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RESEARCH ARTICLE

Integrating Peer-to-Peer Energy Trading and Flexibility Market With Self-Sovereign Identity for Decentralized Energy Dispatch and Congestion Management

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ABSTRACT Addressing the trends of digitalization, decentralization, democratization, and decarbonization, local peer-to-peer (P2P) markets have the potential to significantly accelerate decarbonization at the communal level. However, due to an increase in the number of energy consumers, such as electric vehicles or heat pumps, grid congestion can occur since actual low-voltage grids are not designed to transmit large loads. This paper introduces a novel concept for a platform to combine the advantages of P2P trading with the need for secure, automated low-voltage grid control, ensuring effective congestion management. Therefore, a dual local energy market has been developed, comprising a P2P energy market and a flexibility market with the latter ensures preventively managing congestion. Furthermore, mechanisms exist to provide curative, real-time congestion management. Additionally, the platform empowers prosumers, i.e. end users that produce and consume electrical energy, with intelligent market strategies to maximize their financial outcomes by participating in both markets. To provide a secure trading mechanism, the novel concept of Self-Sovereign-Identity is integrated into the platform. The platform is based on a multi-agent-system developed using the Java Development Environment (JADE) in conjunction with the Energy Option Model (EOM) for the effective modelling of energy systems. Tested in a smart grid laboratory at the University of Wuppertal, the platform provides financial gains for prosumers and effectively manages current- and voltage-related grid congestions.

INDEX TERMS Peer-to-peer markets, congestion management, active network management, decentralization, multi-agent-system.

I. INTRODUCTION

The transformation process towards a carbon-neutral energy supply implies novel structural requirements for the

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existing energy system. Energy production is shifting from central, fossil-based energy resources to decentralized renewable energy resources (RES) [1]. This requires new control concepts, shifting from top-down frequency-controlled to bottom-up voltage-controlled. This also includes standardization, e.g. for the central European grid and regulation in terms of stability, responsibilities, and cybersecurity.

Given the volatility of RES, which is influenced by factors such as solar irradiation and wind speed, there is a need for energy demand to align with energy production, a concept known as demand response [2].

Additionally, the complexity of the electric load in terms of the number of consumers, producers, prosumers and missing standard load profiles increases significantly. While the grid infrastructure remains largely unchanged, it now has to handle a greater energy flow, leading to potential grid congestions [3]. These congestions represent temporary overloads, which can be related to either voltage or current.

When grid congestions arise, the distribution system operator (DSO) must intervene. Congestion management can be classified into economical and technical categories. Given that only technical measures are configured for real-time interventions, they are predominantly deployed for curative congestion management [4].

Traditional centralized control approaches for energy dispatch and grid congestion management may not be scalable and flexible enough to handle the requirements of upcoming power grids [5]. Furthermore, with the decentralization of energy production and the increase in local energy loads, there is an opportunity to produce and consume energy locally, thereby reducing demands on transmissions and respective losses. Consequently, the control mechanisms can also be decentralized [6].

One approach to decentralized grid control is to introduce new incentive structures, such as Renewable Energy Communities (RECs). As per the EU Directive 2018/2001, RECs are characterized as legal entities that enable prosumers, i.e. end users that produce and consume electrical energy, to share renewable energy with other households or organizations, aiming to provide environmental, economic, or social advantages [7].

For instance, in Italy, RECs have been in place since 2020, with outcomes indicating that participants can, on average, cut their energy bills to a quarter of the standard energy prices, given that mathematical optimization is utilized [8].

A notable solution within the REC framework is P2P trading. P2P markets emphasize the direct electricity exchange between equal peers. They aim to simplify energy trading for small-scale prosumers by removing intermediaries. As a result, prosumers can sell the electricity they generate on P2P markets at prices more favourable than those set by regulated feed-in tariffs [9].

Local energy resources also hold the potential to utilize their inherent flexibility for grid stabilization. For example, with the right incentive, prosumers might be willing to postpone the charging of their electric vehicle (EV), the utilization of their heat pump, or might even provide access to their household battery.

Along with flexibility mechanisms, these novel market strategies can leverage this flexibility potential to stabilize the power grid and enhance the integration of RES, as shown in the research project flexQgrid [10]. A flexibility market serves as a dedicated marketplace for trading flexibility within a distribution grid or a confined geographical area. Its primary objective is to facilitate the optimal dispatch of RES with the goal of circumventing the need for costly reinforcements or infrastructure investments. Central to the operation of flexibility markets is the role of the DSO, who typically participates as a principal buyer [11].

However, both grid control and financial transactions are highly sensitive, necessitating robust IT security measures [6].

In several research projects [12], [13], [14], market-based grid control serves as a supplementary mechanism for efficient energy dispatch, preventive congestion management, and promoting RES integration. However, if congestions cannot be addressed through market-based solutions, an automated system is required for curative congestion management. There, the DSO carries out grid interventions aimed at mitigating congestion by curbing load or managing generation from resources primarily responsible for the grid congestion. Consequently, this necessitates the implementation of real-time monitoring and precise state estimation techniques [15].

The authors of [3] show that decentral and automated congestion management is still an open issue regarding the control of low-voltage grids.

In order to apply the dual market mechanism, the prosumers need to be empowered for participation. Therefore, prosumers need to optimize the energy flow within their own household and identify energy surplus or shortage. Based on that, various strategies exist to place energy bids or asks at the local market, e.g. maximization of self-consumption, minimizing energy costs, maximizing profit as reviewed in [16].

To create and deploy a decentralized platform, software agents are frequently utilized as a foundational framework, as evidenced by a comprehensive review on the control and optimization of microgrids [17]. Software agents are computer systems adept at executing tasks both autonomously and proactively, while also interacting with external systems [18]. These agents can also interact, collaborating to achieve the overarching system goal. However, they can also pursue individual objectives. By leveraging agents, the platform distributes both responsibilities and computational power across multiple instances. This agent-based approach offers several advantages in comparison with traditional, centralized control systems, as shown in [6]. By distributing responsibilities and tasks across different agents, the system becomes more resilient and avoids single-points-of-failure. In addition, the decentralized nature of agent-based systems allows for easier scaling. As computational needs and the number of resources grow, more agents can be added without reengineering the entire system. To effectively manage energy systems, including RES, energy storage as well as energy systems consuming energy, it is essential to create accurate models that capture their inherent flexibility in energy production and consumption. In a comprehensive review [19], various existing models of energy systems have been examined, highlighting their capacity for flexibility. These models enable these systems to be seamlessly integrated into planning and optimization applications.

To address the upcoming challenges of low-voltage grid control, this paper provides the following contributions:

- The concept offers a local P2P energy market with self-sovereign identity management, featuring intelligent prosumer market strategies that ensure secure and localized energy trading.
- It presents a market-based approach for harnessing flexibilities to preventively manage both voltage- and current-related grid congestions.
- The paper also proposes an automated mechanism for executing curative congestion management in low-voltage grids.
- The platform is tested on a smart grid laboratory providing real photovoltaic (PV) plants as well as electric vehicle supply equipment (EVSE) and evaluated by different key performance indicators (KPI)s.

The remaining sections of the work are structured as follows.

Some research projects already surveyed the technical feasibility of P2P energy markets, as shown in section II. The proposed platform concept as well as the prosumer´s strategies are presented in section III. Section IV presents the topology of the field test, test scenarios as well as the results and evaluation of the platform. The paper closes with a discussion (section V) and a conclusion (section VI).

A. REQUIREMENTS

The requirements that are explained in this section have been derived from a broader set of requirements that have been established for the P2P markets in general [14], utilized as a basis for the platform developed in this work and the PEAK[1] project.

1) The platform should provide the possibility to trade green and local electricity products directly and automatically with other prosumers.
2) The platform should ensure stable, reliable, and automated curative as well as preventive active grid management, consistent with all traffic phases of the BDEW smart grid traffic light concept.
3) The platform should enable market-based utilization of flexibilities.
4) The platform should provide and enable intelligent strategies for prosumers to be able to trade energy P2P as well as offer market-based flexibility.
5) The platform should provide both estimates and forecasts of grid states.
6) The platform should enable secure trading and comply with privacy regulations.

The requirements serve two main purposes: First, they provide the foundational framework for developing the platform. Second, they highlight the unique aspects of the project. This uniqueness is further emphasized by the analysis of other research projects and scientific papers in section II.

B. ENGINEERING METHODOLOGY

The concept presented is developed according to the “Development Approach for Decentralised Control Systems” (2DECS) [20]. 2DECS offers an agile development procedure specifically crafted for the energy sector, covering the complete life cycle of decentralized control systems. The methodology is structured into eleven phases, starting with the acquisition of preliminary requirements and culminating in life-cycle management. Its core focus is on the development of distributed control systems, making it suitable for the conceptual formation of agent-based power distribution and grid congestion handling. 2DECS provides suitable methods to develop the technical artifacts. It also guides the user during the development of the multi-agent system (MAS) architecture. The most important technical artifacts which should be developed within the eleven phases are described in the following [20].

- Goal-Model: The Goal-Model is structured hierarchically, starting with a primary objective (e.g., consistent energy provisioning) and branching into auxiliary goals contingent on the complexity of the task. The extent and number of goals within each agent are influenced by the system´s overall goal.
- Functions-Model: Emanating from the Goal-Model, it demarcates the critical functionalities required for realizing these goals. Each functionality aids at least one goal, though a solitary goal may necessitate diverse functionalities. Typically, this model is manifested as either a list or matrix, illustrating functionality-goal affiliations.
- Role-Model: The Role-Model aggregates functionalities into distinct roles, with each role potentially encapsulating multiple functionalities. Although roles may overlap in functionalities, they maintain their uniqueness. Roles merge similar functionalities or those imperative for attaining specific objectives. Analogous to the Functions-Model, it might be represented as a list or matrix.
- Interaction-Model: Rendered as a UML communication diagram, this model sheds light on communicative dynamics both within the MAS and with external systems. Each role from the Role-Model is mentioned, underscoring communication datasets and conventions.

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[1] For detailed information on the ’Integrated Platform for Peer-to-Peer Energy Trading and Active Network Management (PEAK)’ research project, please visit: https://www.peak-plattform.de/

- Agent-Models: Building on the Interaction- and Role-Model, it allocates agents to respective roles, while the Agent-Structure-Model focuses on the properties and interrelations of agents, typically via a UML class diagram.
- Resource-Model: This model encompasses the energy systems an agent has control over, ensuring an understanding of their physical behaviour. This knowledge is then integrated into the agent's strategic decision-making.

The specific artefacts developed for the presented concept will be explained in section III.

II. STATE-OF-THE-ART

The state-of-the-art analysis is twofold, it is classified into other research projects addressing similar requirements and further scientific papers.

A. RESEARCH PROJECTS

There are many ongoing and recently completed research projects dealing with the development of flexibilities in the distribution grid and electricity trading between prosumers. In summary, the local P2P energy trading projects all meet R1 and partly R4 and R5. The flexibility trading projects all fulfil the R2 and R3 as well as partly the requirements R4 and R5. The projects that address both aspects in the last category - Local P2P energy and flexibility trading - meet most of the requirements, but never all six requirements.

TABLE 1 gives an overview of the projects that have considerable overlap in content with this paper. For clarity, the research projects were divided into three categories. The first category encompasses concepts aimed at fostering local P2P energy markets. The second category is dedicated to the development of flexibility markets, while the third and most specialized category features studies that explore the intersection of both local P2P energy trading and flexibility trading.

The P2P trading platforms in the first category such as LAMP [21], Lition [22], Tal.Markt [23] etc. focus on pure local energy trading. Thus, all these research projects meet R1. In the LAMP project, a forecast of the grid state is also performed and thus this project additionally fulfils R5. R6 of secure trading is ensured in many of these research projects using a blockchain. The DeTrade project [24], the ETIBLOGG project [24], and the Quartierstrom 1.0 project [25] additionally fulfil R4, as prosumers are given strategic opportunities to participate in the market here.

The research projects to develop local flexibilities to support grid stabilization in the second category, such as ALF [26], ENKO [27], the enera Flexmarkt [28], DEER [29], the flexchain [30], or the flexQgrid project [10], all remain predominantly from the perspective of the DSO and prosumer flexibility is only requested here. Prosumers there are not equipped with intelligent market strategies, which would allow them the freedom to decide how much flexibility they want to offer and at what price.

Furthermore, the use of blockchain technology for secure trading is exclusive to the flexchain, DEER, and flexQgrid projects. The last category only comprises the TUMCreate Market [31] and pebbles [32]. Here, local P2P energy and flexibility trading is addressed, as well as a grid state prediction. Secure trading is ensured via a blockchain in pebbles. However, TUMCreateMarket and pebbles neglect curative and preventive grid management (R2).

In summary, the local P2P energy trading projects all meet R1 and partly R4 and R5. The flexibility trading projects all fulfil the R2 and R3 as well as partly the requirements R4 and R5. The projects that address both aspects in the last category – Local P2P energy and flexibility trading – meet most of the requirements, but never all six requirements.

TABLE 1. Overview of existing research projects.

