Towards ICT-Enabled Multi-agent Based Operations in Local Energy Communities: A Proof of Concept

Haoyu Huang[1(✉)], Natascha Fernengel[2], André Xhonneux[1], Alexander Holtwerth[1], Michael Hehemann[3], Eugen Hoppe[3], Simon Waczowicz[2], Kevin Förderer[2], Veit Hagenmeyer[2], and Dirk Müller[1,4]

[1] Institute of Energy and Climate Research, Energy Systems Engineering (ICE-1), Forschungszentrum Jülich GmbH, Jülich, Germany
h.huang@fz-juelich.de

[2] Institute for Automation and Applied Informatics (IAI), KIT, Karlsruhe, Germany
natascha.fernengel@kit.edu

[3] Institute of Energy and Climate Research, IET-4: Electrochemical Process Engineering, Forschungszentrum Jülich GmbH, Juelich, Germany

[4] Institute for Energy Efficient Buildings and Indoor Climate, E.ON Energy Research Center, RWTH Aachen University, Aachen, Germany

Abstract. The growing decentralization of energy systems requires scalable, flexible coordination of distributed generation, energy storage, and demand-side flexibility among local energy communities. This work builds upon the agent-based scheduling framework MASSIVE, extending its capabilities to operate in real-world settings. Within the extensive framework, agents participate in the local electricity market by submitting bids based on operational constraints and preferences of local energy components or aggregates, such as a campus. Optimized setpoints derived from market clearing are sent as control signals to physical or simulated assets. To enable the transmission to be modular, interoperable, and responsive in real time, we extend the MASSIVE framework with a lightweight, MQTT-based layer. We validate the applicability of these control signals through a series of experiments involving real hardware and technical and safety constraints. Additionally, a geographically distant battery system was incorporated in real time and it effectively followed market-driven setpoints. The results confirm that a decentralized, agent-based market coordination model facilitates flexible integration of physical energy systems. Plug-and-play functionality, heterogeneous control strategies, and interconnection across regions are collectively offered by the framework, thereby providing a robust path to smart energy communities.

Keywords: Decentralized Optimization · Multi agent system · Local energy community · Market-based Coordination · Smart area · Real world hardware connection · Cloud based optimization

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1 Introduction

The concept of local energy communities (LECs) in Europe is undergoing a steady increase in its prevalence. By 2030, LECs are expected to possess up to 21% of installed solar- and 17% of wind-capacity [4]. However, this growing decentralization poses significant challenges for local grid stability, especially as traditional distribution networks were not designed for high shares of bidirectional energy flow [20].

A key notion introduced to address this challenge is flexibility, which describes the ability of a system to adapt generation or demand in response to expected and unforeseen fluctuations [1]. Flexibility is particularly important in LECs, where coordinated actions such as load shifting, energy storage, or curtailment can help maintain balance and support grid resilience [6].

Coordinating these flexibility potentials requires appropriate control strategies. Centralized approaches formulate the entire community as a single optimization problem, aiming for globally optimal solutions. Although this method is effective in smaller systems, there is a limit to its scalability when it comes to more complex systems involving greater participation [35]. Consequently, it often becomes impractical for real-world applications [23].

To overcome these limitations, research has shifted towards decentralized optimization, for which local subproblems are solved independently by each system element. This not only reduces computational effort but also supports modularity and system scalability [13]. In this context, we use the term component to refer to any logical aggregation of sensing, control, and actuation capabilities that can make autonomous decisions. This may represent a building-level system, renewable generation, or a storage unit. When equipped with real-time metering, sensors, and communication capabilities, such components can autonomously monitor their operation and interact with other entities within the smart energy community [7].

These capabilities enables market-based coordination, in which components respond to price signals to optimize both local objectives and system-wide outcomes. Properly designed local energy markets have the potential to align individual incentives with social welfare, supporting the transition toward a more sustainable, decentralized energy system [23,33].

This work builds upon a previously developed framework, Multi-Agent Scheduling Solution In a Virtual Environment (MASSIVE) [11]. Within the MASSIVE framework, each autonomous agent represents one or more energy components and handles communication and forecasting. Local optimization is utilized for components with flexibility potential. These agents collectively form a multi-agent system (MAS) that enables decentralized, market-based coordination [21].

