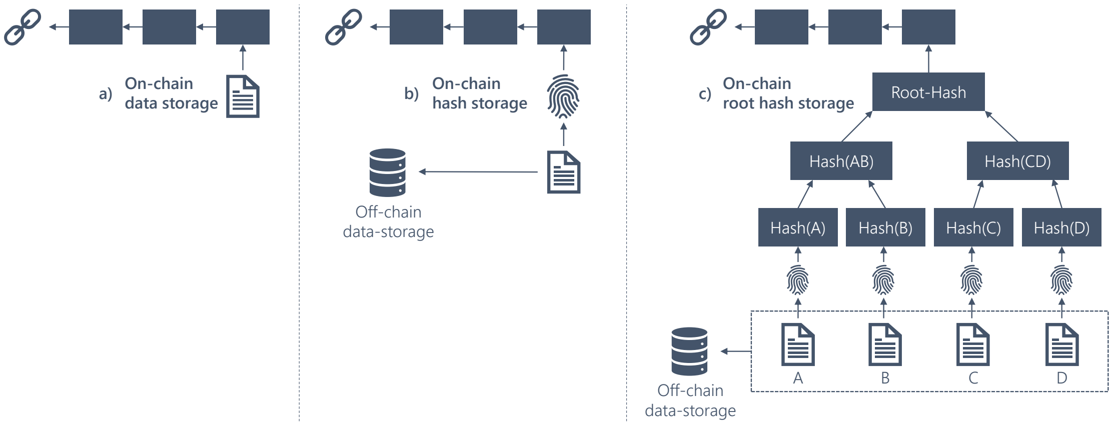

Figure 6.3: On-chain data storage option: a) direct on-chain, plain text storage, b) hash storage, c) Merkle tree root hash storage [13, pp. 113f] [14]

Storing private data is especially a problem on public BCs, where data are openly accessible to anyone. Approaches to preserve confidentiality on BCs include the use of private networks or encryption of stored data. Because encryption algorithms are susceptible to future vulnerabilities, it is questionable whether public storage of encrypted private data is compliant with regulations such as the EU's GDPR [239]. In addition, GDPR compliant data privacy also requires the possibility of erasing data upon request, which conflicts with the immutability of data stored on a BC. [240] Considering these limitations, an alternative is to store only data hashes on-chain and storing data themselves off-chain. [155] This approach is illustrated in Fig. 6.3 b). The integrity of off-chain data can then be proven using the on-chain hash (see Sec. 3.3). Due to the constant length of a hash, this approach requires less storage capacity on-chain, improving scalability. The pre-image resistance of a hash function prevents private data to be inferred from its hash and thus provides the required confidentiality [155]. By further applying the concept of a Merkle tree and only store the root hash of hierarchically aggregated data further reduces storage sizes, as illustrated in Fig. 6.3 c). As the data are stored off-chain, it is also possible to erase them upon request, improving data sovereignty. Nevertheless, this approach sacrifices the BC's improved availability and limits transparency, as data themselves are still provided off-chain.

To evaluate the different storage options, relevant criteria range from privacy, scalability, accessibility, availability, data sovereignty to transaction costs depending on data volumes, as contrasted in Tab. 6.1.

	Plain data	**Encrypted data**	**Hash**
Scalability	no	no	yes
Privacy	no	depends	yes
Data sovereignty	no	depends	yes
Low transaction costs	no	no	yes
Decentralized availability	yes	yes	no
Full transparency	yes	depends	no

Table 6.1: Comparison of different on-chain data storage options [13, p. 114]

To choose a suitable approach, the requirements for the documentation of the SMP process are analyzed, yielding the following results:

- The data storage option must offer enough storage capacity to document the entire process and enough throughput to document it in time.
- Because the SMP also processes private data, data should be erasable and stored confidentially, in order to comply with the GDPR. In addition, inspections by the Federal Network Agency require process data to be traceable and secured against manipulation.

Because of the scalability and privacy requirements, storing data on-chain is not an option for documentation of SMP processes. For this reason, the hash storage approach is further investigated. A key issue of using a BC for tamper-proof process documentation is to assure the correct provision of data to the BC. In the bidding process, input data are user-provided and as such the correctness of data is determined by the user. The most efficient use of a Merkle tree structure is to gather all input data, which however is only possible for the platform operator and not a single user. As a consequence, three different options for creating a Merkle tree and storing its root hash on a BC have been identified.

In the first option, illustrated in Fig. 6.4 a), all user input data for a given time frame are collected by the platform operator and then gathered to create a Merkle tree. The platform operator then stores the root hash of this Merkle tree on the BC, leaving users the ability to validate the integrity of their input ex-post. With this option, however, market regulators can only verify whether data supplied by the platform operator have not been manipulated since the Merkle tree's creation. It is not possible to check if supplied input data are correct from a user's perspective.

In the second option, depicted in Fig. 6.4 b), platform users store their input data hash on the BC themselves, ensuring the correctness of the hash. Input data are supplied to the platform separately. Previous input data hashes, that are already stored on the BC, can be combined by the user with its own hash to create a Merkle tree. The resulting root hash of this Merkle tree can be stored on the BC by the user. This way, one root hash needs to be stored on the BC for each user input. Therefore, this option is less scalable as the number of transactions on-chain increases with the number of platform users.

The third option, illustrated in Fig. 6.4 c), brings together both benefits of the previous options. All user input data for a given time frame are gathered by the platform operator to create a Merkle tree. The platform operator submits the root hash to a smart contract and requests users to verify the correctness of the root hash. Users then need to sign the transaction using a multi-party consensus to ensure its correctness, before the smart contract stores it on the BC.

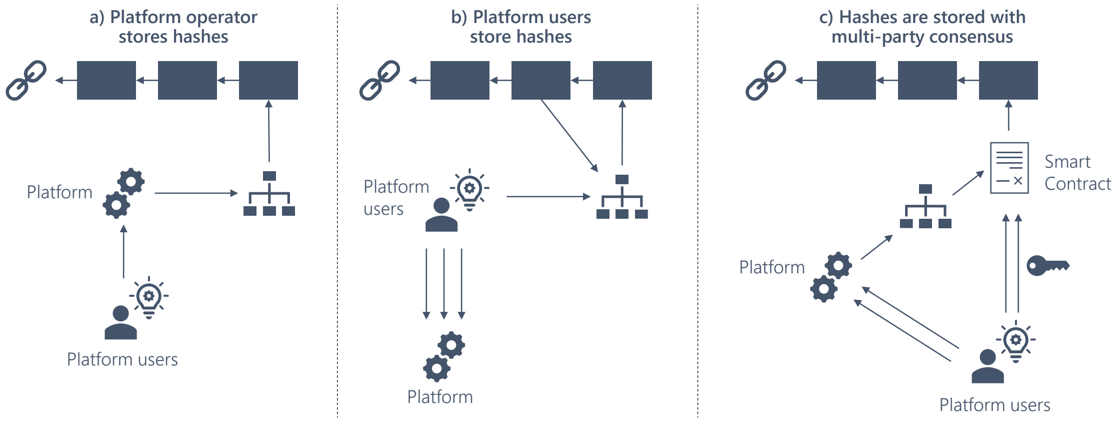

Figure 6.4: Hash storage options [13, pp. 114f]

While the last option is scalable through its Merkle tree use and provides a check for correctness, it requires the availability of users for the consensus process. Difficulties arise from situations, where no majority consensus can be achieved or when users find their input data to have been manipulated.

Regardless of what option would be chosen, once the root hash of a Merkle tree is stored on the BC, it can be used for validating the integrity of data. Assuming the correctness of data used for the construction of the root hash stored on the BC, any data provided by the platform at a later moment can be considered untampered with, if they can be used to reconstruct an identical root hash.

6.2.3 Verification Process and Proof-of-Concept

In the case of the aforementioned first option of storing a root hash on the BC, the correctness of input data used by the platform can be validated by the user ex-post. The user does this by receiving a list of hashes by the platform, which—together with the user's own input data—can be used to locally reconstruct the Merkle tree's root hash. If this local root hash matches the one stored on the BC, this proves that the user's input data has been stored (and potentially considered) correctly by the platform.

Finally, this first option was chosen for a proof-of-concept as it offers the benefits of scalability and guarantees traceability, while being more user-friendly as it requires less user interaction. The approach was implemented in a technical prototype of a verification platform based on an Ethereum BC by using open source libraries, as described in [13, pp. 115-117] [14]. A web-based client further provides all necessary functions for the transparent proof of validity. Fig. 6.5 illustrates the process and the interactions between platform-users, the software client, the SMP, and the BC.

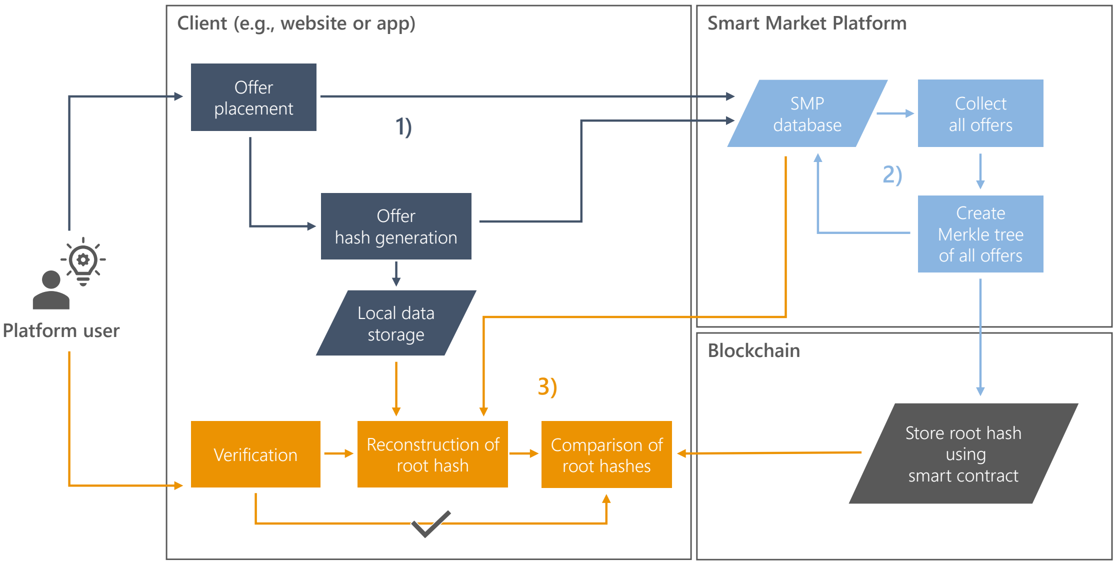

Figure 6.5: Verifiable offer placement [13, p. 115]

In a first step (Fig 6.5, step 1), the user places offer bids and submits them to the platform. While the platform stores the data on its side, the user holds their offers and the corresponding hash values locally. This technical redundancy is later used to execute the proof. Subsequently, after all offers have arrived at the platform, their corresponding hashes are calculated, and used to create a Merkle tree and its respective root hash within the SMP (Fig 6.5, step 2). This root hash is then stored in a smart contract on the BC. Finally, when the user wants to verify if the offer has been included correctly, they can request all necessary Merkle tree leaves from the platform (Fig 6.5, step 3). Using these leaves, the user can recreate a local root hash with the locally stored offer hash on the client-side. The local result can be compared with the root hash that has been stored on-chain by the market operator. In case the root hashes match, the platform operator has correctly received, included, and not tampered with the user's offer bid. In case the root hashes do not match, further investigation is required.