	R1	R2	R3	R4	R5	R6
Local P2P energy trading						
Allgäu Microgrid [12]	Yes	No	No	No	No	Yes
BEST [13]	Yes	No	No	No	No	Yes
Tal.Markt [24]	Yes	No	No	No	No	Yes
RegHEE [34]	Yes	No	No	No	No	Yes
Energy Collection [14]	Yes	No	No	No	No	No
Lition [23]	Yes	No	No	No	No	Yes
Urawamisono [35]	Yes	No	No	No	No	Yes
LAMP [22]	Yes	No	No	No	Yes	Yes
ETIBLOGG [36]	Yes	No	No	Yes	No	Yes
Quartierstrom 1.0 [26]	Yes	No	No	Yes	No	Yes
DeTrade [25]	Yes	No	No	Yes	No	Yes
Flexibility trading						
ALF	No	Yes	Yes	No	Yes	No
ENKO [28]	No	Yes	Yes	No	Yes	No
enera Flexmarkt [29]	No	Yes	Yes	No	Yes	No
flexchain [31]	No	Yes	Yes	No	No	Yes
DEER [30]	No	Yes	Yes	No	Yes	Yes
flexQgrid [10]	No	Yes	Yes	No	Yes	Yes
Local P2P energy and flexibility trading						
TUMCreate Market [32]	Yes	No	Yes	No	Yes	No
Pebbles [33]	Yes	No	Yes	Yes	Yes	Yes

B. FURTHER SCIENTIFIC PAPERS

Cornélusse et al. [36] present a REC where entities can trade energy among other entities in their REC. For the matching of entities, a bi-level optimization approach is applied to consider both, the minimization of energy costs of consumers and the maximization of the profit gained by prosumers selling energy. However, no grid congestion management is implemented and thus R2 is not addressed.

Duchesne et al. [37] examined the design of P2P energy markets to ensure economic viability for all parties involved. In particular, they explored the optimal operator fee that prosumers have to pay for P2P energy trading, in relation to the maximum grid prices. The results show that it should not exceed 1/3 of the maximum energy price in the community. However, in both paper, automated curative as well as preventive active grid management is not integrated into the control [36], [37] and thus R2 is not addressed.

The authors of [38] present a hierarchical bi-level energy market where in the primary market the economic allocation of DERs is regarded. The secondary market ensures the adherence of physical constraints in the low-voltage grid. The simulation is conducted on an IEEE-123 bus network. The authors of [39] and [40] use a household's Home Energy Management Systems (HEMS) as hardware to implement an agent responsible for energy negotiation and preventive grid congestion management. However, all these approaches lack security measures as well as curative congestion management and thus do not fulfill R6 and R2.

The authors of [41] develop a decentralized approach to grid congestion management but do not implement decentralized energy distribution. Del Rosario [42] develops a strategy for both decentralized energy distribution and grid congestion management. However, there is no active involvement of prosumers in the distribution grid control due to a lack of financial incentives. Thus, R3 is not addressed. Other studies also address distributed grid control but similarly do not provide financial incentives [43], [44].

In [45], a distinction is made between active grid management and energy negotiation by sending the results of energy negotiations conducted by the agents to a central grid operator agent. This central agent then imposes penalties on energy supplies that could contribute to grid congestion. However, the approach lacks a differentiation between curative, preventive, and market-based congestion management as well as security measures. Thus, R2 and R6 are not addressed.

The authors of [46] present a secure P2P energy market that is able to actively manage grid operations. However, the paper does not offer an intelligent prosumer strategy, nor does it provide for market-based flexibility utilization.

An example of an intelligent prosumer strategy for P2P energy trading can be found in [47]. This strategy employs a two-sided platform pricing model to satisfy the needs of both the aggregator and the prosumers. Given the absence of a flexibility market, R4 is only partially satisfied, while R3 remains unfulfilled.

As previously demonstrated, none of the existing projects or academic papers comprehensively addresses the full set of requirements discussed in this paper. Specifically, an integrated approach that combines secure peer-to-peer energy trading, flexibility trading, and active grid management has yet to be explored in existing works. In this regard, the PEAK platform distinguishes itself, as it considers all these aspects within a unified framework.

III. PLATFORM ARCHITECTURE

This section outlines the concept of the platform. Included in this framework are the various market roles that have been established, the specific functions assigned to each role, and a functional sequence for all technical platform's interactions.

A. ROLE-MODEL

The Harmonized Electricity Market Role Model by European Network of Transmission System Operators for Electricity (ENTSO-E) describes which roles are involved in electricity markets [48]. This role model helps in standardizing roles and functions across different entities and projects, promoting a more efficient and consistent industry structure.

In PEAK, the following roles are regarded: Consumer, Producer, Prosumer, DSO, Balance Responsible Party (BRP), Metering Operator (MO), Data Provider (DP), Platform Operator (PO), and Balance Supplier (BS). The Transmission System Operator is not regarded due to the project´s focus on the distribution grid level.

A consumer in the energy sector is an entity that transforms electrical energy from the grid into other forms of energy. Conversely, a producer takes various other forms of energy and converts them into electrical energy that is provided to the grid [48].

The term *prosumer* is a blend of *producer* and *consumer*, indicating an entity that both generates and consumes electrical energy but not necessarily at the same time. This dual functionality enables prosumers to optimize their consumption by balancing their energy production and usage. Thus, the prosumer holds a unique position within the energy ecosystem, simultaneously contributing to energy production while consuming as per their requirements [49].

The DSO plays a critical role in the energy sector, with responsibilities including the distribution of electricity, operations, maintenance, and grid expansion [48]. The German Energy Agency (DENA) classifies the tasks of the DSO into several key areas: grid operation, voltage control, frequency control, and supply restoration [50]. However, in the context of PEAK, the focus is primarily on an automated grid operation which includes congestion management.

Furthermore, the PO is another role in [48] that is responsible for the functionality of the automated and secure trading.

It is imperative to note that relying solely on P2P trading does not guarantee a consistent and dependable energy supply. Hence, the integration of a Balance Supplier (BS) becomes essential to deliver residual energy amount.

B. IMPLEMENTATION OF ROLES AND FUNCTIONS

According to 2DECS, each agent is assigned a specific set of functions (F) tailored to its role in the system. The functions are based on the system´s requirements as well as the individual responsibilities of the ENTSO-E´s role model. An overview of the functions is given in Table 10. Given the platform's agent-based approach, the terminologies are adapted accordingly: the PO is termed the *platform-agent*, the DSO becomes the *grid-agent*, and the prosumers are referred to as *prosumer-agents*. Each prosumer is represented by its unique agent.

1) GRID-AGENT

According to R5, the grid-agent needs to identify potential grid congestion areas and forecasts their occurrence (F1).

Based on the identification of congestions, the grid-agent conducts real-time calculations to ascertain the power flow throughout different sections of the grid (F2).

According to R3, the platform should provide a market-based use of flexibilities. Thus, using the power-flow-calculations, the grid-agent formulates flexibility requests to account for to the dynamic energy needs of the grid (F3).

To address R2, the grid-agent takes curative actions in real-time (F4).

2) PLATFORM-AGENT

According to R6, the platform should provide security and privacy. Thus, the platform-agent handles the validation and authentication of prosumer-agents, grid-agent, and market-agent, safeguarding the system's integrity and security (F5). In addition, the platform-agent facilitates interaction among entities by providing communication addresses (F6), similar to the white- and yellow-page service by the Foundation for Intelligent Physical Agents (FIPA) [51].

3) MARKET-AGENT

A core principle for agents is to carry a single responsibility, if possible. This not only ensures reliability by averting a single-point-of-failure but also optimizes performance and reduces the complexity of the software. As such, the market component is distinct from the platform-agent and is termed the *market-agent*.

According to R1, the platform should provide the possibility to trade energy locally. Thus, using a predefined objective function, the market-agent pairs energy requests with appropriate offers (F7). In a similar vein, flexibility requests and offers are paired based on a set objective function to solve grid congestions (F8). Furthermore, the market-agent regularly supplies relevant details about the energy market's dynamics and trends to the prosumer-agents (F9).

4) PROSUMER-AGENT

According to R4, the platform should provide intelligent agent strategies. First, each prosumer-agent estimates its respective energy production and consumption patterns (F10). Second, depending on energy needs and surpluses, prosumer-agents generate market requests or offers (F11). In addition, prosumer-agents actively manage assets, optimize performance, and address any emergent issues in near real-time (F12). Prosumer-agents plan and delineate the potential flexibility they can contribute to the system (F13).

5) EXTERNAL-ENERGY-SUPPLIER

To provide a reliable energy supply, also addressed in R2, the external energy supplier intervenes to either supply the necessary energy or procure excess energy, thereby maintaining market balance and stability. Thus, the external-energy supplier represents the BS in the platform. Since the BS should only deliver the residual load, it is integrated into the market-agent.

C. FUNCTIONAL SEQUENCE OF INTERNAL PLATFORM INTERACTIONS

The functional sequence that is explained in this section refers to the sequence of functions that are executed by the different agents as well as to their dependencies and interrelations.

The operation of the platform is anchored in the smart grid traffic light concept of the BDEW [52]. In this system, the grid's capacity is segmented into three specific color categories: green, yellow, and red. Each color represents a different level of grid load in relation to the nominal current: green for 0-80%, yellow for up to 100%, and red for more than 100%. Additionally, voltage levels are also categorized using this traffic-light colour scheme. A 'green' status indicates a voltage deviation within plus or minus 8%, 'yellow' represents a deviation within plus or minus 10%, and a 'red' status is assigned for deviations exceeding 10%. As a result, the PEAK platform's operation unfolds across four sequential phases: the initialization phase, green traffic light phase, yellow traffic light phase, and red traffic light phase. To respond to transient fluctuations in energy production and consumption, the concept employs a 15-minute market cycle. This is aligned with the current tariff application cases (TAF), wherein energy data is relayed via smart-meter gateways in 15-minute intervals [53]. Moreover, the study by [54] surveys the required level of detail of energy system-models to participate at energy markets. The results show that planning energy dispatch in 15-minute intervals is sufficiently accurate. Although shorter market cycles are feasible, they would significantly increase the computational time and effort required [54].

1) *Initialization Phase*: This phase predominantly focuses on the authentication of all participants on the platform (F5, F6). To ensure IT security during trading operations, the platform employs the self-sovereign identity (SSI) concept. In addition, the prosumer starts to plan their energy consumption as well as energy production. These plans are renewed every 15 min in the market cycle (F10-F12).
2) *Green Traffic Light Phase*: At this stage, a peer-to-peer energy market is activated. This empowers prosumers to conduct energy trades directly amongst themselves (F7). Concurrently, the grid-agent monitors the real-time condition of the grid, using state-forecast calculations (F1) and the results of F7. This ensures that potential shifts in grid status are swiftly identified and addressed.
3) *Yellow Traffic Light Phase*: If the grid transitions into a yellow traffic light phase, the grid-agent determines the sensitivity of each prosumer and creates flexibility requests for each grid node (F2, F3). Subsequently, a flexibility market is launched by the market-agent. Thus, prosumer-agents can place flexibility offers as a response to the requests. Both, flexibility requests and offers are matched by the market-agent. The available flexibility is used to mitigate potential grid congestion (F8).
4) *Red Traffic Light Phase*: If, despite these measures, the congestion persists, the platform moves to the red-light phase. In this critical phase, active grid management starts as a curative redispatch action (F4). Therefore, controllable loads or production systems are

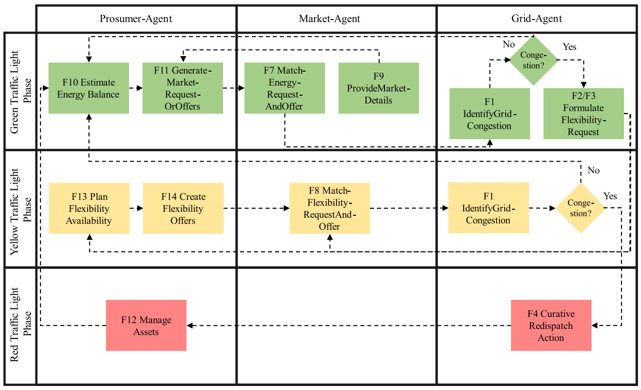

FIGURE 1. UML-Swim-Lane-Diagram internal platform interactions.

downregulated by DSO´s control signals. These control signals must be implemented by the prosumer agents responsible for managing their assets (F12).

The classification of the different agent functions into the three operating phases, neglecting initialization, of the PEAK platform is depicted in the swim lane diagram in FIGURE 1. There, the time sequence between two functions is indicated by dashed arrows.

In essence, the platform's structured, phased-based approach ensures not only efficient energy trading but also maintains the grid's stability and integrity throughout varying load conditions.

IV. ELEMENTS OF THE PLATFORM TRADING CONCEPT

Before explaining the mechanisms and components of the platform´s concepts, a general observation regarding the structure of the platform is required.

In the platform, both, a local P2P trading mechanism as well as market-based grid congestion management should be applied. Instead of designing a single central dispatch mechanism, two separate local markets were implemented, namely an energy and a flexibility market. Resembling the established combination of dispatch and redispatch, e.g. in [26], this maximizes liquidity on the energy market and provides higher financial incentives for prosumer-agents. Moreover, the distributed functions decrease the computational burden at any single point, enhancing scalability. At the same time, the separation of the two markets ensures lower matching complexity and higher transparency for the participants [55]. Despite an overall loss of computational efficiency compared to variants that take grid restrictions into account directly in dispatch, downstream flexibility markets have been the subject of practical research projects for several years [56] and can nowadays meet the regulatory requirements in terms of unbundling better than integrated variants. Therefore, the platform follows this approach.