In theory, the approach above could be used in a diverse set of circumstances and also in other commercial sectors. In market processes, where bidding, offering, or tendering is involved, and the market operator wants to obtain and retain a certain level of credit or trust, the operator might offer this option. [13]

6.2.4 Conclusion and Critical Review

Within this section, several BC-based options were analyzed as possible concepts for tamper-proof and traceable documentation of SMP processes with the aim of providing increased trust to platform users and transparency to regulatory authorities. Scalability and privacy were identified as key issues. Finally, one approach combining on- and off-chain storage using Merkle tree hashes turned out to be the most promising option, providing scalability while preserving GDPR-compliant data protection. Within a proof-of-concept, this approach is then realized [13, pp. 115-117] [14]. Besides the achieved value propositions, the following options for improvement and need for further research were identified:

- The correctness of documented data can only be verified ex-post by the users. Therefore, regulatory authorities depend on users' validation to prove the correctness of data. Data still needs to be provided by the platform operator. The proposed possibilities of data provision using multi-party consensus could provide additional security, but further research on reducing the need for user interaction is required.

- BC and its use for documentation still have to be approved by regulatory authorities as trusted resources. Therefore, further proof-of-concepts and research projects have to prove the applicability.

- Within the proposed implementation, usability was always in focus. In order to reach a productive system, extensive automation (inter alia in the validation process) needs to be provided.

- A detailed evaluation of synergies to other energy platforms (including iMSys infrastructure) needs to be conducted to reach the state of an energy business ecosystem.

- The introduced concept is limited to the integrity proof of provided data. Within a next step, a proof of correct data processing is necessary. Therefore, within the following section, potential solutions for verifiable, scalable, and privacy-preserving computation are introduced and evaluated.

6.3 Proof of Data Properties through Verifiable Computation Techniques

As soon as data is processed within a platform application, the added value of the mere traceability of data provision (as introduced before) reaches its limits. Within an SMP, this directly applies to the matching algorithm (see Sec. 5.5). In order to provide trust in BC-based, distributed use cases that demand data computation, additional verification techniques need to be applied. Smart contracts can provide the basis for these. However, running complex calculations on-chain within a smart contract is significantly limited regarding scalability and privacy. Therefore, Sec. 3.3.2 already introduced so called layer 2 concepts and put a special highlight on VC techniques as summarized in Fig. 3.4. Within [1], these technologies are further analyzed and applied to “blockchain systems for the energy sector” in general, and optimization problems in energy market environments in specific. The following section cites and summarizes the most important findings of this publication.

As a result of an extensive meta study performed in [15], Tab. 6.2 gives an overview including respective advantages and disadvantages of the considered VC options. This forms the basis for the subsequent evaluations in Sec. 6.3.1.

Trusted Oracles	Incentive-Compatible Off-Chaining (IOC) [1, p. 6], [15, p. 9]	+ *mature technology* + *transparent aggregation* + *native execution performance* - *slow aggregation* - *no cryptographic guarantees* - *requires honest majority*
	Trusted Execution Environments (TEE) [1, p. 6], [15, pp. 9-15]	+ *broad availability* + *near-native execution performance* + *encryption of private data* - *vendor as trusted third party* - *no access to hardware (e.g., network)* - *known side-channel attacks*
Zero-Knowledge Proofs	Preprocessing zkSNARKs [1, pp. 6-7], [15, pp. 34-44]	+ *cryptographically secure* + *fully transparent* + *fast verification* - *limited execution environment* - *expensive proof generation* - *requires trusted setup*
	Transparent zkSNARKs [1, pp. 6-7], [15, pp. 34-35]	+ *no trusted setup* + *same security as preprocessing variant* + *similar verification speeds* - *immature technology* - *proof generation even more expensive* - *higher proof sizes*

Table 6.2: Overview and review of the presented verifiable computation technologies [1, p. 8]

Multi-Party Computation	Linear Secret Sharing [1, pp. 7-8], [15, pp. 47-48]	+ *cryptographically secure* + *fully transparent* + *fully trustless* - *immature technology* - *limited execution environment* - *poor execution performance*

Table 6.2: Continued: Overview and review of the presented verifiable computation technologies [1, p. 8]

6.3.1 Evaluation of Solution Approaches

Much literature exists that is specific to each of the three discussed technologies. This includes original specifications, improvement proposals, evaluations, and comparisons. E.g., [241] provides a general analysis of BC-compatible VC on an inter-technological level. As an extension to existing literature, the following evaluation framework considers the most important requirements for IT-infrastructures in energy applications. These include security, performance, and practicality. In total, there are nine criteria belonging to these three different categories. The evaluation criteria are not universal but were particularly chosen for the application within optimization-based energy markets. Since the fulfillment of many of these goals cannot be measured quantitatively, an analytical approach based on a grading scale was applied. A quantitative evaluation is only provided within the proof-of-concept implementation in Sec. 6.3.2 as performance metrics are entirely use case specific depending on the applied VC technique. The possible grades are *excellent (++)*, *good (+)*, *average (0)*, *fair (-)*, and *poor (--)*. The evaluation of financial expenses related to the applied mechanisms was not considered as there are no relevant hardware expenses[2] and transaction fees are highly use-case specific.

As focus lies on the application of the analyzed techniques within a specific field of energy use cases, a partly subjective evaluation is inevitable and therefore justified. Tab. 6.3 compares the verifiable computation schemes based on the preliminary works in [15, pp. 63-70].

	Security				Performance		Practicality		
	I	*T*	*C*	*P*	*TS*	*MC*	*M*	*U*	*E*
Trusted Oracles (IOC)	-	++	--	0	0	++	++	++	++
Trusted Oracles (SGX)	0	--	++	0	++	++	++	+	0
zkSNARKs (Prepocessing)	+	++	0	0	0	+	0	+	-
zkSNARKs (Transparent)	++	++	0	0	0	--	-	0	-
Multi-Party Computation	++	++	++	+	--	+	-	-	-

Table 6.3: Graded evaluation results of selected verifiable computation schemes regarding the following evaluation criteria: ***I**ntegrity, **T**ransparency, **C**onfidentiality, **P**rivacy, **T**ransaction **S**peed, **M**emory **C**onsumption, **M**aturity, **U**sability, and **E**xtensibility* [1, p. 9]

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[2] The only exception is SGX. However, this is a standard component of newer Intel processors.

At first glance, a certain (although qualitative) gradient from top left to bottom right becomes apparent in the selected arrangement of Tab. 6.3. This implies that, as security features increase from Trusted Oracles over zkSNARKS to MPC schemes, at the same time, performance and practicality is significantly reduced. Finally, finding the right balance between these aspects is crucial to the application within a defined use case. The detailed rationale and explanation of the chosen criteria and evaluation in [1, pp. 8-12] are summarized in the following.

Security Aspects related to information security have been grouped together in the *security* category. The concrete evaluation criteria are taken from [242] and are mostly in line with common IT-security goals encountered in other relevant literature on the topic. More specifically, an application's ability to the following aspects is evaluated:

- Denial of unauthorized modification *(**I**ntegrity)*
- Monitoring by an outside observer *(**T**ransparency)*
- Prevention of sensitive data leakage *(**C**onfidentiality)*
- Protection of users' identities *(**P**rivacy)*

Within (energy) market environments, these claims are of particular interest, as they intend to provide proper market operation through transparent allocation and non-discriminatory competition combined with keeping sensitive data secret. All examined technologies are subject to the same privacy model as their respective BC. This includes privacy requirements regarding identification of users and potentially sensitive data. Within energy use cases, especially high-resolution consumption and generation data could contain security-related information or trade and business secrets. Therefore, input parameters to the computation need to be kept secret and are only shared with the computational node. Regarding identities, this means that, even though these are hidden behind public identifiers, these identifiers remain unchanged for every transaction, presenting attackers with opportunities for identity correlation attacks.

Performance The *performance* category comprises criteria which directly impact the efficiency of an application. While performance is a fairly broad term, the applied evaluation framework in [1] is tailored to match relevant use cases in the energy sector. Even though current developments towards close-to-real-time energy markets exist, the introduced use case of an SMP still operates with a certain lead time. Therefore, a distinct quantitative evaluation of throughput metrics is not considered within this study. Thus, the following selected metrics consider only such goals with direct applicability to a BC environment:

- Overall throughput on the BC *(**T**ransaction **S**peed)*
- Space constraints in the context of the underlying consensus protocol *(**M**emory **C**onsumption)*

Practicality As the energy sector is currently in fundamental change, also through process digitalization, the system evolves constantly. Therefore, new functionalities and use cases need to be added dynamically. Nevertheless, establishing new processes also requires long-term functionality and reliability as it is part of critical infrastructure. In consequence, the category *practicality* groups various aspects related to the solution's implicit cost to scale. This includes the current state but also whether the solution is sufficiently future-proof to be considered for long-term projects. Specifically, the following guiding questions are analyzed in [1, pp. 11-12]:

- Is the technology currently in a practice-ready state *(**M**aturity)*?
- How accessible is the system for developers *(**U**sability)*?
- How easy is it to add new functionality *(**E**xtensibility)*?

6.3.2 Application to Optimization-based Matching

In summary, the applied evaluation reveals the specific properties and application scenarios of the presented VC techniques. Choosing the right technology is very use-case specific, specifically regarding its requisitions to security, performance, and practicality (compare Tab. 6.3). In the following, the previously introduced findings of the general assessment are applied to the basic process of a decentralized, BC-based matching function. As introduced in the SMP's matching process in Sec. 5.5, the setup builds on a linear optimization algorithm, generally defined in its canonical form in Equation 6.1. [15, p. 76]

$$\begin{aligned} \text{maximize} \quad & c^T x \\ \text{subject to} \quad & Ax \leq b \\ \text{and} \quad & x \geq 0 \end{aligned} \tag{6.1}$$

where

x	Decision variables, representing the optimized input values
c	Decision variables' contribution to the targeted objective function
A	Coefficient matrix of the different resource equations
b	Constraints of total available amount of each required resource

Solving these types of optimization problems is a well known and explored field of mathematics with several emerged solution approaches. The *Simplex algorithm* is one of the earliest, efficient, and still applied techniques, developed by George Dantzig in 1947 [243]. Therefore, it is also applied within the allocation method in the SMP (see Sec. 5.5.3).

System Architecture Considerations To integrate the already mentioned requirements regarding privacy (due to the use of sensitive data) and scalability (in a system with several million market participants), the choice of an appropriate VC scheme to be applied in a BC environment is decisive. In addition, practicality for broad application at the current or near-future state of development is a relevant factor. To compare the five different VC techniques introduced before, the derived findings in [1, pp. 13-14] and [15, pp. 71-73] are summarized as follows.

1. *Trusted Oracles*
    - Incentive-driven *IOC* oracles are the currently widest spread off-chaining oracle approach within BC environments. Due to their unconstrained execution model, they provide diverse fields of application. However, they largely lack support for secret user data. This means, that potentially sensitive or critical input data is disclosed with all participating computation nodes [241, 172].
    - Oracles using a *TEE*, e.g., based on Intel's SGX platform, can circumvent these shortcomings by secured hardware components. As they provide an extensible execution model, a multitude of use cases can be molded in compliance with relevant security requirements [244]. However, the reliance on the hardware vendor could be a certain drawback, although this also applies to all other energy industrial systems. In consequence, there are already several real-world applications running on SGX (see, e.g., [245, 246]).
2. *zkSNARKs*
    - *Preprocessing zkSNARKs* provide a balance between security and performance. As they only rely on cryptography for their security guarantees, they operate transparently and mostly trustless. However, a certain trust to the executing node of the computation still needs to be provided, as private user data must be shared and is therefore disclosed. Within the given use case of an SMP, this service can, e.g., still be provided by a regulated entity that eventually already has access to this information. Therefore, no confidential data is leaked. Regarding its future-proof application, zkSNARKs still face limited performance. However, there is intensive research into the further development of the technology, including the trusted setup requirement and its mediocre performance. [15, pp. 34]
    - *Transparent zkSNARKs* are quite similar in their features. Their significant advantage is the missing need for a trusted setup that has to be initially performed. However, this comes with significantly lower performance metrics that make them quite impractical for large-scale energy use cases at the current state of development. [15, pp. 34-35]
3. *MPC* meets all the security and trust requirements desired for the application in the energy sector. Unfortunately, its poor performance—that is also not very likely to be resolved in the near future—is a significant drawback. As the application within an SMP demands quite complex computation, it is not foreseeable that these requirements can be achieved through sufficient performance leaps [247]. The hesitant industry-adoption of this technique also reflects this assessment.