This section first addresses the fundamental aspect of privacy. To guarantee a balance between secure and private trading across both markets, the application of self-sovereign-identity (SSI) is explained. Furthermore, it presents the P2P energy market component and the algorithm used for forecasting grid states. It also outlines the flexibility market and the strategies designed for prosumers and presents the concept of curative congestion management.

A. SELF-SOVEREIGN-IDENTITY

In the domain of critical infrastructure, it is particularly important to ensure that every actor in the system is acting in good faith and can live up to their promises. Especially in a P2P energy market, this trust cannot be built by experience and familiarization processes but must be inherent to the system. This is why an SSI-based authorization system for prosumer-agents to participate in trading is used [57]. This section will provide a short overview of the SSI-based authorization architecture, while a more comprehensive description can be found in [58].

SSI is an identity management concept that empowers individuals to control their digital identities. Rather than being controlled by a central entity, this concept not only enhances security and trust but also provides users with the means to decide which data they want to share with peers under consideration of technical and legal needs, constituting SSI ensures secure and traceable identity management for energy providers and consumers. This prevents fraud and cyberattacks and fosters trust among participants and thereby ensures the fulfilment of requirement R6. On the other hand, the data must be kept private, e.g. the prosumer's habits and style must be kept secret.

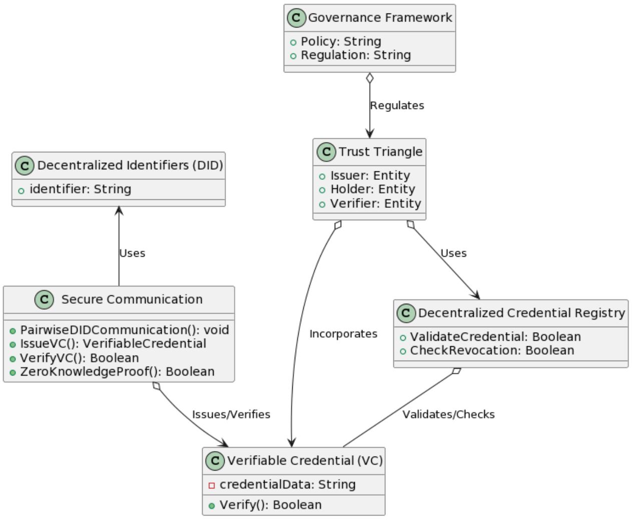

FIGURE 2. UML-class-diagram for SSI on the PEAK platform.

SSI offers a promising framework to achieve the required trust and trading flexibility without compromising privacy between peers.

The SSI authorization system architecture consists of four layers based on the 'Trust-over-IP' stack [59]. Decentralized Identifiers (DIDs) form the first layer, providing unique personal identifiers for participants in the distributed market platform such as a blockchain. Layer two facilitates secure communication between pairwise DIDs. This allows for the issuance and verification of verifiable credentials (VCs). The claims within these VCs can be verified by zero-knowledge proofs. The latter refer to cryptographic methods where one party can prove to another party that a statement is true without revealing any specific information about the statement itself [59]. Utilizing such methods, the VC is a secure means for authentication and authorization purposes. Layer three involves the issuance of VCs and the verification of the incorporated claims in a trust triangle. It describes the VC issuance relationship between the issuer and the holder, as well as the verification relationship between the holder and the verifier of a VC. They can rely on the correctness of claims in the virtual representation of the VC claims by trusting in the issuer of the credential and the SSI system itself through the decentralized credential registry. The registry can be used to verify that the credential has not been revoked by the issuer. The fourth layer comprises governance frameworks, regulating various aspects of the SSI system. The whole process is represented in the class diagram in FIGURE 2.

The implementation of this architecture involves creating additional instances of the SSI-agents as mentioned in section III-B. These agents interact using the Hyperledger Aries [60] and Indy [61] framework to manage DIDs and VCs securely.

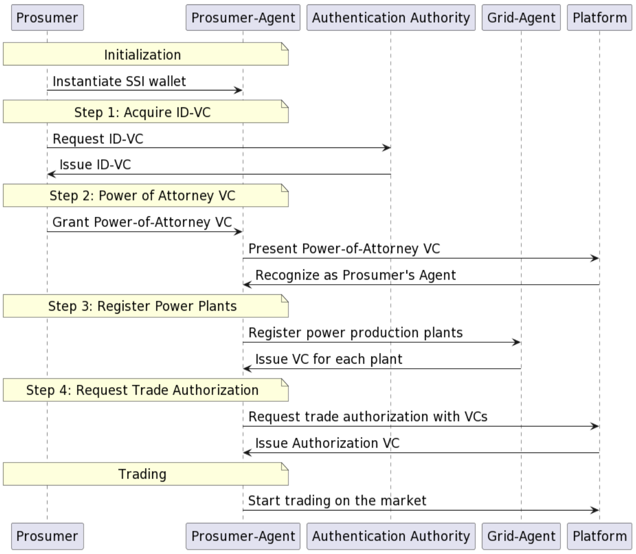

FIGURE 3. **UML-sequence-diagram of agent based SSI.**

To be authorized by the platform as a new prosumer, the prosumer-agents instantiate an SSI wallet to store their credentials and to carry out the algorithms used in the credential exchange as shown in the FIGURE 3. The authorization process consists of four steps: First, the prosumer-agents acquire a personal 'ID-VC' issued by an authentication authority, e.g., the government in a real-world scenario. This VC constitutes the SSI equivalent of a government ID with claims such as name, birthdate, and address of the prosumer. In the next step, the prosumer can integrate the energy- and flexibility-trading on their behalf on the P2P energy market and issue a 'power-of-attorney' VC to it, whereby the prosumer-agent can be recognized by the platform as the agent of the prosumer. Following this, the prosumer-agent registers all its power production plants with the grid-agent, who issues a VC for each plant containing claims such as the maximum and minimum power output and type of plant. Since the accuracy of these claims is paramount to securing grid stability and reliability, the registered plants are individually approved by the grid operator via power plant records such as the German market data main register [62] or via technician examination.

Finally, the prosumer can request a VC containing the trade authorization from the platform. This requests a digital presentation of these VCs and, when the claims are aligned with the market governance framework, issues the authorization VC to the prosumer for trading. Peers can now trust in the ability of the prosumer to deliver the offered flexibilities by the trust they have in the system, without any need for further information.

B. P2P ENERGY MARKET

The energy market is structured as a local P2P energy market, allowing households to exchange energy with nearby residents. Each customer aims to reduce their total electricity costs spanning the asset's lifespan. These costs can be categorized into capital expenditures (CAPEX), representing the initial investment in the asset, and operational expenditures (OPEX), which account for the continuing operational expenses, primarily influenced by energy prices [63]. Since the platform is focusing on developing an energy market that provides the P2P market mechanism, only OPEX is regarded. According to the authors of [64], different categories of pricing mechanisms in a REC exist. For instance, the DSO may introduce incentives to alter energy consumption patterns, known as critical-peak-pricing or peak-load-pricing. Time-of-use concepts also exist, segmenting the day into specific intervals, each with its distinct energy price. Yet another approach is real-time-pricing, where prices are adjusted based on current energy offers and demands. In the presented platform, a real-time-pricing mechanism is employed.

The separation of the flexibility market allowed us to implement the energy market as a double-sided call auction featuring an open order book without the need to account for technical constraints. Double-sided call auction is a trading system where buy and sell orders are collected over a fixed period and then matched at a single price [55]. Compared to continuous auctions that continuously allocate the next matching bid-ask-pair, a call auction can improve the turnover as the market agent optimizes the allocation of bids and asks [55]. This means that a single local marketplace exists where all energy bids and energy asks are sent by the prosumer-agents to the market-agent and the latter stores all the energy bids and asks in the order book. Regarding the trading periods, an intraday auction is applied since individual prosumer-agents cannot reliably forecast their load profile several days in advance. The trading cycle was set to 15 minutes to match the usual balancing time in electricity trading [65] and account for high volatility with a high timely resolution. Since the platform uses an open order book, every prosumer-agent can get important information about the status of the order book, representing F9. To address privacy issues and therefore address R6, the order book does not provide information about every energy bid and energy ask. Instead, it offers information on the average and maximum bid and ask prices. After that, every 15 minutes all energy bids and energy asks are optimally matched based on the objective function of the market-agent. Participants have 15 minutes to submit their bids and asks to the market. Following this period, the market is closed off, referred to as the 'gate closure'. Over the subsequent 15 minutes, market optimization is undertaken, the grid state is forecasted, and optionally, a flexibility market becomes accessible. Therefore, while the gate closure occurs 15 minutes after the begin of the trading period, the actual delivery of energy is scheduled for 30 minutes afterward. The market-agent aims to minimize the ratio between initially bid price and the asked price of matched bids and asks, thereby optimizing for social welfare. The market-agent's objective function implements function F7.

$$\min \sum_{a=1}^{|A|} \sum_{b=1}^{|B|} d_{a,b} \cdot e_{mat_{a,b}} \tag{1}$$

$$d_{a,b} = \begin{cases} \frac{p_a^e}{p_b^e} & if\ p_b^e < p_a^e \\ \frac{p_b^e}{p_a^e} & otherwise \end{cases} \tag{2}$$

This objective function is subjected to equations (3) and (4).

$$\sum_{a=1}^{|A|} e_{mat,a} = e_b \forall b \in B \tag{3}$$

$$\sum_{b=1}^{|B|} e_{mat,b} = e_a \forall a \in \tag{4}$$

The energy price, measured in €/kWh, is presented by p^e and the energy amount by e. Both, energy price as well as energy amount are indexed by a and b represent asks and bids in the sets A and B respectively. The maximum price is set to 0.36 €/kWh as this represents the average household electricity price in Germany 2022 [66] and the relation between p_a^e and p_b^e is depicted in $d_{a,b}$. Energy amount which is matched is indexed by mat.

To satisfy equations (3) and (4), sufficient energy must be available. It's improbable that the energy quantity provided by prosumer-agents matches the amount requested exactly. Therefore, any discrepancy in the amount must be offset by an external energy supplier. When there is a deficit in the market, this supplier provides the remaining energy at the current electricity price, which is set to 0,36 €/kWh. Conversely, during an energy surplus, the excess energy is fed into the grid at the feed-in-tariff, set to 0,08 €/kWh. Following the energy market outcome, a grid state forecast is undertaken. However, as these prices mark the limits of what prosumers are willing to accept, the optimization of Eq. 1 and 2 leads to the minimal amount of energy that is traded with the grid operator.

C. GRID STATE FORECAST

To detect future grid congestions and consequently, the demand of grid-serving flexibilities, a grid state forecast is necessary. The grid state forecast developed in this project builds on the preliminary work described in [67]. It follows a bottom-up approach, which divides the electrical distribution grid into smaller grid areas, depending on the available sensors. For each grid area, one grid-agent is assigned to perform the grid area forecast, using the individual energy consumption and production forecasts of prosumer-agents as well as historical measurement data. Since each node has an actively participating prosumer-agent in the field test, focus of this work is on the creation of a grid state forecast based on the individual forecasts. The interaction between historical measurement data and individual forecast within the grid state forecast will be addressed in future work.

This is followed by a power flow calculation to determine a coherent grid state, which contains voltage values for all nodes and current values for each component.

In PEAK, the described bottom-up approach is implemented as MAS and extended by an additional layer: the forecasting of individual households, including their energy systems, by prosumer-agents. The implementation of these forecasts as well as the required planning and real-time control processes are described in section IV-E For each grid area, one grid-agent is assigned to perform the grid area forecast, using the individual forecasts of the prosumer-agents as a basis. Within one market cycle, the grid state forecast is started after the energy market gate closure by the corresponding grid-agent of the grid area. Following the work in [68], the grid state forecast is assigned to the three phases of the BDEW smart grid traffic light phases. If no grid congestion is predicted the energy market results are validated, the green traffic light phase is initiated, and no further actions are needed. In case of a predicted grid congestions, in the form of an equipment overload or a voltage band violation, the yellow traffic light phase is called.

To open the flexibility market, a list of flexibility requests is needed. The required flexibility, more closely defined as the power adjustment at each node needed to solve the grid congestion, can be calculated in several ways and is strongly dependent on the position of the node in the grid. In addition to an iterative calculation through several load flow calculations, it is also possible to calculate the flexibilities through a sensitivity analysis in one step. Past work has shown that a sensitivity analysis provides sufficient accuracy in determining flexibility [69], [70]. The sensitivity analysis is based on the linearization of the power flow problem at the operating point. As shown in equation (5) the sensitivity z'_{ji} indicates how a change in current $\Delta \vec{I}_j$ at node j results in a change in voltage $\Delta \vec{U}_i$ at node i which can be calculated based on Kirchhoff´s laws. With the combination of equation (5) and the calculation of complex active power in equation (6) it can be determined which apparent power adjustment $\Delta S_{j,U}$ is required at node j to solve a voltage violation of $\Delta \vec{U}_i$ at node i [70]. The voltage violation $\Delta \vec{U}_i$ corresponds to the deviation of the node voltage from the permissible voltage band while the voltage U_j corresponds to the voltage at the node j without power deviation.

$$\Delta \vec{U}_i = z'_{ij} \cdot \Delta \vec{I}_j \tag{5}$$

$$\Delta \underline{S_{j,U}} = 3 \cdot U_j \cdot \Delta \vec{I}_j^{\,*} = 3 \cdot U_j \cdot \left(\frac{\Delta \vec{U}_i}{z'_{ij}} \right)^{*} \tag{6}$$

In case of a thermal current limit violation the calculation of the required apparent power adjustment $\Delta S_{a,I}$ at node a is also based on equation (5). As shown in equation (7) the current change between node i and j can be calculated using the difference of the voltage drops of both nodes with Y_{ij} being the admittance between these nodes. With equation IV-D, it can be determined which apparent power adjustment $\Delta S_{a,I}$ is required at node a to solve a thermal current limit exceedance of ΔI_{ij} between nodes i and j [70]. The required apparent power adjustment at node a depends on its sensitivity to node i and j. Only if these differ the node under consideration can contribute to the solution of the grid congestion.

$$\Delta I_{ij} = Y_{ij} \cdot (\Delta U_i - U_j) \tag{7}$$

$$\Delta \underline{S_{a,I}} = \frac{Y_{ij}^{-1} \cdot \Delta I_{ij} \cdot 3 \cdot U_j}{(z_{ai} - z_{aj})} \tag{8}$$

As the sensitivity analysis is a linearization at the working point, calculation errors occur when calculating the required power adjustment. In FIGURE 4 the relationship between the voltage error e_{Vi}, the apparent power adjustment ΔS_j and the sensitivity z_{ji} is shown using the low voltage distribution grid of the field test (see Section V).

With a power adjustment capability of up to 30 kVA in both positive and negative directions, the voltage errors are limited to slightly above 1%. The greatest errors are concentrated in the highest apparent power adjustment and sensitivity. As power forecasts are subject to errors anyway, these errors are acceptable.

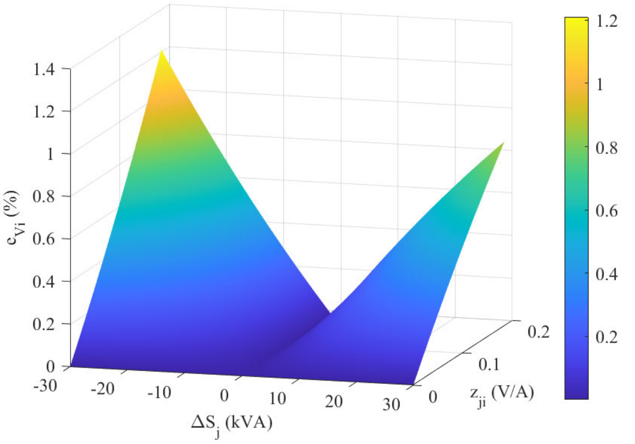

FIGURE 4. **Error distribution of a sensitivity analysis in the field test grid.**

D. FLEXIBILITY MARKET

The flexibility market enables a market-based approach to manage grid congestions by utilizing the flexibilities of prosumers. According to [71], market-based congestion management mechanisms can be classified into energy-tariff, capacity-tariff, and flexibility market. While energy- and capacity-tariffs primarily involve the DSO setting price signals to influence behaviour, the flexibility market offers a more interactive approach. Specifically, the flexibility market allows for the trading of energy adjustments, thereby more actively integrating prosumers into the congestion management process.

As congestions are physical occurrences with a limited radius of effect, the market-agent only considers flexibility bids from prosumer-agents that are affected by the congestion or could contribute to manage it. According to [71], grid congestions due to excessive load are much more common than those caused by over-generation of energy. Therefore, this paper only addresses the former phenomenon. Further, to make power adjustments at different locations in the grid comparable in terms of their effectiveness to solve congestions, a flexibility request-table is applied. This matrix contains factors that describe how much power a prosumer-agent has to adjust to manage the forecasted congestion. Every prosumer has the autonomy to determine the amount of flexibility they are willing to offer at a specified price. In response to the request-table, prosumer-agents submit flexibility bids to the market-agent, which subsequently matches these bids with asks and therefore addresses F8. As a result, the market-agent minimizes the costs for the DSOs while simultaneously providing financial incentives to the prosumers.

$$\min \sum_{b=1}^{|B|} f_{mat,b} \cdot p^{f}_{mat,b} \tag{9}$$

The objective function is subjected to:

$$\sum_{n=1}^{|N|} \frac{f_{mat,k,b}}{f_{k,a}} \geq 1, \mathit{if} \sum_{n=1}^{|N|} \frac{f_{k,b}}{f_{k,a}} \geq 1 \tag{10}$$

where f is the power adjustment integrated for a 15 min time interval. Each $f_{k,a}$ at node k should be sufficient to manage the entire grid congestion. Moreover, for each $f_{k,a}$ there is at most one corresponding $f_{k,b}$. Assuming enough flexibility bids are available, the matched flexibility amount should adequately address grid congestion. This is depicted in (10).

In addition to the flexibility request table, the grid-agent sends the maximum price it is willing to pay to manage the congestion which results in the following constraints:

$$\sum_{b=1}^{|B|} f_{mat,b} \cdot p^{f}_{mat,b} \leq p^{f}_{max} \tag{11}$$

Since it is not ensured, that either (10) or (11) is fulfilled, the optimization is not always feasible. Since for the grid-agent, the fulfilment of (11) is more important than (10), this constraint is prioritized. If the amount of flexibility bids is in total not enough to manage the congestion, without regarding price issues, constraint (10) will not be regarded in the optimization and the objective function changes to:

$$\max \sum_{b=1}^{|B|} f_{mat,b} \tag{12}$$

Matching flexibility means that the planned energy consumption for the next 15 minutes has to be adjusted by the flexibility amount matched. Thus, the energy matches of the previous conducted energy market are adjusted as well. However, to avoid that one prosumer-agent selling energy now receives a worse offer than without the adjustment due to the flexibility market, the grid-agent has to pay the upcoming costs to the affected prosumer-agents. Concretely, this means that prosumer-agents who sold their matched energy amount are feeding in their energy independently of the flexibility market results. If a consuming prosumer-agent ends up consuming less energy due to flexibility market adjustments, they only pay for the actual energy consumed. The grid-agent pays for the remainder. In addition, the energy market is opened again only for those prosumer-agents who have not been asked to provide flexibility and those whose energy bid got reduced by the flexibility market. Thus, the consumption of these agents is not leading into a congestion and feeding energy into the grid results in reducing grid load anyway.

E. PROSUMER-AGENT

The prosumer-agent is designed to empower prosumers by providing them with sophisticated tools for active market participation, enabling them to make informed decisions that can maximize their financial returns. Those are planning functions, which include an estimation of the own energy balance during the planning horizon (F10), the determination of locally available flexibility potentials (F13), as well as the generation of bids or asks for the energy market (F11) and the flexibility market (F14) respectively. In addition, the prosumer-agents provide the ability to transfer planning results to control decisions in near real time (F12).

All this requires that the prosumer-agent can understand which energy systems are under its control, and what flexibility each individual system offers. This knowledge is provided by the Energy Option Model [72], a generalized modeling approach to describe the capabilities and thus the flexibility potential of arbitrary energy conversion systems.

Depending on the locally available energy systems and a corresponding configuration, these models are used by so-called Energy-Agents, that provide the software-technical foundation for the implementation of prosumer-agents in the context of PEAK [73]. Energy-agents implement a generalized concept that enables the combination of planning processes and real-time control capabilities. Several planning strategies with different goals can be executed in parallel. Based on those different planning results, a single execution plan for the real time control process of the agent is to be extracted. The energy-agent's control concept allows to merge differently planned execution schedules so that a summarized schedule can be used by the real time control process of the prosumer-agent.

This real time control process requires the consideration of different situations that may be imposed by the PEAK-scenario and the involved participants, especially also by the owner of the prosumer-agent. Consequently, a prosumer-agent cannot just follow its planned execution schedule since grid operator interventions or user preferences may require a different behavior. For this, the energy-agent's control concept allows to dynamically switch between different types of real-time decision processes and, thus, enables a dynamic way of energy systems usage that is always adapted to the current situation. The energy-agent concept, as detailed in [73], has been expanded to include optimized planning and real-time control strategies. Additionally, a time-coordinated control process has been introduced to guide the market activities of a prosumer-agent.

The planning strategies of the prosumer-agents are timed by the market cycle, in this case 15 minutes. Within a market cycle, two points in time are particularly important, the gate closure of the flexibility market, 5 minutes before the beginning of the delivery period, and the gate closure of the energy market, 15 minutes before the beginning of the delivery period. Since the flexibility market corresponds to the next upcoming market cycle period, and its results can implicate modifications to the original execution plan, flexibility market tasks must be considered before energy market tasks. The general sequence of these two different tasks, as well as the possible states of a prosumer-agent within a market cycle, are shown in FIGURE 5 and described below.

1) FLEXIBILITY MARKET TASKS

When entering a new market cycle, the prosumer-agent verifies whether the requirements to participate in the flexibility market are met (state 1). The main requirement is that a power forecast has to be sent for the considered trading period. If no power forecast has been sent by the grid-agent, the prosumer-agent stops the flexibility market tasks and switches to the energy market tasks starting with state 8 (FIGURE 6a). However, if a power forecast has been sent, the prosumer-agent now waits for flexibility requests (state 2).

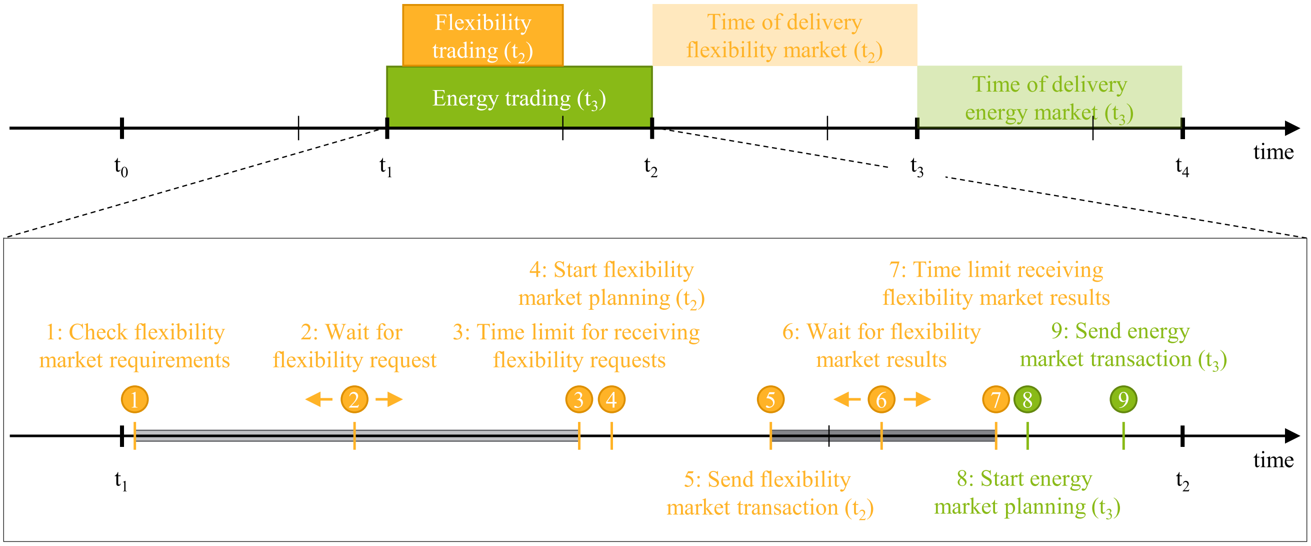

FIGURE 5. Overview of trading times, delivery times (top) and state process of a prosumer-agent in a market cycle of 15 min (bottom).

The waiting time is limited by the computation time for flexibility planning and ends in state 3, which depends on the existing systems and the granularity of the energy models. Based on the completed planning processes, the time limit is calculated and updated individually for each prosumer-agent. This ensures that each prosumer-agent has sufficient time to complete the flexibility market planning by the gate closure of the flexibility market. If state 3 is reached without receiving a flexibility request, the prosumer-agent switches to state 8 (FIGURE 6c). In case of a flexibility request, the prosumer-agent starts to plan its available flexibility (state 4). Thus, the inherent flexibility concerning consumption is ascertained, and a price is randomly chosen between 1€/kW and 2€/kW. This aligns with other flexibility markets such as [74].

On completion, the results are translated into a market transaction and sent to the market agent (state 5). In order to decide whether the flexibility planning should be adopted for the next market cycle, the flexibility market result must be awaited (state 6). Similar to the time limit from state 3, state 7 describes the last point in time at which it is ensured that the prosumer-agent still has sufficient time to complete the energy market planning by the gate closure of the energy market. When the prosumer-agent receives the results and is rewarded for its offered flexibility, the agent's planning is updated (FIGURE 6b). If the flexibility is not matched or state 7 is reached without receiving flexibility market results (FIGURE 6d) the prosumer-agent switches to state 8 without updating its planning for the upcoming market cycle.