In summary, the two most promising VC techniques are, on the one hand, *Trusted Oracles with SGX* and, on the other hand, *Preprocessing zkSNARKs*. Both of them show a good balance for the required features, especially through decent security features and scalability. Strikingly, these two options show quite similar architectural setups, based on the execution by a specific and defined computational node. However, their specific value propositions still have to be evaluated in further research. As the SGX setup is not directly dependent on an adaption of the actual algorithm, within the following prototype implementation, only a zkSNARK approach is tested to reveal and test the necessary increase in complexity.

Prototype Implementation To provide a proof-of-concept, a prototypical implementation of a zkSNARK (based on the ZoKrates framework [248]) for the proposed linear optimization (see Equation 6.1) was implemented [1, p. 14]. Further performance tests and sensitivity analyses have been conducted in [15]. Depending on the number of variables and the number of conditions in the optimization problem, three key evaluation metrics have been measured: compile time for a single instance of the optimization circuit, compute time for a witness for the compiled circuit, and number of R1CS[3] constraints (see Figure 6.6).[4]

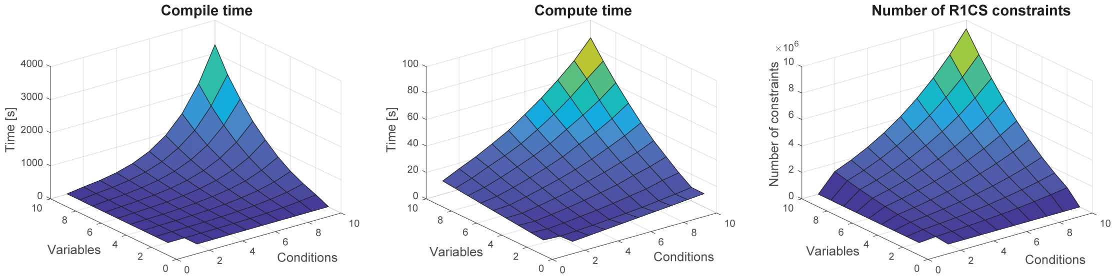

Figure 6.6: Overview of performance metrics for different numbers of decision variables and conditions [1, p. 15], based on the measurements conducted in [15, pp. 84-88]

A detailed interpretation of the results can be found in [1, p. 14]. The most important findings can be summarized as follows:

- The intended approach is feasible and realizable. Nevertheless, this could only be proven for very small problem instances with a limited number of variables and conditions. As problem size increases, all three performance metrics grow infeasibly large, albeit at different rates.
- The specific properties of the underlying circuit compilers of ZoKrates (based on R1CS[3]) lead to the fact that the algorithm's runtime is always determined by a

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[3] *Rank-1-Constraint-Systems* are "a mathematical representation of a circuit's architecture, describing all of its properties, including input variables, output variables and logic gates." [15, p. 37]

[4] All tests were run on a worker node in an isolated environment. The node possesses an Intel Xeon Gold 6152 CPU with 22 Cores, 44 Threads and 30MB of cache. Each core runs at a clock speed of 2.1GHz. The used RAM is a 32GB DDR4 Dual Rank RDIMM module with a clock rate of 2666MHz. Data is read from an SAS SSD with a transfer rate of 12Gbps. [15, p. 84]

fixed number of iteration loops. In consequence, within an optimization algorithm like Simplex, iteration can not be skipped over with conditional statements. This undermines the initial efficiency of the algorithm and finally leads the computation to always have a worst-case performance. Even if an optimum is reached early, the remaining iterations of the loop must be taken. Accordingly, this is not a quality feature of the proposed implementation in [15, pp. 78-83] but a property of this type of algorithm. [1, p. 14]

- In consequence, the given results are not specific to certain optimizations but hold true for all possible problem instances as the arithmetic circuit's runtime is fixed to that of a worst-case problem instance.
- A first curve fitting approach to the quantitative results of Fig. 6.6—although to this quite limited number of experimental results—suggests an exponential dependency in the form of $f(x, y) = a \cdot e^{b \cdot x + c \cdot y}$.[5]

6.3.3 Conclusion and Critical Review

Applying the findings illustrated in the case study before to a potential application of a zkSNARK scheme within the SMP's matching process obviously reveals the infeasibility of its application. As an example, assuming the given input parameters in Sec. 5.2.2, with approx. 76,000 conditions (x) and 58,000 variables (y) to be considered per matching run, the approximated runtime grows towards ad infinitum.[6] In consequence, the obtained results do not support the idea of zkSNARKs as an optimization method with currently available frameworks [15, p. 85]. Nevertheless, the current developments in the field of ZKP are rapidly progressing and proposed alternative implementations promise to provide significant performance leaps. [1, p. 15]

Although the given results dampen expectations for timely practical implementation, the introduced VC technologies yield great potential, especially in the energy sector. Besides that, applicable solutions such as hardware-secured Trusted Oracles are already available and in experimental use in other industries. Furthermore, significant research effort is currently put in the further development of VC techniques, mainly driven by various BC applications in all kinds of sectors. Despite their limitations in terms of performance and scalability, zkSNARKs currently receive the most attention. But also methods for fully homomorphic encryption are constantly evolving.

In conclusion, it is already possible to run VC in a BC-based environment and profit from the respective properties. Still, more research is required until this technology becomes practical for large-scale adoption.

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[5] with x = *number of conditions* and y = *number of variables* leaves a $R^2 = 0.9955$ for compile time ($a = 2.71$, $b = 0.4225$, $c = 0.2908$), $R^2 = 0.9861$ for compute time ($a = 1.49$, $b = 0.1961$, $c = 0.2175$), and $R^2 = 0.9888$ for the number of R1CS constraints ($a = 1.115e + 05$, $b = 0.2217$, $c = 0.2278$)

[6] Underlying assumption: approx. 3.800 bids with 20 potential call conditions per bid and approx. 15 considered variables per bid

7 Evaluation of Design Alternatives

The previous two chapters introduced and specifically analyzed different approaches for realizing the intended goal of providing an efficient and sustainable SMP design. Based on the functional description of the platform process and relevant functions, reasoned proposals for the respective implementation are given in Chapter 5. Based on these initial and centralized design options, Chapter 6 outlined decentralized and, in specific, distributed, technical implementation options, including their particular added value. However, a detailed evaluation of the introduced design alternative with reference to the derived (non-functional) requirement specifications in Chapter 4 is still necessary and done in Sec. 7.1 to provide a recommendation for implementation. To further enable a comprehensible assessment of the decentralization alternatives, an evaluation framework and mapping approach is introduced and applied in Sec. 7.2.

7.1 Requirements-specific Assessment

The following appraisal directly refers to the (non-functional) requirements derived in Chapter 4 and summarized in Tab. 4.1. The considered dimensions include practicality, accessibility, and usability (1), market potential and scalability (2), efficiency and market quality (3), costs (4), security features (5), and, finally, transparency and data protection (6). An analysis of these dimensions is addressed from the identified perspectives (A–D) in the following.

A - Market Perspective Market requirements include all aspects to provide an efficient market performance as derived in Sec. 4.1. Therefore, relevant market principles should be achieved as far as possible.

A1	High market liquidity	Market liquidity is affected by several design decisions. On the one hand, this is addressed by the general timing and integration into the existing energy market (see Sec. 5.1 and Fig. 5.3). On the other hand, specific marketing opportunities (i.e., the aggregation service in Sec. 5.3) and product specifications (Fig. 5.2) allow the participation of small scale FOs. As limited liquidity may further encourage market manipulation based on market power, the introduction of a market monitoring scheme is essential (Sec. 5.4).

A2	Sufficient performance	This aspect mainly addresses the matching process (Sec. 5.5). Even if complex in its computation, the proposed constrained optimization shows better performance compared to alternative heuristic matching approaches (Sec. 5.5.5). The concept of decentralizing the allocation scheme by the proposed VC techniques in Sec. 6.3 eventually reduces the performance, especially within a zkSNARK approach, leading to a potential bottleneck for scalability.
A3	Optimal market results, avoidance of market manipulation	The proposed matching process in Sec. 5.5 primarily pursues the objective of system-optimal market results. Through its global cost minimization under consideration of all relevant boundary conditions, it is superior to alternatives like regional order books (see Sec. 5.5.1). It shows similar results as heuristic approaches using iterative grid optimization as introduced in Sec. 5.5.5. Market monitoring (Sec. 5.4) addresses the identification of structural market power. Nevertheless, further market manipulation is generally possible (Sec. 5.4.5) and shows the need for further research.
A4	Minimal operational costs	Standardized products and interfaces intend to reduce operational costs trough individual adaption (Sec. 5.1). Decentralization—as proposed in Chapter 6—generally increases complexity but is not necessarily linked to increased operational costs.
A5	Reliable, robust market operation	The optimization based matching (Sec. 5.5.3) typically implies a black box for outside observers (without insight into detailed offer and demand bids). Verifiable computation (Sec. 6.3) provides a solution to this challenge through a proof of correct execution and, eventually, reduces the power of individual actors (i.e., a single platform operator) and single-points-of-failure.
A6	Maximum transparency	As introduced, a constrained optimization only allows limited transparency towards correct consideration of bids and allocation results. Therefore, verifiable offer bids as introduced in Sec. 6.2.3, and the proof of correct computation in Sec. 6.3.2 can provide increased transparency to all relevant actors

B - Platform Participants' Perspective By addressing relevant demands of actors interacting with the SMP, both the flexibility supply and demand sides need to be considered (see Sec. 4.2).

B1	Asset-specific products	To open the market to all different types of FOs and market actors, a product differentiation is introduced in Sec. 5.1 and illustrated in Fig. 5.2.
B2	Inclusion of all types of potential market participants	From a supply perspective, besides a generic product open to all technologies, a specific long-term contraction is proposed using the aggregation and pooling concept in Sec. 5.3. In consequence, relevant constraints need to be considered in the matching process (Sec. 5.5.3). Demand side access is limited to the prevailing DSO. This can eventually be opened to overlying system operators to tap all relevant flexibility potentials (see Fig. 3.2).
B3	Demand side: reliable delivery Supply side: maximum revenue	Demand side: Reliable flexibility provision should be ensured as far as possible. Especially within long-term contracted flexibility (see Sec. 5.3), only statistical availability can be considered. Therefore, a certain safety margin is considered as the LoS. In addition, the SMP concept acts in the amber traffic lights phase (introduced in Sec. 3.1.2). Consequently, the DSO still has the option of emergency measures in the red phase (see Tab. 3.1 and Fig. 5.3). However, further regulatory instructions and standards need to be provided to ensure a secured performance of participating FOs within the selected limits (ultimately even with penalization measures). Supply side: A fair allocation is provided by system-optimal market results. Nevertheless, individual profitability could not be evaluated within this thesis due to limited real market behavior. This leaves room for further research.
B4	Minimal costs for participation	The transaction costs for market participants are kept low due to standardized interfaces and minimized interaction needs (see Sec. 5.1, Fig. 4.1, and Fig. A.1).
B5	Reliable interaction and access	As reliability is the key to trust in the market and platform architecture, additional features (besides the standard protection of digital processes) provide added value. In Sec. 6.1, options for distributed data management and storage have been introduced and address identity management through SSI (Sec. 6.1.1). In addition, the proof of data integrity (Sec. 6.2) can further ensure secure communication to safeguard critical data.