2) ENERGY MARKET TASKS

The goal of the energy market tasks is to create bids or asks for each trading period based on the current forecasts of the individual energy systems and the selected strategy. The strategy used in PEAK for the prosumer-agents with energy storage systems is the commonly used self-consumption optimization. In this case, an attempt is made to increase the proportion of self-consumed energy by charging the energy storage system when there is a surplus of power and discharging it when there is a shortage. The selection of the strategy used for both the flexibility and energy market is freely configurable, according to R4.

When the prosumer-agent reaches state 8, the energy-based planning is started with the selected strategy. On completion of the planning process, the results are translated into a market transaction and sent to the market-agent (state 9).

The price of energy, whether being offered or demanded, is determined by two main factors: weather information and order book values. Both are categorized into high, medium, and low by the following procedures and the categories are individually quantified. For weather classification, the day's highest forecasted radiation value is divided into thirds. Zero radiation up to this maximum is separated into these three classifications: high, medium, and low. Every 15-minute radiation forecast is then classified based on this. Since a high solar radiation leads to lower energy prices, high, medium, and low are quantified with 0,1, and 2 respectively. An overview about the quantification is given in Table 2

In addition, insights into the average prices of existing bids and asks are provided by the order book. The price range, stretching from the external energy supplier price to the feed-in tariff, is also divided into thirds and classified in a similar manner. Depending on which is being observed, the average ask or bid price, classifications are made by each prosumer-agent. Since a low market price also means a low price for an energy offer or ask, high, medium, and low are quantified with 2,1, and 0 respectively. Both the weather and order book classifications carry equal weight. Thus, based on a sum of the quantified values, the prosumer-agent decides to select either a higher or lower price for its ask or bid. The

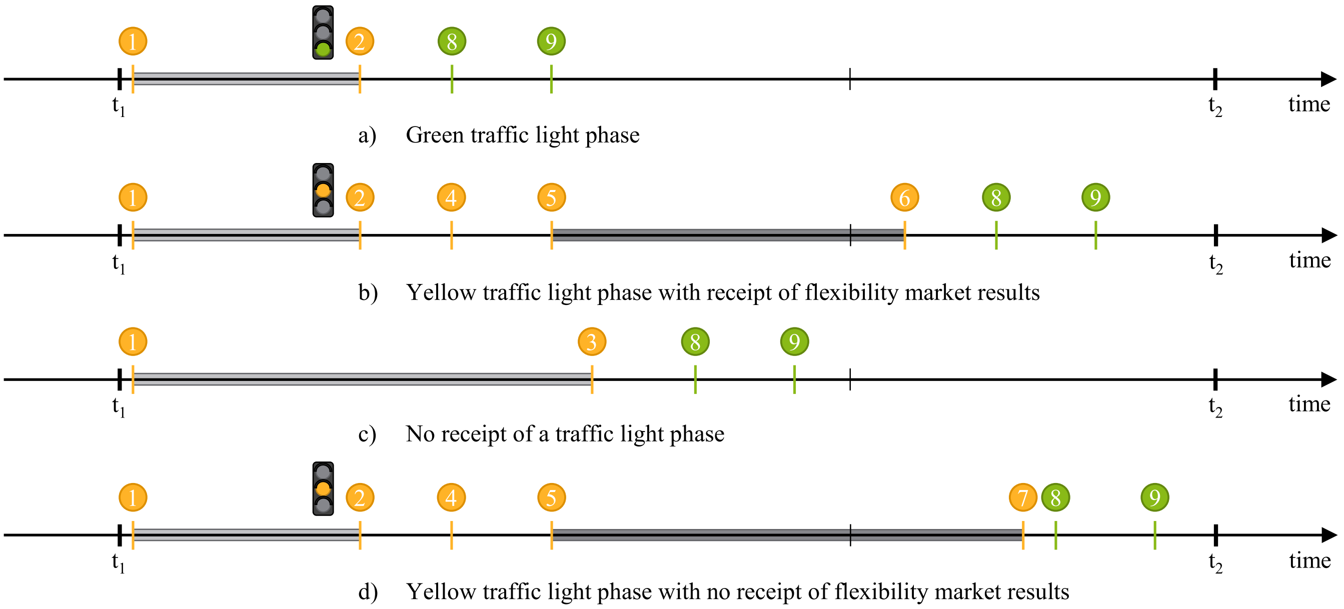

FIGURE 6. Example of possible state processes of a prosumer-agent within a market cycle.

actual energy price is randomly selected within the specified energy price range. For example, during midday when a high radiation is provided, the weather factor is high. For a prosumer willing to buy energy, the currently average ask price is interesting. Assuming that in midday there is less consumption than production, the average ask price will be low. Consequently, a combination of high solar radiation and a low order book value leads to a low price that this prosumer can request.

TABLE 2. Classification of Weather Factor and Order-Book Factor.

Category	Weather Factor	Order Book Factor
High	0	2
Medium	1	1
Low	2	0

Besides the planning functions, the prosumer-agents provide real-time control processes as well.

Real-time control processes:

As previously described, the real-time control process of the prosumer-agent requires the consideration of different situations, which can be classified into five types:

1) Local planning
2) Fulfilling energy market results
3) Fulfilling energy and flexibility market results
4) Grid operator interventions
5) Agent Stakeholder interventions

These types can be further subdivided into schedule-based (i-iii) and event-based (iv-v) control processes. In the schedule-based processes, an attempt is made to achieve a predefined goal by real-time controls. These can be the locally defined goal to reach a desired battery state of charge (SOC) (i) or the fulfilment of a certain amount of locally traded energy or flexibility (ii, iii). In the event-based processes, new temporal targets with a higher priority than the schedule-based goals need to be considered. In case of a grid operator intervention (iv), an upper and lower power limit is sent which needs to be met. In case of agent stakeholder interventions, new energy system setpoints deviating from the original planning need to be fulfilled.

F. CURATIVE CONGESTION MANAGEMENT

An essential functional component of the PEAK platform is congestion management by active grid management using the ''Intelligent Grid Operator'', a smart grid system (SGS). Via the flexibility market, grid-serving measures can be initiated preventively and eliminate grid congestions in advance. If there is not enough flexibility available on the market, curative measures are initiated to ensure reliable grid operation, including high security and quality of supply. Curative congestion management is addressed by the SGS. The SGS collects measured values in real-time from the grid and autonomously derives control commands for the optimal resolution of the congestion. On the one hand, measured values are recorded by conventional measuring equipment in the secondary substation and cable distribution stations and transmitted to the platform every minute via secure communication links. In addition, metering data from prosumers is made available for grid management via the smart meter gateway. In accordance with German standards and norms, measurement data in the format of tariff application cases 1, 7, 9, and 10 are available here [53]. SGS uses the data to determine the grid state in real time (especially at unmeasured grid nodes) using a state estimation based on a weighted least square method developed specifically for low-voltage grids. Built upon a grid state analysis, congestions, caused by voltage range violations and overloads of electrical components, are identified and a state control algorithm is activated as required. In the context of real-time state control, it is particularly important to select the right actuators according to suitable prioritization criteria. Technical effectiveness on the congestion (based on a sensitivity analysis) and non-discrimination must be ensured. The calculation logic determines optimal set points to eliminate the respective congestion with minimal impact on the prosumers. As soon as free grid capacity is available again, control interventions are being reset in a controlled manner. The grid state and condition information are also provided for the state forecasting component.

V. FIELD TEST

The evaluation of the concept was carried out through field tests at the Freudenberg Campus of the University of Wuppertal, guided by principles of the ISO29119 standard for software testing. The following sections are structured as follows: Section V-A introduces the ISO29119 software testing standard and explains how it is applied to assess the PEAK platform's performance and functionality. Section V-B focuses on outlining various grid and market scenarios. These scenarios are then combined to form a set of five test cases that have been executed during field tests to evaluate the PEAK platform. Section V-C delves into the hardware and software configurations used for the field tests which took place at the Freudenberg Campus of the University of Wuppertal. Finally, Section D presents the results and analyses of these five test cases, assessing the impact of the PEAK platform on both grid state dynamics and market conditions.

A. APPLICATION OF ISO 29119 ON PEAK PLATFORM EVALUATION

The evaluation of the PEAK platform is carried out by applying the standard ISO 29119, a standard defining a framework for testing software systems [75].

ISO 29119-1 describes concepts and definitions of software testing for an overall testing strategy. Test phases and test types are instantiations of test sub-processes that describe activities that are carried out to collect information about the quality of a software product. Test phases are usually understood as component, integration, system, and acceptance test.

In the context of testing the PEAK platform, components evaluated within this paper can be specified as the P2P energy market, flexibility market, and the SGS. Test practices used to test the PEAK platform are requirements-based testing and experience-based testing.

Requirements-based testing was carried out during the phase of component testing to test the functional requirements of each component on a technical level, based on defined requirements in [76]. As these requirements are fulfilled for each component on its own, this paper focuses on the integration and the system test of the components. Thus, experience-based testing is now applied to address R1 to R6 (see section I).

The ISO29119-4 describes the method to create test conditions, test coverage items as well as test cases. In case of the described platform, test conditions are characterized by distinct market and grid scenarios. These scenarios contain different operating conditions, each designed to test the performance of the platform under different circumstances. Since experienced-based testing is applied, these operation conditions are developed based on the researcher´s experience. The test coverage items are the P2P energy market, grid state forecast, flexibility market, the prosumer-agents, and the SGS.

The test cases combine the market and grid scenarios, which are executed in the field test to evaluate the integration of the test coverage items. Test conditions, coverage items, and cases are described in the following section.

B. TEST SCENARIOS

The test conditions that define the subsequent test cases are grid scenarios, market scenarios as well as projection year and season. A grid scenario is classified into a current-related and voltage-related grid congestion as well as a normal operation without an excess of boundary conditions. Market scenarios vary, based on the status of the energy and flexibility markets, as well as the state of the grid assessed by the SGS. To investigate future grid scenarios with a high penetration of decentralized generators and consumers, three *projection years* were chosen: 2030, 2040, and 2050. In each of these years, the addition of decentralized generators and consumers is projected from an initial state of an electrical distribution grid. Furthermore, each test process was carried out during different *seasons*, namely summer, winter, and transition period. Based on these conditions, respective test cases are defined.

The field test takes place in a real low-voltage grid with 16 nodes, out of which 12 can be actively controlled with load and power generation. A prosumer-agent is instantiated for each of these nodes, who controls the systems and actively participates in the PEAK market. The topology and configuration of the field test grid are described in more detail in Section C. To ensure high market liquidity and accommodate different test objectives despite the low number of market participants, the year 2050 and the summer season are chosen as the standard parameters for all test processes within the field test. Moreover, the field test defines three distinct grid scenarios and five different market scenarios. These scenarios are elaborated upon in the subsequent sections. Every scenario is tested once.

1) GRID SCENARIO 1

In this scenario, the grid is in a stable state throughout the entire period which corresponds to a constant green traffic light phase in the BDEW smart grid traffic light concept. Due to the year 2050 and the resulting high number of photovoltaic systems, the ratio of generation and load is balanced, making it suitable for test-processes addressing R1 and R5.

2) GRID SCENARIO 2

In this scenario, the limits of electrical current are exceeded, primarily due to a significant increase in the simultaneity while charging EVs resulting in grid congestion. The grid is configured as a long line so that components are particularly affected at the beginning of the line. This configuration is chosen to ensure that all prosumers have the potential to influence the exceedance of current limits. Consequently, this paves the way for robust market liquidity on the flexibility market. The scenario contains both green- and red traffic light phase making it suitable for test-processes addressed to R1, R2, R3, and R5.

3) GRID SCENARIO 3

In this scenario, the lower limit voltage is violated mainly due to a high level of simultaneity in the charging of EVs like grid scenario 2. The possible voltage drop in the field test is limited due to the installed components in the low voltage grid. To still cause a limit violation, the allowed voltage band is virtually lowered from $\pm 10\% U_n$ to $\pm 8\% U_n$. With this adjustment, the scenario contains both green- and red traffic light phases states making it suitable for test-processes addressed to R1, R2, R3, and R5.

4) MARKET SCENARIO A

In the market scenario a, only the P2P energy market is enabled. Both the curative and preventive grid congestion management are disabled. The main purpose of this scenario is to obtain a baseline load profile for subsequent evaluation of the grid congestion management components. In addition, the energy market results can be compared to other market scenarios to evaluate the impact of active grid congestion management on P2P energy trading, which addresses R1.

5) MARKET SCENARIO B

Within this scenario, both the energy and flexibility markets are enabled, whereas the SGS remains inactive. The aim here is to assess the influence of the flexibility market on grid congestion management. The flexibility market uses grid forecasts and market-based utilizations of flexibilities to mitigate the grid congestion which aligns with the requirements R2, R3, and R5. In addition, the influence of preventive grid congestion management on energy market trading results can be investigated, addressing R1.

6) MARKET SCENARIO C

The primary objective of this scenario is to assess the impact of the SGS on the energy market and on stabilizing the grid in the event of grid congestion. The aim of this scenario is to assess the cooperation of the SGS with the prosumer-agents when the flexibility market is inactive. The SGS uses this information about the prosumer's consumption and production limits to implement the appropriate control actions. The SGS uses state estimations to analyse the condition of the grid aligning with the requirement R4. Furthermore, the effectiveness and the sensitivity of curative congestion management by the SGS, thereby bringing the grid back to a stable condition, is also assessed.

7) MARKET SCENARIO D

In this scenario, the impact of the SGS on both the energy and flexibility market is tested. This test case combines the benefits of scenarios b and c.

In market scenario b, while the prosumers achieve financial gain, the ability to potentially resolve all congestion hinges on the availability of flexibilities; hence the congestion in the grid cannot be fully mitigated. On the other hand, market scenario c effectively addresses the congestion, yet it curtails the financial incentives for prosumers and restricts their participation in the open market.

An overview of the test cases is given in Table 3.

TABLE 3. **Overview of testing scenarios with P2P Energy Market (P2P EM) and Flexibility Market (FM) and Grid Congestion Management (GCM).**

ID		Testing objective	Grid Scenario	Market Scenario		
				P2P EM	FM	SGS
1		P2P EM	Normal operation	X	X	X
2	a	GCM	Current limit violation	X		
	b	GCM	Current limit violation	X	X	
	c	GCM	Current limit violation	X		X
	d	GCM	Current limit violation	X	X	X
3	a	GCM	Voltage violation	X		
	b	GCM	Voltage violation	X	X	
	c	GCM	Voltage violation	X		X
	d	GCM	Voltage violation	X	X	X

By activating the flexibility market and SGS simultaneously, the drawbacks observed in scenarios b and c can be overcome. This approach effectively combines preventive b and curative c congestion management techniques. With available flexibilities, the flexibility market preventively resolves congestion, enabling prosumers to engage in trading green, local electricity meeting the requirements R1, R2, R3, and R4. When the flexibility market cannot resolve all the congestion, the SGS sends control signals to prosumers, as specified by requirement R4.

C. SMART-GRID-LABORATORY

The Smart Grid Laboratory is located at the Freudenberg Campus of the University of Wuppertal and includes a low-voltage distribution grid with 16 grid nodes and 32 branches with a total length of 750 meters. The grid can be configured in different grid topology configurations and connected to different controllable loads as well as feeders. The topology selected for the field test is depicted in FIGURE 7.

The grid is fed by a 250-kW line voltage regulator which makes the testing of critical grid situations possible. Loadbanks with a total power of 45 kW and bidirectional power

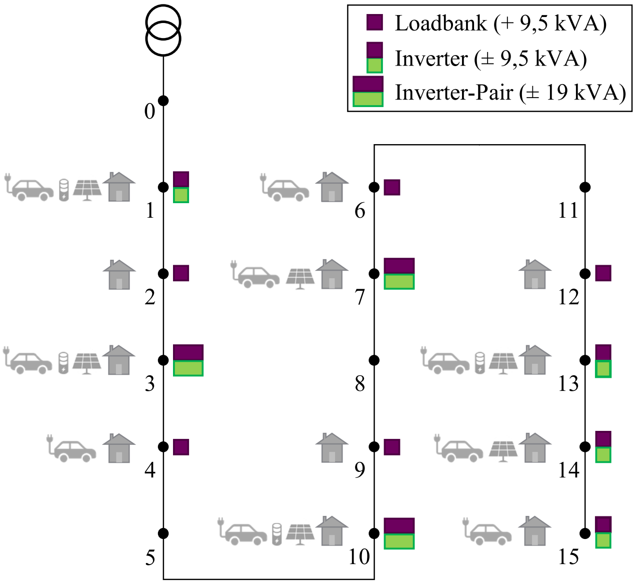

FIGURE 7. Topology and energy system distribution of the field-test.

electronics with a total power of 97 kVA are available as controllable systems. At nodes 5, 8, and 11, there are no households, resulting in no consumption or production. The low-voltage grid is completely monitored by measurement technology, making it possible to simulate different levels of measurement equipment [77].

In addition to the topology, the distribution of the energy systems to the individual nodes is also shown in FIGURE 7. The setup includes six PV systems, three electrical energy storage (EES) systems and nine EVs. In addition, a household load from the dataset described in [78] is selected for each prosumer node. The corresponding annual energy consumption E_{annual} of the selected household loads as well as the configuration of the other systems are listed in Table 4. For the configuration of the individual systems, the operating limits of the controllable systems in the smart grid laboratory had to be considered. The following parameters were determined: PV rated power $P_{PV,r}$, EES energy storage capacity E_{EES}, EV storage capacity E_{EV}, and EV charging power P_{EV}.

TABLE 4. Prosumer-agent system configuration for the field test.

Node-ID	E_{annual} (kWh/a)	$P_{PV,r}$ (kW)	E_{EES} (kWh)	E_{EV} in(kWh)	P_{EV} (kW)
n1	5,220	8	6	60	11
n2	6,620				
n3	6,904	11	7	60	22
n4	3,775			60	11
n6	2,630			60	11
n7	4,287	10		60	22
n9	4,147				
n10	4,495	9	6	60	11
n12	3,239				
n13	4,364	7	6	60	22
n14	3,391	5		60	11
n15	5,230			60	11

D. RESULTS AND EVALUATION

This section presents the results of the investigated *test cases*. To ensure adequate automation, tools are employed to facilitate manual testing activities. Specifically, Agent.Workbench [79] integrates a tool to automate the formulation of test configurations. Additionally, data analytics are executed through R and MATLAB scripts to ensure result comparability. These scripts evaluate time series data derived from the energy market, flexibility market, and grid-related data.

The evaluation the test coverage items of the PEAK platform, namely the P2P energy market, flexibility market, and the SGS are performed in the following subsections.

1) GRID ESTIMATION AND FORECAST

The grid estimation and forecast are two parts of the platform´s concept which can be tested in test cases 2a, 2b and 3a, 3b. To distinguish the quality of the grid forecast several key performance indicators must be introduced. With regard to the forecast of the node voltages, these are the average percentage voltage forecast error $e_{U,rel,k}$ at a node k as well as the average percentage voltage forecast error $e_{U,rel}$ over all nodes K, which are shown in equation (13) and equation (14). The error per node k is calculated for a number of T timesteps with the measured voltage value $U_{k,t}$ and the forecasted voltage value $U^p_{k,t}$ for each timestep.

$$e_{U,rel,k} = \frac{1}{T}\sum_{t=1}^{N_t}\left|\frac{U_{k,t} - U^p_{k,t}}{U_{k,t}}\right| \cdot 100\% \tag{13}$$

$$e_{U,rel} = \frac{1}{K}\sum_{t=1}^{N_k} e_{U,rel,k} \tag{14}$$

With regard to the forecast of the node apparent powers, the considered key performance indicators are the average percentage power forecast error $e_{S,rel,k}$ at a node k as well as the average percentage power forecast error $e_{S,rel}$ over all nodes N_k, which are shown in equation (15) and equation (16). The error per node k is calculated for a number of N_t timesteps with the measured apparent power value $S_{k,t}$ and the forecasted apparent power value $S^p_{k,t}$ for each timestep. At nodes with prosumer-agents, $e_{S,rel,k}$ also corresponds to the forecast quality of their planning, as these are adopted in the grid state forecast. Especially with low apparent power amounts, very high relative errors distort the evaluation, although their impact in the grid state forecast is low. Therefore, the relative error $e_{S,rel,k}$ is related to a predefined apparent power S_k, to the measured apparent power $S_{k,t}$, or the rated power of the PV system $P_{PV,r}$ at the corresponding node depending on the value of $S_{k,t}$. The rated power is additionally reduced by a factor of 0.85 to account for shading and cloud cover. In this work, a value of 4.2 kW is defined for S_n, as this corresponds to the minimum value to be granted in the event of a reduction of the grid-effective power consumption in the

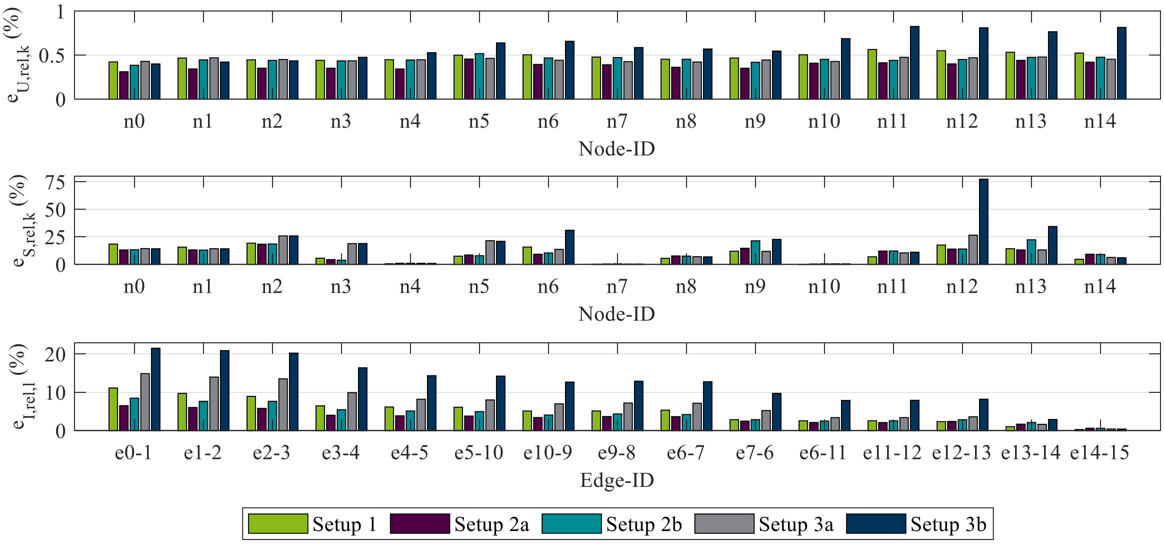

FIGURE 8. Grid state forecast key performance indicator results for all nodes and edges in each setup.

current national draft law of §14a EnWG [80].

$$e_{S,rel,k} = \begin{cases} \frac{1}{T}\sum_{t=1}^{N_t}\left|\frac{S_{k,t}-S^p_{k,t}}{S_{k,t}}\right|\cdot 100\% & S_{k,t} \geq S_n \\ \frac{1}{T}\sum_{t=1}^{N_t}\left|\frac{S_{k,t}-S^p_{k,t}}{S_n}\right|\cdot 100\% & 0 \leq S_{k,t} < S_n \\ \frac{1}{T}\sum_{t=1}^{N_t}\left|\frac{S_{k,t}-S^p_{k,t}}{0.85\cdot P_{PV,r}}\right|\cdot 100\% & S_{k,t} < 0 \end{cases} \tag{15}$$

$$e_{S,rel} = \frac{1}{K}\sum_{k=1}^{N_k} e_{S,rel,k} \tag{16}$$

With regard to the forecast of the edge currents, the considered key performance indicators are the average percentage current forecast error $e_{I,rel,l}$ of a line l as well as the average percentage current forecast error $e_{I,rel}$ over all lines N_l, which are shown in equation (17) and equation V-D2. The error per edge l is calculated for a number of T timesteps with the measured current value $I_{l,t}$ and the forecasted current value $I^p_{l,t}$ for each timestep. The relative error $e_{I,rel,l}$ is particularly important for currents in the operating range of the continuous current limit. Especially with low current amounts, very high relative errors distort the evaluation, although they are not relevant for the load. Therefore, the relative error is related to the thermal current limit $I_{th,l}$ of the corresponding cable l.

$$e_{I,rel,l} = \frac{1}{T}\sum_{t=1}^{N_t}\left|\frac{I_{l,t}-I^p_{l,t}}{I_{th,l}}\right|\cdot 100\% \tag{17}$$

$$e_{I,rel} = \frac{1}{L}\sum_{l=1}^{N_L} e_{I,rel,l} \tag{18}$$

In FIGURE 8 the results of $e_{U,rel,k}$ and $e_{S,rel,k}$ for each node as well as $e_{I,rel,l}$ for each edge are shown in all five test cases. In case of the voltage forecast, a majority of the results remain below a value of 0.5 %. There is a slight tendency towards a higher error at the end of the grid line. The outliners in test case 3b at the last four nodes can be explained by the large amount of used flexibility and the lack of an update of the grid state forecast after a successful flexibility market result. There are significant differences in the apparent power forecast error both between nodes and between test cases. Since the error is normalized either by $S_{k,t}$, S_n or $P_{PV,r}$ nodes with a high load during the test case also tend to have higher errors. The big difference between test case 3a and 3b at node n12 is caused by a high number of matched flexibilities at this node. The results of the current errors, in contrast to the voltage errors, tend to get lower the further the edge is at the end of the grid strand. This is caused by the decreasing value of the current in the strand and the normalization with the thermal current limit.

In Table 5 the results of the key performance indicators of the grid state forecast in all five test cases of the field test are shown. The voltage forecast errors are in all test cases are in the very low range of less than one percent with a maximum of 0.61 %. The power forecast errors are in the lower two-digit percentage range between 15 % and 25.91 % and the current forecast errors in the range between 3.48 % and 12.21 %. The difference between two test cases with the same grid scenarios but different market scenarios (e.g. Test case 2a and 2b) can be explained by the fact that the grid state

TABLE 5. Grid forecast error results.