B6	Data privacy to protect sensitive data	The more data is solely stored and processed by an individual entity (i.e., the platform operator), the more risk for data breach, privacy violations, or even manipulation is given. Assuming a centralized setup, all relevant data lie with the platform operator. The techniques introduced in Chapter 6 open alternative pathways to handle these data implying more data sovereignty, cross-checking, and system-inherent trust and reliability.

C - Technological perspective Technical aspects to interaction with the SMP mainly refers to efficient integration of different FO types through standardized interfaces.

C1	Standardized market access, defined interfaces	Defined data formats for asset-specific products, including described interfaces, provide low-threshold technical access (Sec. 5.1).
C2	Little technical restrictions	Only mandatory data need to be provided with the platform (Sec. 5.1). As these data are formulated generic, technology neutrality can be ensured. In addition, technical restrictions are reduced and offer market access for FOs on household level with the goal to reduce entry barriers (Sec. 5.3).
C3	Consideration of technical constraints	The provision of generic data implies sufficient setting options based on technical constraints. Especially when considering different types of FOs and pooled units (Sec. 5.3), specific call constraints need to be considered within the matching (see Sec. 5.5.3, Fig. 5.15, and Fig. 5.16).
C4	Minimal extra costs through additional functions	Digitalization of all relevant end-points is the prerequisite for market-based flexibility allocation and, therefore, an SMP. iMSys infrastructure provides this fundament (Sec. 1.2.2) and is included in the SMP's structural setup and process (Fig. 4.1 and Fig. A.1). In consequence, all necessary interactions are covered by iMSys or web interfaces.
C5	High availability and reliable interaction	Secured interaction is, on the one hand, covered by fulfilling existing industry standards. In addition, added features through BC technology can be used for revision safe documentation and traceability. Generally, BC is only applied for storing proofs of data integrity and data properties. This allows the reduction of data transmission.

C6	Protected communication and data storage	Applying iMSys infrastructure already provides sufficiently secure communication for measurement data. By adding features of SSI (Sec. 6.1.1), data sovereignty can be increased. Distributed data storage potentially provides an alternative for data storage (Sec. 6.1.2), although privacy standards still need to be evaluated. The introduced proofing opportunities can add extra security features (see Sec 6.2).

D - Regulatory perspective Energy-economic and regulatory requirements address a system-optimal and non-discriminatory market behavior. This includes the avoidance of market inconsistencies.

D1	Non-discriminatory access	Technology neutrality and the avoidance of preferential treatment of individual actors or technologies is ensured by standardized access and data minimization. This aspect is considered in the registration and bidding process. Information regarding the type of FO is not even necessary as long as all needed master and bidding data is provided in the standardized form (Sec. 5.1, Fig. 4.1 and Fig. A.1). The application of SSI (Sec. 6.1.1) can further support these intentions.
D2	Large-scale application	With the goal to develop a blueprint for large-scale adoption, standardization is necessary. So, isolated solutions should be avoided. Therefore, the applied techniques and functions are kept as lean and efficient as possible. To start with the aggregation scheme (Sec. 5.3), a simple but effective way of pooling similar units is applied based on grid topology, existing regulatory frameworks, and statistical simultaneity factors. The market monitoring (Sec. 5.4) further focuses on the comprehensive metrics of the RSI to identify structural market power. The matching process shows more complexity by using a constrained optimization, but in consequence, provides all features to consider necessary boundary conditions (Sec. 5.5). The application of BC technology to increase trust, transparency, and data security leads to additional complexity and challenges regarding scalability. The choice of an appropriate system architecture is consequently decisive for large-scale application (see Sec. 6.1, 6.2.4, and 6.3.3).

D3	System-optimal results, avoidance of market inconsistencies	From a macro-economic perspective, system-optimal matching results are fundamental. Seamless integration into existing electricity market and CM processes is another prerequisite for an efficient SMP operation. Several aspects need to be considered, starting from the scheduled time of flexibility contraction to the consideration of opportunity costs in competing markets. Eventual market inconsistencies could lead to susceptibility for market manipulation. Therefore, a market monitoring, as introduced in Sec. 5.4, is necessary. Nevertheless, an extension to identify and mitigate applied market power, strategic bidding, gaming, or collusion would be reasonable (Sec. 5.4.5).
D4	Minimized system costs	The overall goal of an SMP is to reduce system costs by an efficiency increase in CM through a market-based approach (Sec. 3.1.2). The provided implementation suggestion covers this prerequisite from a overriding standpoint (see Sec. 5.1), and in the detailed design of the individual functions (Sec. 5.3, 5.4, and 5.5).
D5	Defined responsibilities, reduction of single-points-of-failure	SMP operation needs to be provided by a defined role, independently of the actual setup. Different constellations for market operation are conceivable. However, a regulatory definition is still lacking. This marks an open order for the regulator. Structural decentralization can apply to the operation itself or the area of application, as discussed in Chapter 6. These structural decisions are mostly independent of the technical deployment, which can be realized using a distributed setup with BC technology. This technical decentralization only provides added resilience and/or transparency. So, a single-point-of-access doesn't necessarily lead to a single-point-of-failure.
D6	Transparency to review market operations	External review of market activities represents a core responsibility of the regulator. As outlined in Sec. 6.2, it needs to ensure the correct function of the market and its respective functions. To avoid complete disclosure of all data and reduce the cumbersome detailed analysis of each market process, the proofing methods introduced in Sec. 6.2 and 6.3 can significantly reduce the effort for market review. Even though the techniques promise transparency and system-inherent trust, they still have to be accepted by the regulatory bodies.

Conclusion Non-functional requirements were already picked up by deriving the functional requirements in the respective sections 5.3.1, 5.4.1, and 5.5.1 as an input for the elaboration of the SMP functions. In consequence, most defined requirements could already be achieved implicitly. However, open questions, challenges and decision options can still be identified.

Decentralization options, introduced in Chapter 6, only show impact in certain specifications, mainly addressing performance, scalability, security, and transparency. These aspects culminate in their impact to the following requirements: *A2*, *A5*, *A6*, *B6*, *C6*, *D2*, *D5*, *D6*. In consequence, the following section illustrates the involved architectural implications based on a derived visualization method.

7.2 Comparative Description of Decentralization Alternatives

In the following, the respective system architectures of a centralized design compared to the decentralized variant (through added or altered features) are directly compared.

7.2.1 System Cartography and Evaluation Framework

The need for illustrating data processes and functions is an already omnipresent topic in software engineering and the development of IT architectures [249]. As the energy system becomes more and more digitalized, the ever-increasing focus on data-driven applications makes it necessary to visualize relevant data traces within the system architecture [250]. Increasingly complex interactions with a rising number of DER and the use of (distributed) technologies like BC imply additional features but also challenges [251, 252].

The following approach to a system cartography and evaluation framework for complex energy BC architectures was developed and published in [16]. The development process was conducted and described according to the Action Design Research methodology proposed by Sein et al. [253]. Based on the identification of process steps dealing with data acquisition, transmission, processing, and storage within energy architectures, a visualization tool is introduced. Fig. 7.1 illustrates the framework including the integration of different domains, application layers, clusters, and connection types as described in the following.

Domains Three relevant domains have been selected. *Local hardware and interfaces* include all different types of facilities including power plants, consumer appliances, measurement gear, sensors, terminals, communication devices as well as data management and computation systems that are located on-site at the customer premises. *Central server* infrastructure provides the middleware or backend involved in the use case process. *Blockchain* or DLT promise certain advantages regarding transparency and manipulation resistance and can bring benefits for energy use cases. On-chain data storage can therefore be stored in different forms (see Sec. 6.2.2). Related computation can be performed on-chain using smart contracts or via outsourced service nodes (see Sec. 3.3.2) [233, 252, 254]. The non-conformity of storing personal or sensitive data on a BC makes it necessary, to only file non-personal, anonymized, or just a proof with reference to externally stored data or computations there (see pink border with reference to GDPR and § 50 MsbG in Fig. 7.1).

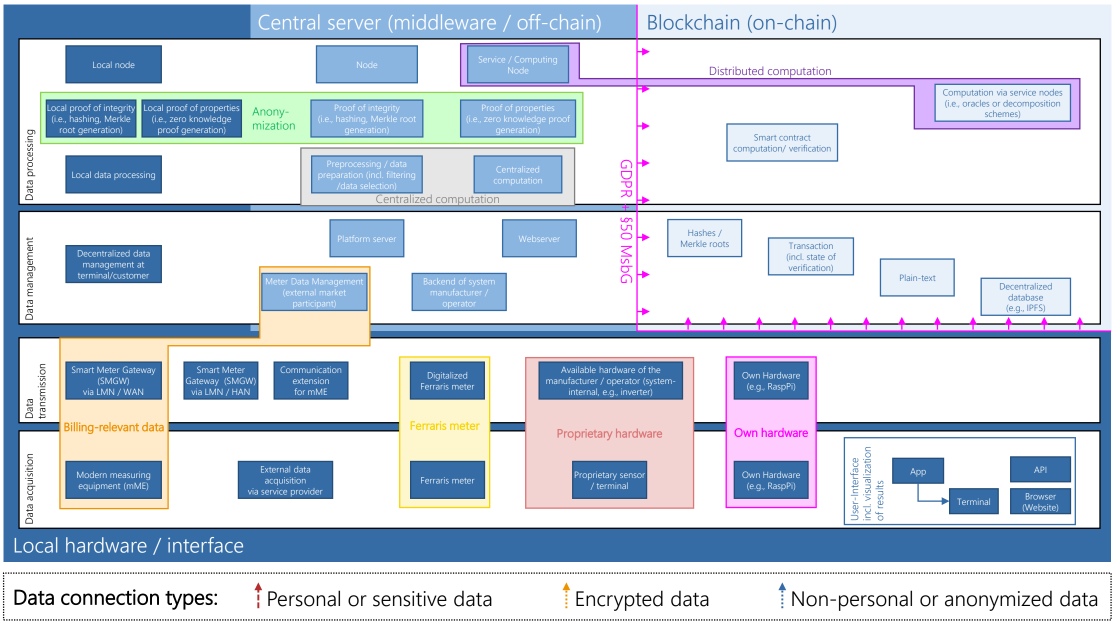

Figure 7.1: System cartography visualization including *layers* (data acquisition, transmission, processing and storage), *domains* (local hardware / interface, central server / middleware / off-chain and blockchain / on-chain), selected *clusters* and *data connection types* [16, p. 281]

Layers Besides the described domains, four data layers provide the second dimension. *Data acquisition* as the base layer includes all types of measurement gear, data input and forms of interaction with the end user or respective facility. *Data transmission* is conducted through communication endpoints at the customer premise. SMGWs provide this functionality and are intended to become the future communication standard for energy applications including the provision of billing-relevant data (see Sec. 1.2.2) [36]. *Data management* can be conducted in all three defined domains and includes data storage at the customer premise, a centralized platform or web server hosted by the system operator, or a specific regulated energy role (e.g., metering endpoint operator). In addition, data storage can also be realized on a BC or in a decentralized database like IPFS (see Sec. 6.1.2 [231, 232]). *Data processing* finally describes the layer where use case relevant result-generation (i.e., the business-logic) is conducted. The actual computation can be processed on- or off-chain, involving the benefits and drawbacks described beforehand.

Clusters of interrelated components After defining domains and layers as the main structuring elements, additional clusters can be identified. They connect components that have a direct interrelation through technological affiliation or similar functional behavior. One example is the acquisition of billing-relevant data as the only available path of digital metering data (in Germany) is through iMSys infrastructure that is calibrated and acknowledged for billing processes [255]. *Anonymization* includes proof generation and the associated transformation of plain data to anonymized data as well as the removal of all personal affiliation.

Components The relevant components describe the smallest elements addressed within the framework and include hardware or functional entities.

Connection types In order to map specific use cases and their data processes within the framework, all relevant pathways need to be represented by arrows that interconnect the components involved across the relevant layers and domains. The paths show the data flow through the infrastructure.

7.2.2 Framework Application to Identified Design Alternatives

Applying the framework to the SMP layout offers the illustration and distinction of structural properties of different (de-)centralization grades. The following descriptions are user-centric, focusing on the flexibility provider, their interaction with the platform, and consequential execution of SMP functions.

Centralized Implementation Fig. 7.2 depicts the centralized version, as initially described in Chapter 5 and Fig. A.1.

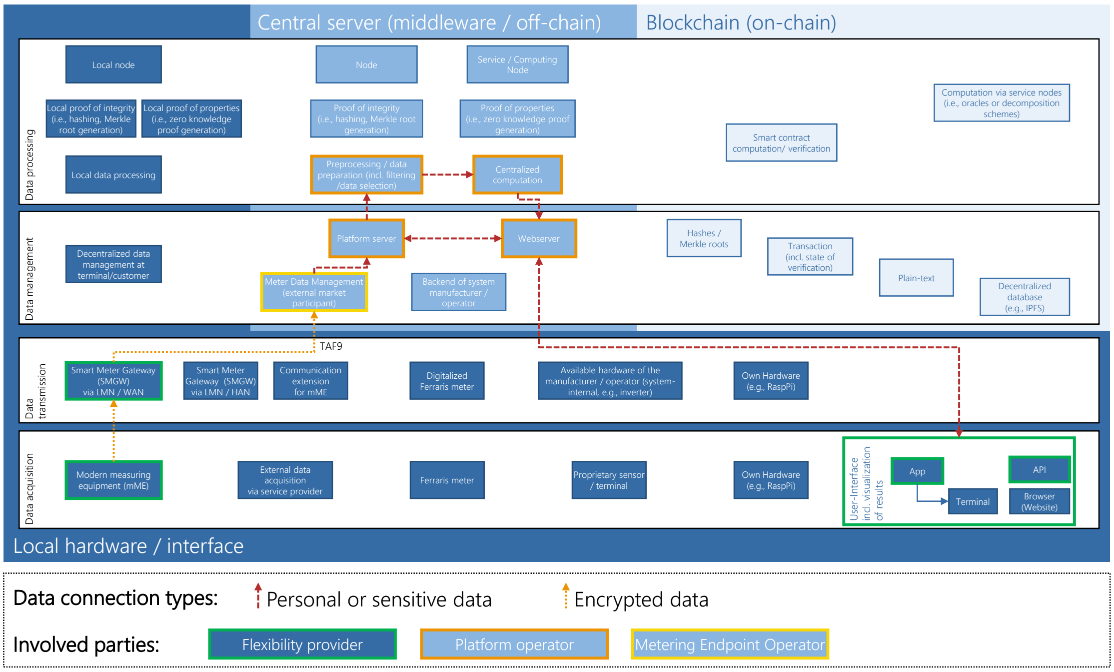

Figure 7.2: Centralized Smart Market Platform system architecture

The centralized approach in Fig. 7.2 involves two relevant tracks of interaction originating at the flexibility provider's premise[1]. The first interaction is initiated by providing offer bids through the SMP's interface (bottom right). The data is transferred to the platform server via a web service. Within the server environment, all relevant processing steps (i.e., within the SMP functions) are centrally computed and stored at the platform operator's local infrastructure. After the matching was conducted, the results (incl. potential contraction details) are returned to the flexibility provider that can then adjust the operational planning of their FO. The second pathway starting at the flexibility provider's mME relates to the proof-of-flexibility provision by reading FO's operational data via iMSys infrastructure (see [17] for further details).

Only a limited number of components is activated, illustrated by the highlighted boxes. The direct reference from the flexibility provider to the platform operator reduces the number of necessary interfaces. As sensitive data is mainly exchanged openly, the platform operator needs to fulfill security standards and should eventually be filled by a regulated role. However, this could also lead to a potential single-point-of-failure as all functions are centralized and responsibilities are concentrated to one intermediary.

Decentralized Implementations The illustrations in Fig. 7.3 depict the introduced options for decentralization referring to a *proof of data integrity* (Sec. 6.2) and the *proof of data properties* by application of VC techniques (Sec. 6.3).

Verifiable Offer Placement As introduced in Sec. 6.2.3 and depicted in Fig. 6.5, a verifiable offer placement allows to transparently trace and verify the correctness of a provided offer bid by combining on- and off-chain storage using a Merkle tree approach. In consequence, an additional process to the ones described beforehand is necessary (ceteris paribus), as illustrated in Fig. 7.3 (a).

On the SMP side, the integrity proof is generated by forming the Merkle tree's root hash and its storage on the BC. On the user's side, an additional hash generation (including its local storage) is necessary by bid submission. For the verification process, the user receives the Merkle tree leaves from the SMP, locally reconstructs the root hash, and compares it to the one stored on the blockchain.

Decentralized Matching Sec. 6.3.2 introduces different options for realizing a decentralized, optimization-based SMP matching process. Finally, two different VC techniques came into closer consideration (Trusted Oracles with SGX and Preprocessing zkSNARKs). Although different in their function, the underlying architecture is similar by outsourcing computation to specific nodes (see Fig. 7.3 (b)). The SMP provides all necessary data to the computing node that in turn conducts the optimization calculation. The choice of the respective node can be predefined or individually selected for each instance. The eventual generation of a proof of correct computation (e.g., via ZKP) provides information for verification and is published on-chain (without disclosing private input data). This can then be easily checked by all involved stakeholders.

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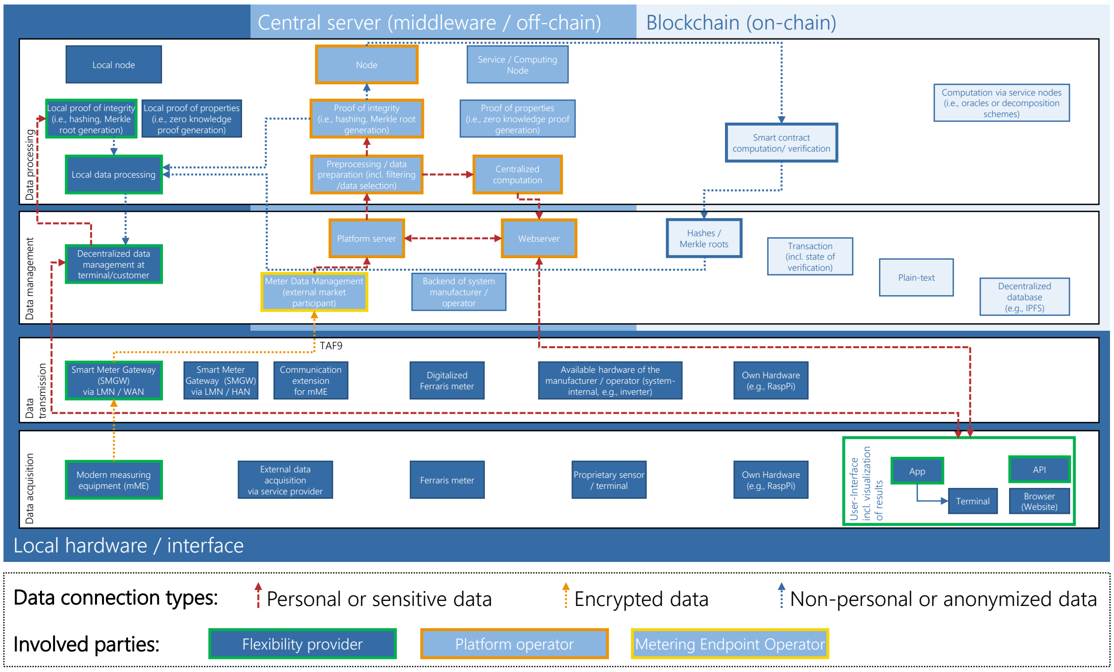
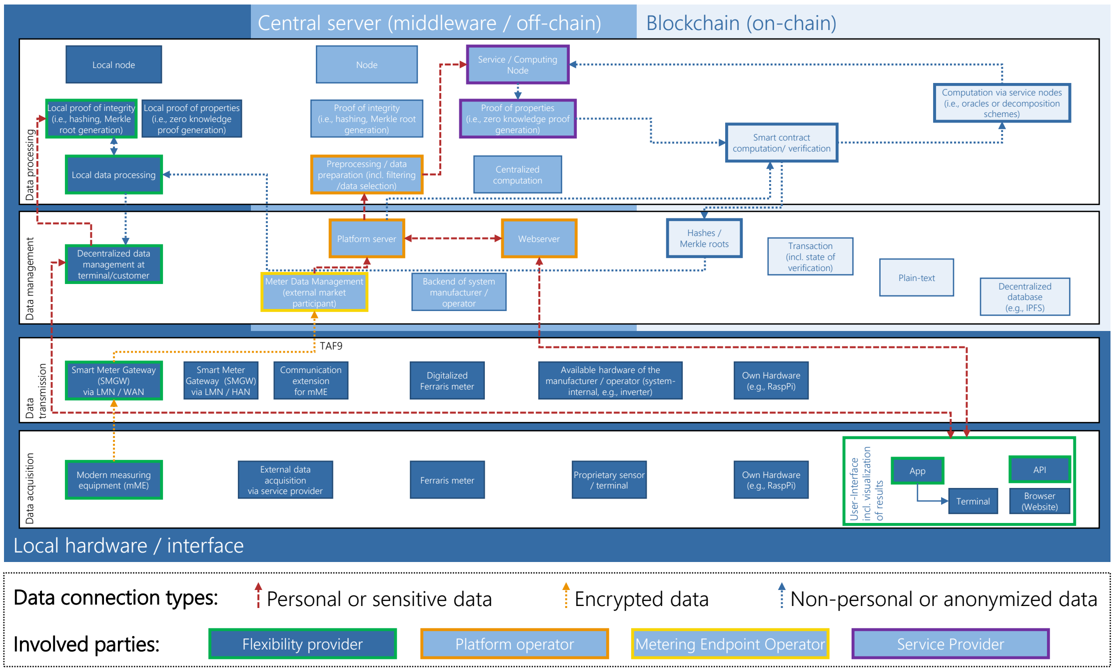
[1] The description exemplarily assumes a schedule offer bid, see Sec. 5.1.



(a) Verifiable offer placement



(b) Decentralized matching using verifiable computation

Figure 7.3: Decentralization options within Smart Market Platform design (adapted according to [16, p. 283])

To summarize, transparency with simultaneous data privacy can be provided through application of appropriate means of decentralization. However, these demand higher complexity as contrasted in the architectural setups of the centralized version in Fig. 7.2 compared to the decentralized setups in Fig. 7.3. On the one hand, decentralization demands a relevant increase of interactions of more components and potentially more parties to be involved. On the other hand, this also leads to more data sovereignty and individual responsibility, which also come with duties. This could be particularly beneficial for end-users (i.e., flexibility providers) and regulators (in case the proposed architecture and the use of BC technology are legally accepted). However, further developments and testing (e.g., within regulatory "sandboxes") are highly recommended to find a reasonable balance between applicability and necessary system complexity.