Test Case	$e_{U,rel}$ (%)	$e_{S,rel}$ (%)	$e_{I,rel}$ (%)
1	0.49	15.41	5.06
2a	0.38	15.00	3.48
2b	0.45	16.14	4.38
3a	0.45	19.64	7.18
3b	0.61	25.91	12.21

forecast is not updated after a successful flexibility market, which leads to larger deviations due to the schedule changes of the prosumer-agents.

2) GRID CONGESTION MANAGEMENT

In FIGURE 9 the current measurements of the cable subjected to the highest current load is depicted for both test cases 2a and 2b. In each test case, a current limit violation is observed. While in test case 2a only the P2P energy market is active, resulting in unmanaged current limit violations, whereas test case 2b employs a flexibility market to help mitigate these violations.

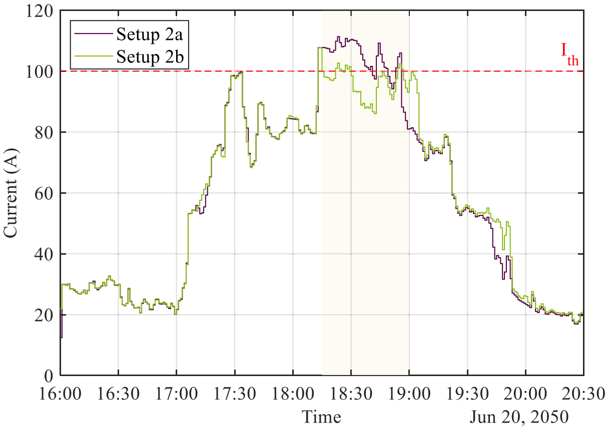

FIGURE 9. **Measured current (average of all three phases) at edge 1-2 for Test case 2a and 2b with highlighted active flexibility market periods.**

The analysis reveals that a current surge occurring at 18:15 leads to a peak in current that exceeds I_{th}. Without any intervening control actions, this grid congestion would persist until 19:00, risking a thermal overload of the affected cable. However, when the flexibility market is engaged, much of this grid congestion is successfully mitigated. The initial current peak still occurs, despite the application of the flexibility market, due to the underestimation of the magnitude of the current surge. It is worth noting that short-term current overloads do not instantly result in thermal overloads, given the time-dependent nature of the heating process [4].

In summary, the flexibility market is effective in reducing a significant portion of grid congestion. However, to ensure covering all grid congestions, additional curative measures are still required. Table 6 consolidates the instances of grid congestion across all grid nodes, revealing a 44.5% reduction in grid congestion due to the application of the flexibility market.

In FIGURE 10 the voltage measurements of node 15 for both test cases 3a and 3b are depicted, which is located at the end of the grid strand and therefore because of its sensitivity subjected to the highest voltage changes. In contrast to the previous comparison, there are already differences between the measurements without the flexibility market being active. This is because the field test grid is fed from a public distribution grid and is therefore subject to its voltage levels and transformer tap changes.

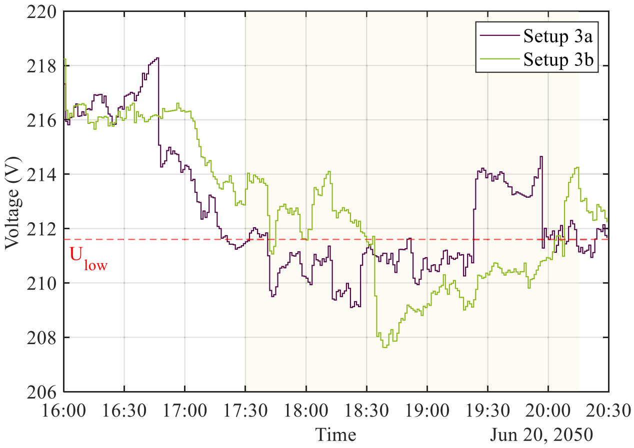

FIGURE 10. **Measured voltage (average of all three phases) at node n15 for Test case 3a and 3b with highlighted active flexibility market.**

The flexibility market is continuously active from 17:30 to 20:15, which corresponds to a total of 11 market cycles. There are lower voltage violations both in test case 3a without activated flexibility market, mostly between 17:40 and 19:20, and in test case 3b with activated flexibility market, mostly between 18:35 and 20:10. In this regard a voltage drop in test case 3b of around 4 V at 18:35 from 212 V to 208 V should be highlighted. This voltage drop is not caused by a significant change in the load conditions but by the circumstances of the field test grid described above. Although the voltage violations are forecasted by the grid state forecast, so that the flexibility market is opened, the matched and used flexibility does not solve the entire voltage violation during this time.

The impact of the preventive grid congestion management is shown in Table 6, where the time of congestion is aggregated over all nodes and the total testing time. While there are 38 minutes of congestion in grid scenario 2 without activated flexibility market, there are only 17 minutes in test case 2b with activated flexibility market. In grid scenario 3 the time span with voltage violation is reduced from 155 to 115 minutes i.e. by 26 %. Since the grid state forecast is calculated in a resolution of 15 minutes, the number of 15- minute-intervals with grid congestions is also listed in Table 6.

The comparison of the number of 15-minute-intervals with grid congestions shows a reduction from 2 to 1 in grid scenario 2 and a reduction from 10 to 6 in grid scenario 3.

In summary, the preventive grid congestion management can identify and partially eliminate grid congestions in the

TABLE 6. **Evaluation of the grid congestion management, aggregated over all nodes and the total testing time.**

Test Case	$t_{I,violation}$ (min)	$t_{U,violation}$ (min)	$n_{I,violation}$ (15-min)	$n_{U,violation}$ (15-min)
1	0	0	0	0
2a	38	0	2	0
2b	17	0	1	0
3a	0	155	0	10
3b	0	115	0	6

field test. In case of the current-related grid congestion (*grid scenario 2*), most congestions are solved, while in the case of the voltage-related grid congestion (*grid scenario 3*), only part of the congestion could be solved. In both test cases, there is the demand for curative grid congestion management in addition to the preventive grid congestion management. The curative grid congestion management can solve short-term congestions, react to hardly predictable situations like transformer tap changes, and thus complements the preventive grid congestion management.

3) PROFIT OF PROSUMER

To evaluate the P2P energy market, a heat map is created based on the trading activity between different prosumer-agents.

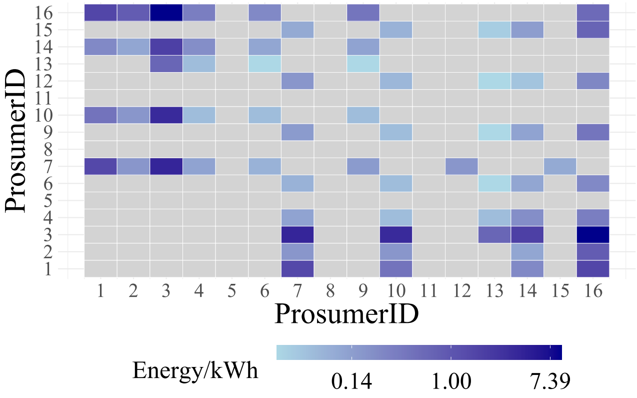

FIGURE 11. Heat-Map of trading energy between single prosumer-agents.

In FIGURE 9, the trading activity which is the average energy traded in a 15 min trading cycle of all prosumer-agents, numbered 1 to 15, along with an external energy supplier represented as 16, is depicted. The figure reveals that agents 5, 8, and 11 are inactive in trading because these positions do not host prosumer-agents. Additionally, nodes 3, 7, 10, 13, and 14 are equipped with PV-plants, making them more active in the marketplace compared to other nodes.

The KPI Financial-Gain-Prosumer (FGP), as represented by Equation (19) provides an analysis of the average financial gain realized by all prosumers participating in the P2P energy market within on test case. Gains received by trading at the flexibility market are not regarded in that KPI. (19) considers both energy demand and supply by a set of binary variables $l_{ask,t,n}$ and $l_{bid,t,n}$ which get 1 if prosumer n demands or offers energy during time interval t, respectively. The constant pricing parameter p_{gridIn} indicates the feed-in tariff for selling energy back to the grid while $p_{gridOut}$ represents the constant tariff for energy purchased from the grid. They contribute to financial gains or losses associated with energy trading. The individually negotiated price for the matched energy of prosumer n during time interval t is denoted as $p_{match,t,n}$. It reflects the price for energy $e_{match,t,n}$ that the prosumer has either sold to or purchased from other prosumers.

$$\begin{aligned} FGP = \frac{1}{N} \sum\nolimits_{t=0}^{t=4h} \sum\nolimits_{n=1}^{N} e_{match,t,n}[l_{ask,t,n} \\ \cdot \left(p_{gridOut} - p_{match,t,n}\right) - l_{bid,t,n} \\ \cdot \left(p_{gridIn} - p_{match,t,n}\right)] \end{aligned} \tag{19}$$

The trading data in each conducted test case covers a 4-hour period in 15-minute time steps. While transaction data for $e_{match,t,n}$ and $p_{match,t,n}$ was recorded for each participating prosumer as timeseries data, p_{gridIn} and $p_{gridOut}$ were constantly set to 0.08 €/kWh and 0.36 €/kWh, respectively. p_{gridIn} is determined based on the feed-in-tariff in Germany, currently fixed at 0.08 €/kWh.

The results obtained by applying the KPI to trading data collected from test cases 1, 2a, 2b, 3a, and 3b, can be seen in Table 7. The total group of prosumers was able to generate positive financial gain from their consolidated energy trading activities.

TABLE 7. Overview of FGP.

Test Case	FGP (€)
1	1.026
2a	0.089
2b	0.088
3a	0.090
3b	0.088

Analysing individual prosumer outcomes, results revealed a wide range of financial outcomes among prosumers, depicted in Table 8. For example, in test case 2a, prosumers gained between 0.02€ and 0.34€ from energy trading, with one prosumer achieving an average FGP of 0.36€. The fact that it is the same value as $p_{gridOut}$ is coincidence.

TABLE 8. FGP (€) per prosumer and test case.

Hardware additional to household consumption	Node	Scenario						
		1,00	2a	2b	2b/ Flex	3a	3b	3b/ Flex
PV, E, EV	n1	0.93	0	0.11	0.00	0	0.12	0
	n3	2.25	0.14	0.15	0.00	0.15	0.15	0
	n10	2.51	0	0	7.82	0	0.19	6.8
	n13	1.24	0	0.19	0.00	0.07	0	39.67
PV, EV	n7	3.48	0.34	0.36	4.64	0.34	0.33	11.62
	n14	1.16	0.36	0.12	10.10	0.23	0.06	15.70
EV	n4	0.1	0.16	0	0.00	0.22	0.16	0
	n6	0.09	0	0.02	0.00	0.02	0	0
	n15	0.12	0.05	0.04	0.00	0.02	0.02	0
None	n2	0.22	0	0.06	0.00	0.03	0.03	0
	n9	0.13	0	0	0.00	0	0	0
	n12	0.08	0.02	0	0.00	0	0	0

Since in scenarios 2a, 2b, 3a, and 3b daytimes with less renewable energy production and a lot of consumption are regarded to provoke grid congestions, the P2P energy market is less active and thus the financial gain per prosumer is less than in scenario 1.

Seen over all test cases, prosumers experienced fluctuations in their financial gains. The wide spread of prices is also seen in the results of [13] where also a P2P-market is developed and analysed. The analysis also reveals that no prosumer-agent experiences a negative FGP, thereby indicating that no prosumer-agent incurs financial losses. This outcome is attributed to the fact that all the matched prices for energy trades fall within a constrained range of € 0.08/kWh to € 0.36/kWh. In addition, no taxes, duties, and levies are regarded.

By aggregating the financial impacts across all prosumers and temporal intervals, the formula offers an encompassing perspective on the potential financial benefits that prosumers may realize through their energy trading activities in various test scenarios.

Additionally, the discrepancy observed in FGP values between scenarios 2b and 2a as well as 3b and 3a for a specific prosumer-agent cannot be attributed to the opening of the flexibility market. This is evident because grid congestion occurs at 18:15, a time when there is no available PV production, making it impossible for prosumer-agents to contribute energy offers to the market agent. Consequently, all energy supplied during this period is sourced from the external energy supplier at a fixed price of 0.36 €/kWh.

The observed differences in FGP values are instead rooted in the P2P energy market activities that transpire prior to the onset of grid congestion. In this pre-congestion phase, prosumer-agents engage in energy transactions at varying prices determined by their respective pricing strategies. A component of these strategies incorporates a random factor, making the offered prices inherently non-deterministic. Therefore, the exact energy prices in these transactions lack reproducibility, explaining the variation in FGP values between the two scenarios. In addition to FGP in the P2P energy market, columns labelled '2a/Flex' and '3a/Flex' show the earnings accrued by each prosumer in the flexibility market. Like the FGP for the energy market, these numbers represent the total earnings across the test cases. It is evident that prosumers stand to gain significantly from both current-related (in column 2a/Flex) and voltage-related (in column 3a/Flex) congestion scenarios. These earnings, however, are highly contingent upon the assumption that the prosumers' offer prices range between 1 €/kW and 2 €/kW. It is worth noting that test cases 2a and 3a are specifically designed to provoke grid congestions that, according to a study by DENA [81], would typically only occur about 5% of the time. Furthermore, comparable studies on flexibility markets corroborate these findings on the profitability of such endeavours. For instance, the FlexHub project indicates that prosumers participating in a flexibility market could expect an annual financial gain of approximately 200 € [74].