8 Synthesis, Conclusion, and Outlook

With the goal to design a (decentralized) SMP, the contents of this thesis proceed from the general to the detailed and finally back to the bigger picture. SMP, therefore, stands for a platform tool that enables an efficient market-based, grid-supportive flexibility allocation, involving several features and functions within a consistent CM process. With the intention of always keeping an eye on the broader context, the thesis first introduces the current and upcoming challenges in energy transition, illustrated by the 4 D's in Chapter 1. *Decarbonization* by integration of renewable energies into the energy system defines the overall objective. As the focus lies on efficient grid operation, prospective and improved congestion management processes rely on using grid-supportive flexibility. The decentralized character of generation, load, and flexibility corresponds to an increasingly apparent *decentralization* tendency. This also applies to the system architecture, including distributed setups involving BC technology. *Digitalization* provides the basic infrastructure for tapping the available flexibility potential with iMSys providing the common standard as the standardized edge device. This, in turn, can create market access for small players and thus lead to a *democratization* of the energy economy. LFMs serve as the basis for the SMP development and address a cross-section of these aspects. Their main purpose lies in the exploitation of regionalized flexibility for market-based CM. However, the integration of the rising number of small assets, associated with increased interactions of a wide variety of (new) actors, demands innovative concepts and new technical solutions. The introduction of an SMP, as proposed in this thesis, therefore extends the concept of an LFM by adding additional features that profit from novel platform architectures. BC as a platform and business ecosystem technology offers promising possibilities to meet these requirements. By providing a high degree of automation, transparency, and security-by-design, it offers opportunities for the efficient implementation of new coordination and allocation schemes, such as within an SMP.

Applied Methodology Based on a digitalized energy system combined with the value propositions of BC technology, the objectives and research questions are outlined in Chapter 2, followed by the methodology applied in this thesis. The given hypotheses and respective research questions are then formulated to be answered in the subsequent chapters. Chapter 3 provides the background analysis and bridges from current developments in flexible grid operation to the future relevance of (distributed) platform technologies. The inner structure of the chapters contains the analysis of relevant aspects and methods and finally leads to intermediary results and respective design suggestions. The applied systems engineering methodology implies a V-model approach to structure the development procedure. The thesis structure is consequently designed to find specific answers to the research questions. They can be summarized as follows.

RQ1: What non-functional requirements can be derived for the design of an SMP from relevant perspectives? Starting with the defined “business case” of an SMP, a consistent “requirements elicitation” sets the ground for the development process, equal to the first steps within the V-model. For the big picture, non-functional requirements are derived in Chapter 4. They define the expected qualities of an SMP, identified according to four different perspectives in six respective dimensions.

Market requirements as the first dimension contain demands ranging from basic market principles (i.e., transparent allocation and prize formation, non-discrimination, erosion of market power, and competition) to the specific challenges of market power mitigation in regionalized electricity markets.

Platform participants' requirements extend these from the disparate stakeholders' perspectives of all involved actors that interact with the SMP. From the flexibility provider's side, the needs contain product differentiation to cover individual marketing abilities, procedural integration, financial incentives, and reliability. From the demander's side, applicability as well as planning and data security need to be sufficiently fulfilled.

Technical requirements are closely linked to the type of participating FOs on the flexibility supply side and grid-related needs from the DSO on the demand side, e.g., regarding the LoS and backup measures. A low-threshold market access requires a careful balancing of little technical restrictions, on the one side, and sufficient setting options to avoid extra costs for adaption, on the other side.

Energy economic and regulatory requirements finally incorporate the overarching framework guidelines that need to be considered when aiming for large scale integration in the energy system. Although, regulations are not static and evolve according to the industry's and system's needs, focus was put on an evolutionary integration into the existing environment. As regulatory legacy systems do also have a technical impact (e.g., § 14a EnWG for controllable loads in LV grids), they still need to be considered. Designing new systems, like an SMP, integrated into the grown energy systems—and not in a mere greenfield approach—can reduce friction and increase acceptance. Last but not least, there are also dependencies to other markets and existing processes that could, e.g., reduce market liquidity.

Finally, the identified non-functional requirements cover the most relevant quality features that need to be fulfilled to allow a successful SMP design. In consequence, they form the basis for the subsequent functional design of the SMP architecture, market process, and associated functions, as addressed in the following *RQ2*.

RQ2: Which core functions, processes, and interfaces are needed within an efficient SMP design, and how can they be technically implemented according to their functional requirements? The SMP provides an interface between network operators and flexible assets in the grid area. The overall objective is to ensure a cost-optimized, safe, and reliable grid operation. Consequently, the SMP allows network operators to react flexibly to network bottlenecks in their operational planning, tap the available flexibility potential, and reduce their need for emergency measures such as feed-in management. Thus, a market mechanism for congestion management fills the gap in market-based measures for the DSO. The functions and processes have therefore been designed in Chapter 5 with the relevant requirements defined.

The fundamental description of the *SMP layout and process* are defined in Sec. 5.1, by including all involved stakeholders and their interactions with the necessary functions. These aspects define the overall "system architecture" as the next step in the V-model. Three core functions have been identified and are further investigated in the subsequent sections. Within these sections, in a first step, functional requirements (as the detailed aspect of the "requirement elicitation") are specified for each platform function to objectively discuss available design alternatives and, finally, give an implementation proposal. Based on these proposals, quantitative analyses are conducted within simulations using a consistent modelling environment, as defined in Sec. 5.2. These numerical analyses allow to derive additional findings and identify the proposed approaches' strengths and weaknesses under real-world conditions. The named aspects include the respective V-model steps of "implementation of system elements", "system integration & verification".

Aggregation and pooling, described in Sec. 5.3, provides an option to integrate small-scale flexible units into the SMP. Based on the derivation of statistical simultaneity factors (Sec. 5.3.2), the impact of different pool formation approaches are discussed in Sec. 5.3.3. Finally, the method is implemented and applied to the simulation results (Sec. 5.3.4) and reviewed critically (Sec. 5.3.5). The method proves its applicability, especially in the prevailing legacy systems of ESHs and HPs. The underlying effectiveness evaluation has the most significant impact on the chosen pooling scheme. As historical measuring data is lacking, the implementation relies on synthetic data. Applying actual measurements could therefore increase reliability.

Market monitoring is the second function, presented and applied in Sec. 5.4. Its purpose is to detect and, eventually, avoid structural market power tendencies. By applying an adapted version of the RSI to the specifications of an SMP in Sec. 5.4.3, several simulated events are analyzed within Sec. 5.4.4. It finally proves its function in static evaluations considering installed capacities and dynamic analyses within realistic market constellations. The main findings are summarized in Sec. 5.4.5 and highlight its strength by considering the supply and demand side. Further, the approach is understandable by providing easily interpretable output values with clearly defined thresholds. Limitations contain the restriction to potential (in contrast to exercised) market power and the negligence of deceitful conduct by gaming or collusive behavior.

Matching as the central allocation function, represents the core of the SMP. Within Sec. 5.5, the necessity and derivation of an optimization-based trading logic is presented based on auction design basics. The chosen constrained optimization setup is then formulated in Sec. 5.5.3. After defining the optimization problem, the case study evaluations in Sec. 5.5.4 illustrates its performance characteristics. A comparison to alternative approaches is presented (Sec. 5.5.5). These facets then provide input for the conclusion and critical review in Sec. 5.5.6. Finally, the proposed allocation method represents an efficient solution for matching grid-supportive flexibility with demands under consideration of all necessary requirements and constraints. Nonetheless, future development potential could be achieved by calibration of considered factors based on large-scale field tests involving realistic demand composition and bidding behavior.

RQ3: Which design options and benefits can decentralization offer, and what value propositions can blockchain technology bring to the platform? Given the iteration loop proposed in the V-model, alternative implementations addressing decentralization options are introduced and analyzed in Chapter 6. Decentralization is specified in more detail involving operational, structural, and technical dimensions. The analyzed potential of BC technology for alternative implementations of specific SMP functions, therefore, addresses the technical dimensions. The following three different application scenarios of suitable decentralization options are then analyzed.

Distributed data management and storage involves two different aspects addressed by identity management and distributed data provision in Sec. 6.1. The former allows the verifiable provision of master data based on end-to-end communication and can be realized by an SSI approach (Sec. 6.1.1). The latter includes data storage in a decentralized database (e.g., IPFS, see Sec. 6.1.2). As both solutions mainly address processes outside the actual SMP, they are not in focus within this thesis and only generally introduced in their function and application scenarios.

Proof of data integrity allows the documentation of relevant data processes in general, and the proof of correct data input in specific (Sec. 6.2). By addressing the so-called "oracle problem", processes of different on-chain data storage options are compared to each other (Sec. 6.2.1 and 6.2.2). Applying these options to the given application scenario of verifiable offer bids to an SMP is further specified by an aggregated version of hash storage by creating a Merkle tree. Finally, a proof-of-concept for the verifiable offer placement gives an example on how to increase trust and transparency whilst ensuring scalability and privacy (Sec. 6.2.3). However, for practical use in future (energy) systems, the approach still needs to be approved by regulatory authorities. As the approach can only ensure the integrity of provided data, a proof of correct data processing demands additional measures.

Proof of data properties, or in more specific, the application of *verifiable computation techniques*, closes the aforementioned gap in Sec. 6.3. In a trilemma of transparency, scalability, and privacy, so-called "layer 2" concepts promise a solution by verifying off-chain computations through a BC. In practice, this refers to three different approaches: trusted oracles, zero-knowledge proofs, and multi-party computation. In a comparative assessment, the selected VC schemes are analyzed regarding security, performance, and practicality aspects (Sec. 6.3.1). Under consideration of system architecture aspects, the approaches are then applied to the proposed optimization-based matching within an SMP (Sec. 6.3.2). Finally, two options come to the fore: hardware-secured trusted oracles (in a TEE, using Intel SGX technology) and zkSNARK (as the most prospective representative of a ZKP). A prototypical implementation of the latter still reveals significant challenges of its application in the current stage of development and the given demands of the SMP matching process. In conclusion, VC allows the complex processing of sensitive data in a trusted, BC-based environment. Specific solutions are already in practice in other industries. To finally reach large-scale adoption in an SMP, their applicability still needs to be proven in further research.

RQ4: Which of the identified design alternatives offer the greatest added value with regard to the specified requirements? In a first approach, design alternatives refer to different variants of the SMP functions plus the respective options for decentralized technical implementation. Chapter 7 evaluates the identified design proposals based on the initially defined (non-functional) requirements (Sec. 7.1) and regarding their potential grade of decentralization (Sec. 7.2).

Starting with the design of the envisioned SMP functions, the final proposed versions result from the individual functional requirements. For the individual SMP functions (Sec. 5.3, 5.4, and 5.5), these refer to the following design choices.

- *Aggregation:* topological pooling (under consideration of homogeneous effectiveness factors) and prognosis of available flexibility, based on statistical simultaneity factors (depending on the chosen LoS)
- *Market Monitoring:* application of an adapted version of the RSI, taking into account the effectiveness and the respective locations of considered demand and supply
- *Matching:* allocation based on a constrained optimization setup, applied over the entire contraction period (day-ahead), under consideration of technical boundary conditions, call restrictions, and localities via effectiveness values

All suggested options prove their applicability in a consistent simulation environment. The options for a decentralized technical implementation using BC technology (Sec. 6.1, 6.2, and 6.3) are further introduced and evaluated as follows.

- *Distributed data management and storage:* introduction of the basic architecture of an SSI framework and distributed data provision through a decentralized database
- *Proof of data integrity:* verifiable offer placement based on a Merkle-proof, providing an option for validating correct data input through the participant by comparing the hash stored on the BC with the locally reconstructed root-hash
- *Proof of Data Properties through Verifiable Computation Techniques:* prospective application of SGX-based trusted oracles using a TEE, and ZKP using zkSNARKs[1]

In addition, a distinct juxtaposition of the centralized and the distributed setup provides further insights. Although, most non-functional requirements can be equally met in the design alternatives, distributed system setups can provide added value, especially for end users and the regulatory bodies. Notably, requirements associated with security and data protection can particularly benefit from a decentralized setup. The given redundancy promises higher robustness and reliability. The protection of sensitive data, i.e., personal, generation, or consumption data, can be better ensured through increased data sovereignty. Only hash representatives or proofs need to be stored on-chain to verify correct operation. In contrast, (non-functional) requirements related to

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[1] zkSNARKs only partly fulfill the given requirements, although expected technical progress can pave the ground for its technical maturity.

scalability and performance reveal specific shortcomings of prospective technologies, e.g., within VC techniques. Therefore, certain challenges still have to be mastered to reach industry standards for large-scale application, especially in a granular energy system involving millions of DER and FOs. Technical decentralization also increases the system's complexity. The introduced and applied system cartography (Sec. 7.2) and evaluation framework visualizes the respective architectural differences in the system landscape.

To summarize, a centralized setup can already fulfill all relevant requirements. Nevertheless, the value proposition of a distributed setup using BC technology is present and realizable. The final decision regarding the application of a decentralized setup is still dependent on the valuation by the respective parties involved. As this raises questions in the socio-economic or legal-regulatory sphere, it was intentionally excluded in this thesis. However, the topics of decentralization, data sovereignty, transparency, and system resilience already become increasingly relevant and present in public discourse.

Conclusion, Outlook and Need for Further Research This thesis closes the gap between addressing the initial needs for an efficient platform- and market-based CM, the functional design of a resulting SMP, and the introduction of decentralization options using BC technology. SMPs serve as an example of the increasing relevance and complexity of energy platform applications. A successful and sustainable (decentralized) smart market design relies on the consideration of the big picture within a historically grown energy system and the detailed assessment of the procedural and functional implementation options. Within an increasingly complex and granular energy system, involving a multitude of different actors, the establishments of common standards are crucial for their integration. The proposed SMP includes the integration of various types of assets and market actors to provide a level-playing field. Finally, by exploiting locally assigned flexibility, the grid can be utilized more efficiently. On the other hand, this also leads to more data sovereignty and individual responsibility, which also come with duties.

Regarding further development of the proposed SMP towards large-scale application, an assessment of market behavior in a running market, including individual bidding and revenue strategies, is recommended. This also allows developing and analyzing further techniques for mitigation of (applied) market manipulation. The coordination between grid levels and system operators is still an open task. This also applies to a deeper analysis regarding the impact and effectiveness of SMPs from a system's perspective and their specific contribution to the systemic integration of REs (see [6, pp. 254-260]). Regulatory instructions and standards for grid-supportive flexibility provision and market operation (including a defined role for the market operator) are further outstanding issues.

To fulfill all relevant requirements, it is necessary to strike a fair balance between functionality, scalability, and system integration on the one side and transparency, privacy, and data protection on the other side. The consideration of BC technology, demonstrated by the application scenarios within this thesis, can provide significant added value as an underlying ecosystem infrastructure. As it is still a young technology, its applicability needs to be proven in further research initiatives and under real-world conditions. A crucial challenge, therefore, is the acceptance of BC as a trusted entity by relevant authorities. So-called regulatory sandboxes can provide a fitting playground to foster open discussion on the regulatory recognition of BC-based proof mechanisms in the energy sector. Finally, applied research prepares the blueprints for a decarbonized, decentralized, digitalized, and democratized energy future.

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A Annex

A.1 Blockchain Consensus Mechanisms

Proof-of-Work *PoW* is based on a cryptographic puzzle that must be solved by all participating nodes (so-called “miners”). The determination of the right to propose the next block is conducted by a competition of computing power (“hashing power”) between the miners. PoW is still the most applied consensus mechanism in public BCs. The amount of electrical energy needed to run the network is often topic of critical discussions. [92]

Proof-of-Stake *PoS* algorithms have been developed to overcome the disadvantages of PoW algorithms with respect to the high energy consumption in PoW-“mining”. PoS is therefore based on a quasi-random selection of the validator based on its financial deposit. Consensus is found through stakeholders that invest money instead of hardware and (energy) resources. Vitalik Buterin, the founder of Ethereum, summarizes the difference between PoW and PoS as “thus not ’security comes from burning energy’, but rather ’security comes from putting up economic value-at-loss” [256].

Proof-of-Authority *PoA* BCs are “permissioned” as access to the consensus mechanism for participating validators must be authorized and are specially used for private or consortium BCs. PoA algorithms belong to the family of so-called “Byzantine fault-tolerant” consensus mechanisms, in which consensus only has to be found among a limited number of validators. Instead of a large number of validators, a selection of “authorities” get the right to validate and write blocks and, thus, secure the BC. These are often identical with real, legal authorities. [257, 258]

A.2 Sequence Diagram of the Smart Market Platform Process

The following UML (Unified Modeling Language) sequence diagram in Fig. A.1 describes relevant actions and interactions of the relevant parties within the SMP process. These include the *flexibility provider* as the operator and marketer of the FO, the *ANO* as the network operator in whose grid the FO is connected, the DSO as *flexibility demander*, and finally the *SMP* itself. As this work focuses on the supply side of flexibility and its platform integration, the demand side processes are only described as far as necessary. A detailed flexibility demand process description can be found in [17] and [7].

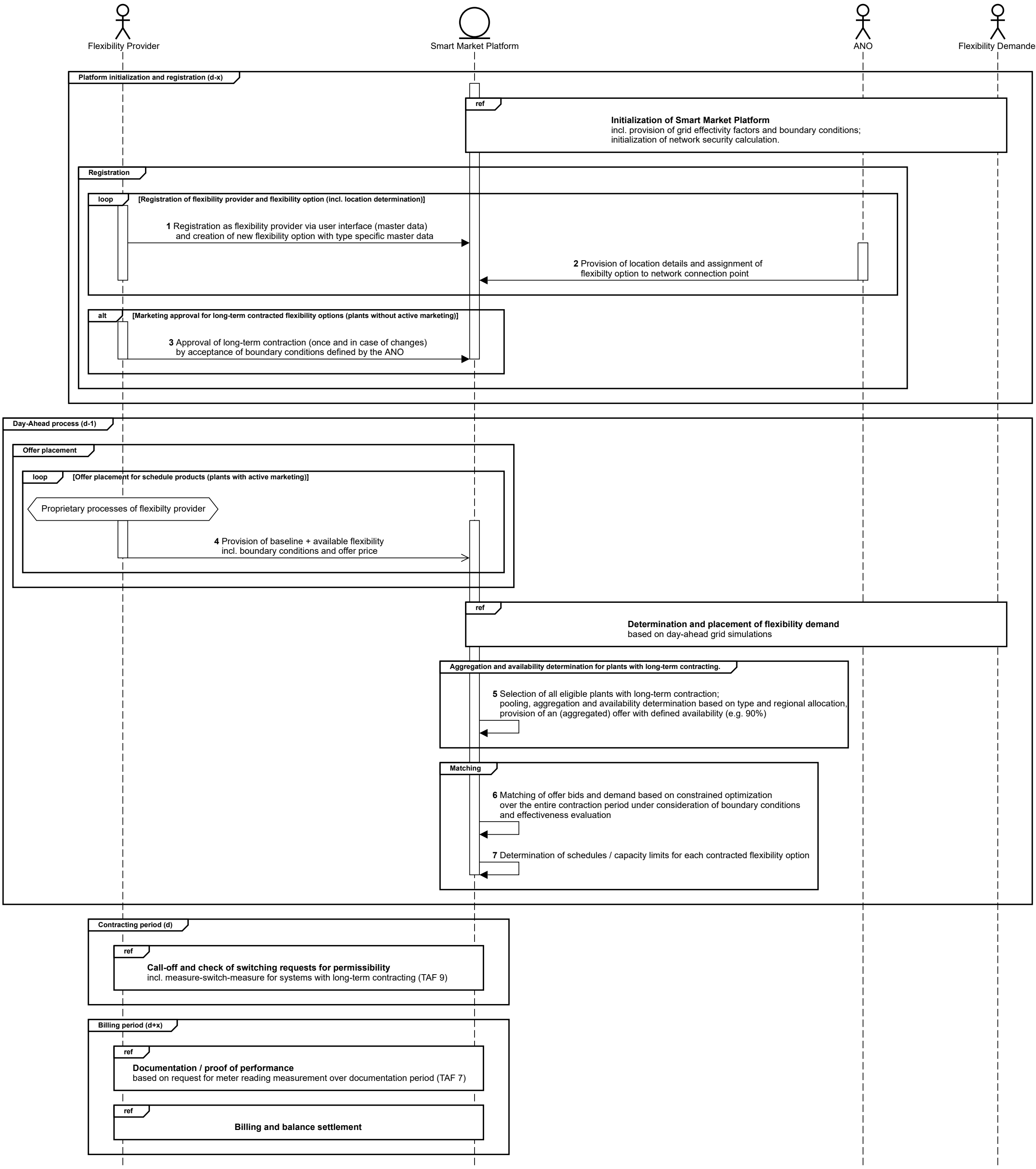


Figure A.1: Sequence diagram visualizing the smart market process and relevant interactions; the entity “Flexibility Provider” includes associated components, functions, and actors (i.e., SMGW, CLS-Management, Smart Meter Gateway Administrator, active External Market Participant), adapted according to [17, p. 21]

A.3 Additional Simulation Input Data

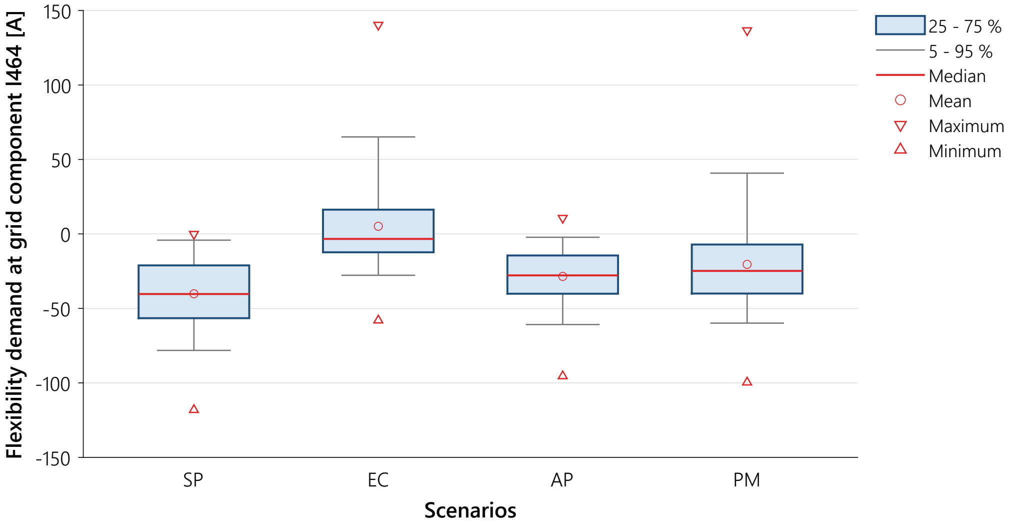
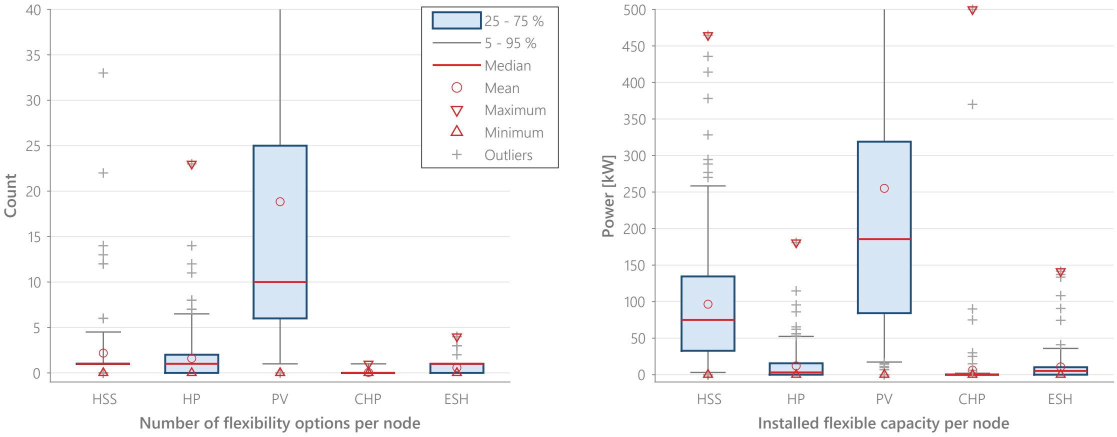