The financial benefits prosumers derive from engaging in local P2P markets are significantly influenced by the composition and capacity of their energy systems, as well as the level of market participation. Additionally, the range of earnings for prosumers is subject to regional taxation and regulatory frameworks. Furthermore, the FGP metrics from the flexibility market indicate that this market is not entirely equitable, suggesting the presence of some form of discrimination. Even among households providing the same hardware, prices between the nodes differ enormously. The notable financial gains of n13 and n14 in the flexibility market during test case 3a can be attributed to their geographical positioning within the grid topology. As demonstrated in Section IV-C, households at the end of a lane exhibit higher sensitivity. This makes their flexibility offers more cost-effective for the DSO.

While R4 is technically fulfilled, the results of the KPI can be further used. Additional benefits can be achieved by using the data for implementing learning strategies for the prosumer-agents. However, this is not the focus of the current paper.

4) SELF SUFFICIENCY RATE

The Self-Sufficiency Rate (SSR) serves as an indicator for the proportion of energy that can be locally matched and subsequently supplied by private households. In doing so, it quantifies the level of autonomy inherent in a P2P energy market, as well as the degree of dependency on external energy suppliers.

$$SSR = \frac{1}{T}\sum\nolimits_{t=0}^{t=T}\frac{\sum_{m=1}^{M}(e_{ask,m,t}+e_{bid,m,t})}{\sum_{n=1}^{N}e_{match,n,t}} \tag{20}$$

While in the numerator, $e_{bid,n,t}$ and $e_{ask,n,t}$ represent the amount of energy in kWh offered or asked by prosumers, $e_{match,n,t}$ in the denominator indicates the amount of matched energy with other prosumers as well as with the external energy supplier. T represents the number of trading cycles t. N denotes the set of all prosumer-agents, inclusive of the external energy supplier n, while M defines the set of prosumer-agents m excluding the external energy supplier. Thus, M is a subset of N.

The SSR can take any real number between 0 and 1. While a value of 1 indicates that all energy offered and asked is matched within the local market, a value smaller than 1 indicates that not all offers and bids could be answered by a match meaning that the remaining energy quantity must be fed into the grid or purchased from the external energy supplier by a prosumer.

The calculated SSR in Table 9 shows varying degrees of energy matching efficiency across different test cases. The calculated value ranged from around 50% in scenarios 2a to 3b and was 89.5% in scenario 1.

The calculated SSR for values are notably low. However, this is to be expected when considering that the analysis focuses solely on low-voltage grids with PV-plants as the single energy source. Low-voltage grids inherently exhibit a high degree of dependency on external energy suppliers, a characteristic that is also shown by [13] and [46]. The

TABLE 9. **Field test results for SSR (%) per test case.**

Test Case	SSR (%)
1	89.5
2a	51.2
2b	52.2
3a	51.3
3b	54.9

discrepancy between test case 1 and the other test cases can be attributed to the timing of the scenarios. Specifically, test cases 2a to 3b take place later in the day, during periods of lower PV production and higher energy consumption. Thus, more energy needs to be obtained by the external energy supplier.

5) FLEXIBILITY-COSTS OF THE DSO

During a flexibility market, prosumers on the PEAK platform charge a price $p_{match,n,t}$ in €/kW for the provision of flexibility capacities with which a DSO can compensate grid congestion. The KPI Total-Price-Flexibility (TPF) quantifies the costs for the flexibility, considering the matched flexibility $f_{match,n,t}$ in kW and the corresponding price paid by the DSO for the matched flexibility for prosumer n at time period t.

$$TPF = \sum_{t=0}^{T} \sum_{m=1}^{M} f_{match,m,t} \cdot p_{match,m,t} \tag{21}$$

This KPI is evaluated only for test cases in which the flexibility market is enabled, and flexibility matches occur, specifically test cases 2b and 3b. The results show an average TPF of 8.19€ in test case 2b and 7.21€ in test case 3b, both for a time period of four hours.

The TPF serves as an indicator for assessing costs associated with flexibility provision from the perspective of the DSO by considering both the amount of matched flexibility and the corresponding costs. The results from test cases 2b and 3b demonstrate the varying average TPF values. These variable TPF figures enable DSOs to more accurately assess whether investing in grid expansion is more cost-effective than purchasing flexibility.

Further investigation can contribute to the understanding of how prosumer-driven flexibility impacts the financial considerations of DSOs. A comparison with alternative measures, such as grid expansion or the implementation of central storages operated by DSO, could lead to insights for pricing strategies.

VI. DISCUSSION

The paper introduces a platform that integrates a P2P energy market, a market-based approach for preventive congestion management, and curative congestion management mechanisms. Additionally, the paper showcases the results of various test cases to demonstrate the platform's functionality and quantify its performance.

In the analysis of prosumer profits and energy pricing, only a variable rate between 0.08 €/kWh and 0.36 €/kWh is considered. Notably, a detailed breakdown into components such as grid charges has not been conducted in this study. The PEAK platform, as demonstrated, is only functional in real-world voltage grids when equipped with the appropriate smart meter infrastructure. Additionally, each prosumer needs to have a prosumer-agent implemented for the system to operate as intended.

It is important to note that the platform's conceptual framework does not account for nowadays barriers facing prosumers in becoming active market participants, as discussed in [82]. Especially nowadays taxes, duties, and levies would render local energy platforms economically unviable for prosumers in Germany.

Furthermore, the outcomes of this analysis are highly contingent upon the integration and size of PV-plants as well as energy storage capacities. The primary findings suggest that P2P energy markets not only offer financial benefits to prosumers but also contribute to effective congestion management. It has been shown that prosumers with PV-plants profit to a much larger extent from such a P2P market than those without respective infrastructure. In addition, the energy price prosumer-agents pay having the same hardware differ as well, which is because of the low number of market-participants. Another limitation of the market is that every energy amount bidden or ask at the energy market is matched. Thus, the prosumer-agents only have limited possibility to react to current market situation. Their primary metric for gauging the current market situation is the order-book values.

In addition, prosumer having a battery gain financially less than households without a battery. The FGP metric, however, only illustrates the monetary gains from P2P trading. Since prosumer-agents with a battery directly charge it with surplus energy, they achieve a higher level of autarky. As a result, they are less active on the energy market compared to households with limited energy storage capabilities.

The study also reveals that the two-stage market introduces the potential for increase-decrease gaming. In increase-decrease gaming, prosumer-agents bid strategically on the market so that they intentionally increase their electricity consumption in order to provoke a grid congestion. If a grid congestion is forecasted, the prosumer-agents can reduce their electricity consumption again by offering their flexibility and are remunerated for the flexibility offered.

However, the implemented prosumer-agents aren´t equipped with such manipulating market-strategies, thus, no measure for prevention is implemented.

Furthermore, the implementation of SSI preserves prosumers privacy on a public, distributed market-platform while at the same time providing all legally required identity information.

The platform demonstrates a high degree of adaptability to various electrical grid infrastructures, contingent upon the provision of network topology in the pandapower format. The modular construction of Agent.Workbench further facilitates the effortless integration of additional prosumers or energy systems into the grid, underscoring its flexible and scalable nature.

Furthermore, the platform is designed to be responsive to regulatory fluctuations. Minor regulatory alterations, such as increments in energy taxation or revisions to the ceiling of energy prices, can be readily accommodated by simple parameter adjustments within the platform's configuration. However, substantial regulatory modifications that affect the market structure pose a greater challenge, necessitating a more comprehensive engineering response to align the platform with the new regulatory framework. This delineation of adaptability highlights the platform's capacity for quick adjustment to a spectrum of regulatory environments, although with varying degrees of engineering intervention.

The platform contributes to decarbonisation in several significant ways: Primarily, the platform supports the decentralization of the energy market by enabling P2P energy trading by incentivizing the local production and consumption of renewable energy. This shift encourages communities and individuals to become both consumers and producers thereby reducing reliance on centralized, fossil fuel-dependent energy generation and advancing decarbonization efforts.

Furthermore, by leveraging automated and market-based grid operations that adapt to fluctuating grid states, the platform optimizes the distribution of electricity. This not only enhances the efficiency of the grid but also indirectly contributes to decarbonization by reducing transmission losses and, consequently, diminishing the overall energy demand from carbon-intensive generation sources.

Thirdly, the platform's sophisticated forecasting tools enable the more effective integration of renewable energy sources into the grid. With better predictions of renewable output, grid operators can plan accordingly, ensuring that renewable energy sources are used to their fullest potential, thus minimizing the need for backup power from fossil fuel plants and further supporting emission reduction.

However, implementing a P2P energy market and flexibility market introduces a complex array of challenges concerning market dynamics and regulatory compliance that must be navigated with precision.

Market liquidity and participant engagement emerge as significant determinants of a successful P2P market deployment. A liquid market with robust participation is essential to facilitate efficient energy transactions and price discovery mechanisms. Therefore, strategies aimed at incentivizing a diverse range of market participants are critical. Such strategies may include, but are not limited to, subsidies for renewable installations and the implementation of energy tariffs that more accurately internalize environmental externalities. These measures could stimulate broader market engagement, ensuring the requisite dynamism and resilience of the P2P market.

In addition, the integration of P2P and flexibility markets with traditional energy systems requires careful orchestration. This integration involves establishing clear protocols for interactions between various market actors and ensuring that emerging P2P markets are complementary to existing structures, rather than disruptive. The intricacies of this integration must be addressed through thoughtful policy and regulatory measures that not only promote seamless market operation but also bolster the resilience and reliability of the overall energy system.

Regulatory challenges regarding the implementation of P2P markets are discussed in [82].

VII. CONCLUSION

This paper presents a concept for an innovative energy trading platform with SSI-based privacy. It marks a promising solution for the challenges of future, decentralized and complex grid control. Financial benefits are offered to participating prosumers in P2P energy markets, thereby accelerating the transition to a more sustainable and decentralized energy ecosystem.

Grid reliability is ensured by the concept of automated and market-based grid operating, designed to adapt to various grid states which are incorporated into the platform. Current-related grid congestions can be effectively forecasted and managed by market-based mechanisms integrated into the system. However, voltage-related grid congestions are identified as being more challenging to be managed and controlled through market-based approaches alone.

Intelligent strategies for profitable participation in both the electricity and flexibility markets are provided to prosumers. The democratization of the energy landscape is thus significantly advanced. Accurate estimates and forecasts of grid states are made possible by the platform, providing essential information for decision-making to stakeholders ranging from individual consumers to large grid operators.

Security and privacy are prioritized, ensuring that all trading activities are conducted in compliance with prevailing privacy regulations. Trust among the user base is thereby fostered, and ethical and responsible operation of the platform is assured.

In conclusion, a scalable, adaptable, and robust solution for the challenges of a rapidly transforming energy sector is offered by the proposed platform. Such platforms will play a critical role in shaping a more sustainable, efficient, and inclusive energy future as the ongoing revolution in energy production, distribution, and consumption continues.

In future research, scaling the platform to cover multiple low-voltage grids in addition to a medium-voltage grid is conducted. In this expanded setting, the values for system SSR and FGP will also be surveyed to elaborate the scalability of the platform. Further performance indicators will be needed in these broader contexts. Furthermore, a distinct examination of curative congestion management will be conducted to validate its functional efficacy. This testing is crucial for substantiating the platform's capabilities in real-world congestion scenarios. Moreover, resilience against manipulative activities is another avenue that is being explored. Specifically, the SSI concept will be subjected to further testing to assess its robustness against manipulative actions.

TABLE 10. **Functions of the different Agents.**

No.	Function	Assigned to agent
F1	Identify grid congestion: Monitoring network parameters to identify and forecast grid congestion before it impacts stability.	grid-agent
F2	Identify sensitivity of prosumer-agent to the identified grid congestion.	grid-agent
F3	Create flexibility request for the most sensitive prosumer-agents.	grid-agent
F4	Executes real-time curative redispatch actions to address grid congestion which couldn´t be addressed by the flexibility market.	grid-agent
F5	Handling the validation and authentication of prosumer-agents, grid-agent, and market-agent, safeguarding the system's integrity and security.	platform-agent
F6	Facilitating interaction among entities by providing communication addresses.	platform-agent
F7	Match energy requests and offers send by the prosumer-agents.	market-agent
F8	Match flexibility requests and offers of grid-agent and prosumer-agents.	market-agent
F9	Provide market details for the prosumer-agents.	market-agent
F10	Estimate and forecast own energy balance.	prosumer-agent
F11	Generate energy request and offers and submit it on the energy market	prosumer-agent
F12	Manage assets efficiently according the own energy plan and market results.	prosumer-agent
F13	Identify the own flexibility availability for participating at the flexibility market.	prosumer-agent
F14	Create flexibility offers to respond to grid-agent´s flexibility requests	prosumer-agent

Furthermore, for the practical deployment of the platform within the grid infrastructure, the development of a user-friendly interface is essential. This will be a focus of subsequent research and development efforts.

Additionally, future research will include economic investigations to assess the financial benefits for all participants involved.

APPENIX

See Table 10.

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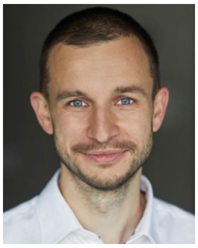

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