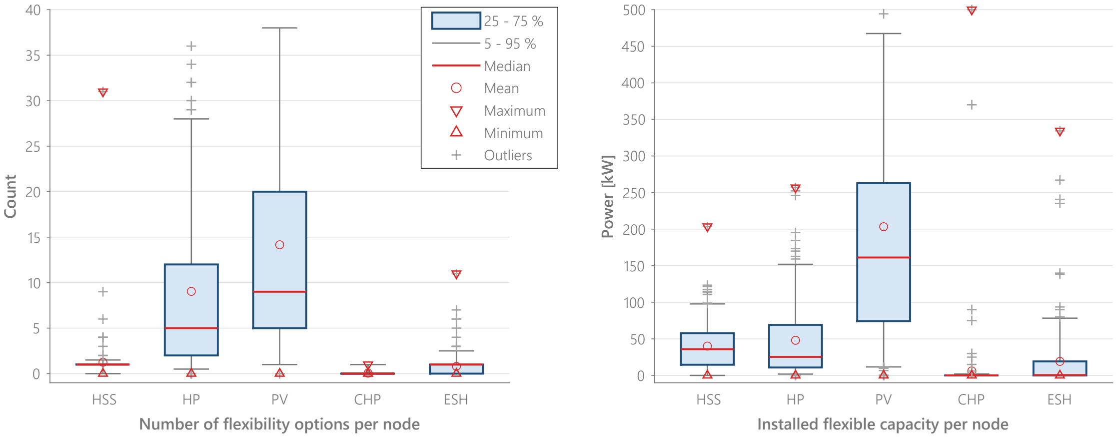
Figure A.2: Flexibility demand distribution at grid component *l464* exhibiting the highest number of congestions within the analyzed medium-voltage grid in the four scenarios

FO	**Parameter**		**Reference**
HSS	E/P ratio	2,27 h	[6, p. 157], [74]
	Offered power	± 50% P_{inst} (band)	
	Maximum call duration	2 h	
	Minimum time interval between two calls	2 h	
CHP	Offered power	± 20% P_{inst} (band)	[201, pp. 17-18]
PV	Orientation	South	
	Tilt	30°	
HP, ESH	Partial call	No	[8] and Sec. 5.3
	Maximum number of calls per day	2	§ 14a EnWG
	Maximum call duration	2 h	
	Minimum time interval between two calls	2 h	
	Share of engagable HP (SG-ready)	50%	
Offer prices (normalized)	PV, CHP	10	[259]
	HSS	2	
	ESH, HP	1	

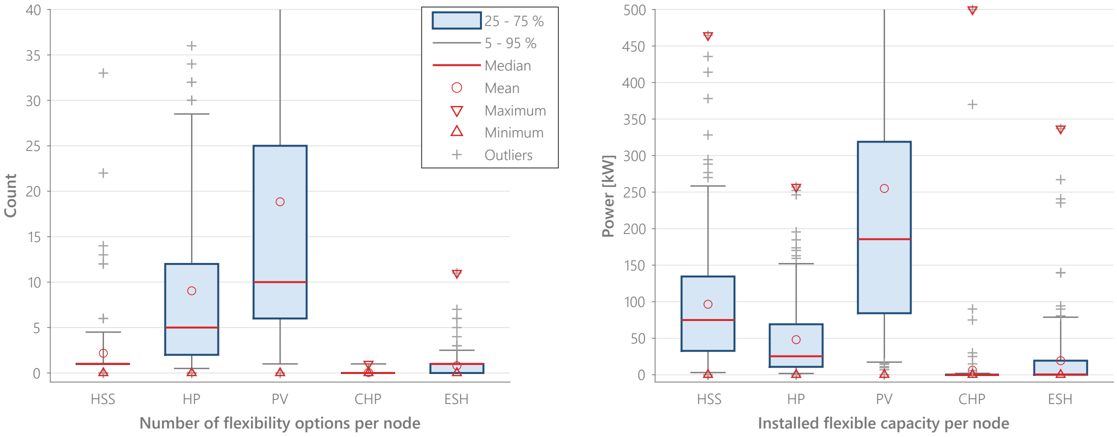
Table A.1: Selected parameters to describe the flexibility offers and potential call restrictions



(a) “Solar Producer” (SP)



(b) “Electrified Consumer” (EC)



(c) “Autonomous Prosumer” (AP) / “Market-oriented Prosumer” (PM)

Figure A.3: Number and installed capacity of flexibility options per low-voltage grid in the four scenarios

A.4 Additional Constraints and Parameters to the Optimization Problem

The matching process takes into account all constraints and boundary conditions resulting from the specifications of supply and demand as published in [77, pp. 12-14]. Additional constraints are shown in the following equations containing the variables defined in Tab. A.2.

- Consideration of the effectiveness evaluation by conversion of offered flexibility in kW at the point of supply into a change of current in A (or voltage in V) at the congestion (Section 5.5.3).
- Boundary conditions for the flexibility offers, i.e.,
  - Maximum number of calls per day (Equation A.1):
    The sum over all state switches plus the state of the FO in the first as well as the last time step must not exceed twice the number of allowed calls.

$$x_{i1} + x_{im} + \sum_{j=2}^{m} a_{ij} \leq 2 \cdot N_i \tag{A.1}$$

  - Maximum duration of a call (Equations A.2 and A.3):
    After activation, a FO can remain switched on for a maximum time period. The first condition covers the case that the FO is activated in the first time step, while the second condition deals with later activations.

$$\begin{gathered} x_{i1} + \sum_{k=1}^{\min(T_i^{\max}, m-1)} x_{ik+1} \leq \ T_i^{\max} \\ (\forall\ i \in I) \end{gathered} \tag{A.2}$$

$$\begin{gathered} (x_{ij} - x_{ij-1}) + \sum_{k=1}^{T_i^{\max}} x_{ij+k} \leq T_i^{\max} \\ (\forall\ i \in I,\ j\ \in \{2, .., m - T_i^{\max}\}) \end{gathered} \tag{A.3}$$

  - Minimum duration of a call (Equations A.4 and A.5):
    Depending on the moment of activation, the two conditions ensure that FOs remain activated for a minimum defined time period.

$$T_i^{\min} \cdot x_{i1} \leq \sum_{k=0}^{\min(T_i^{\min}-1, m-1)} x_{ik+1} (\forall\ i \in I) \tag{A.4}$$

$$\begin{gathered} (x_{ij} - x_{ij-1}) \leq x_{ij+k} \\ (\forall\ i \in I,\ j \in \{2, .., m\},\ k \in \{0, .., \min(T_i^{\min} - 1, m - j)\ \}) \end{gathered} \tag{A.5}$$

- Minimum time interval between two calls (Equations A.6 and A.7):
  After a call of a FO has occurred, the FO in question must remain deactivated for a defined blocking time. The second condition extends this constraint to blocking times remaining from the previous day.

$$(x_{ij} - x_{ij-1}) + x_{ij-k} \leq 1$$
$$(\forall k \ \in \{1,\ .., \tau_i\},\ i \in I,\ j \ \in \{k+1, .., m\}) \tag{A.6}$$

$$P_{ij} = 0$$
$$(\forall\ i \in I,\ j \ \in \{1, .., \tau_i^{\mathrm{rem}}\}) \tag{A.7}$$

- Maximum call duration per day (Equation A.8):
  The total call duration per day must not exceed a defined limit. The factor $\frac{1}{4}$ *accounts for 15-min intervals.*

$$\frac{1}{4}\sum_{j=1}^{m} x_{ij} \leq T_i^{\mathrm{sum}}$$
$$(\forall\ i \in I) \tag{A.8}$$

- Possibility of partial performance of the offer including discrete call levels (Equation A.9)
  In the case that FOs do not feature continuous power modulation, discrete switch settings (e.g., 0%, –30%, –60%, and –100%) must be considered.

$$\eta_{ij} P_{ij} = \eta_{ij}(P_{ij}^{\mathrm{max}+} + P_{ij}^{\mathrm{max}-})\sum_{s \in S} \xi_{ijs} S_{ijs}$$
$$(\forall\ i \in I, j \in J) \tag{A.9}$$

- Minimum and maximum retrievable power (Equations A.10–A.13):
  In the case of continuous power modulation, minimum and maximum power restrictions must not be violated. The four conditions cover the lower and upper bounds for power increase and power decrease.

$$(1 - \eta_{ij}) \cdot x_{ij}^{+} \cdot P_{ij}^{\mathrm{min}+} \leq (1 - \eta_{ij}) \cdot P_{ij}^{+}$$
$$(\forall\ i \in I,\ j \ \in \ J) \tag{A.10}$$

$$(1 - \eta_{ij}) \cdot x_{ij}^{-} \cdot P_{ij}^{\mathrm{min}-} \geq (1 - \eta_{ij}) \cdot (-P_{ij}^{-})$$
$$(\forall\ i \in I,\ j \ \in \ J) \tag{A.11}$$

$$(1 - \eta_{ij}) \cdot P_{ij}^{+} \leq (1 - \eta_{ij}) \cdot P_{ij}^{\mathrm{max}+} \cdot x_{ij}^{+}$$
$$(\forall\ i \in I, j \in J) \tag{A.12}$$

$$(1 - \eta_{ij}) \cdot (-P_{ij}^{-}) \geq (1 - \eta_{ij}) \cdot P_{ij}^{\mathrm{max}-} \cdot x_{ij}^{-}$$
$$(\forall\ i \in I, j \in J) \tag{A.13}$$

Parameter	**Description**
I	Set of FOs, $\|I\| = n$
J	Set of time periods , $\|J\| = m$ (default: 96)
L	Set of demands, $\|L\| = o$
$a_{ij} \in \{0, 1\}$	Indicator of a state switch of FO i at time period j
S	Set of percentages, |S| = q (default: 4)
$D_{lj} \geq 0$	Flexibility demand l at time period j
$N_i \in \mathbb{N}$	Maximum number of calls of FO i per day (default: 96)
$T_{\mathrm{i}}^{\mathrm{sum}} \geq 0$	Total call duration per day (h) (default: 24)
$T_{\mathrm{i}}^{\mathrm{max}} \geq 0$	Maximum call duration per call (h) (default : 24)
$T_{\mathrm{i}}^{\mathrm{min}} \geq 0$	Minimum call duration per call (h) (default: 0.25)
$\tau_i \geq 0$	Minimum time between two calls (h) (default: 0)
$\tau_i^{\mathrm{rem}} \geq 0$	Remaining blocking time of the previous day (h) (default: 0)
$x_{i,\ j} \ \in \{0, 1\}$	Indicator of the state of the FO i at time period j
$\xi_{ijs} \in \{0, 1\}$	Auxiliary variable for the restriction to a percentage
$P_{\mathrm{ij}}^{\mathrm{max}} \geq 0$	Maximum available power
$P_{\mathrm{ij}}^{\mathrm{min}} \geq 0$	Minimum available power
$e_{il} \geq 0$	Effectivity factor
$K \geq 0$	Auxiliary constant (large enough)
$S_{ij} \in \mathbb{R}^q$	Possible shares of power (default: $[0,\ 0.3,\ 0.6, 1]$)
$\eta_{ijs} = \begin{cases} 1, & \text{if } \sum_{s \in S} S_{ijs} \geq 0 \\ 0, & \text{else} \end{cases}$	Indicator for P (continuous or restricted to power steps)
$\delta_{lj} = \begin{cases} 1, & \text{if } D_{lj} \neq 0 \\ 0, & \text{else} \end{cases}$	Indicator for zero demand for a flexibility demand l at time period j

Table A.2: Additional parameters of the optimization problem [11, p. 14]