For rapid experimentation, the framework initially integrated agents and the local energy market within a monolithic simulation script executed sequentially under perfect foresight, thereby constraining its utilization to theoretical studies. Despite the implementation of an Message Queuing Telemetry Transport (MQTT)-based communication layer to support future deployment modes, initial research remained in the tightly coupled version. In this work, the communication layer is adapted for real-time operation and validated under real-world conditions with live message exchange.

This study investigates the following research questions:

- To what extent can market-based multi-agent coordination enable reliable energy balancing across distributed resources in real-time settings?
- What role does MQTT communication infrastructure play in enabling scalable and flexible agent interaction?
- How accurately can market-cleared setpoints be applied to physical hardware, and what constraints must be considered in practice?

To explore these questions, we implement and evaluate a proof of concept by making use of the extended MASSIVE framework. Our contributions are demonstrated through a stepwise validation process, including simulated agent interaction, hardware validation with market-derived control profiles and the real-time market participation of a remotely located physical battery storage system.

This paper is structured as follows: Sect. 2 presents and distinguishes related work and the current state of technology. In Sect. 3, the infrastructural basis of our experiment is introduced. In Sect. 4, the architecture of the MASSIVE framework as well as the tools and infrastructures that were used are laid out. In Sect. 5, the results of the experiments are presented. These results are interpreted and discussed in Sect. 6. Section 7 concludes this work and motivates for future work building on the proof-of-concept presented in this paper are explored.

2 Related Work

In the early stages of research on multi-agent systems (MAS), McArthur et al. [21] proposed the utilization of MAS in power engineering in 2007. Kumar Nunna et al. [18] developed a model for a virtual energy market for microgrids, introducing a two-level agent architecture to analyze supply–demand mismatches among distributed energy resources. Focusing on increasing energy self-sufficiency in communities, Reis et al. [27] and Prasad et al. [25] applied MAS to coordinate energy communities. Prasad et al. [25] integrated deep reinforcement learning to examine cooperative behavior among buildings, while Reis et al. [27] used real-world data to explore fair cost and benefit allocation within communities. Stennikov et al. [31] extended the MAS modeling framework to encompass centralized generation, thereby facilitating analysis of the interaction between centralized and distributed energy generation. Open-source MAS frameworks, including AMES [19], AMIRIS [28], and ASSUME [12], facilitate a thorough examination of energy wholesale market coordination. The aforementioned frameworks are lacking at this time in the incorporation of physical assets. In order to facilitate real-time control, it is necessary to implement communication protocols that are well-suited to distributed and time-sensitive energy systems. In their 2017 study, Ozgur et al. [24] implemented an MQTT-based framework to coordinate remote cyber-physical testbeds. This implementation demonstrated the framework's resilience under cyber-attack scenarios. Jamborsalamati et al. [17] developed a hierarchical MQTT-enabled architecture for autonomous resource allocation and grid demand reduction in smart areas. Estebsari et al. [9] proposed a real-time coordination schema for distributed energy resources and used MQTT as a communication adapter to facilitate interaction between aggregators and system operators. Despite the limitations of the studies, which rely on simulation or restricted testbed validation, they collectively underscore the aptitude of MQTT for real-time, scalable control in distributed energy systems [8].

Conversely, the FlexQGrid project conducted a field experiment in a residential neighborhood, examining household participation in a quota-based demand response program [30]. However, FlexQGrid did not prioritize component-level optimization or incorporate sector-coupling technologies, such as hydrogen storage, which are imperative for achieving seasonal flexibility.

3 Research Environment

Functioning as a LEC, the Living Lab Energy Campus (LLEC) at Forschungszentrum Jülich Germany (FZJ) serves as a flexible testbed for the exploration and evaluation of innovative monitoring and control solution for district energy systems such as LEC with a high share of renewables [2]. Beyond the shelf components, the LLEC hosts multiple advanced technologies for the conversion and storage of energy to explore cross-sectoral flexibility. This includes a low-temperature district heating network with heat pumps and associated thermal storage, large-scale battery energy storage systems and a hydrogen energy infrastructure that encompasses production, storage, and reconversion. The hydrogen infrastructure comprises e.g. a 400 kW proton exchange membrane (PEM) electrolysis test stand, which is capable of investigating different stacks, ranging from in-house developed to commercial products, to characterize their distinct electrochemical behaviors [8]. The test bench employs a programmable logic controller (PLC) from Beckhoff. This controller facilitates the integration of electrolysis into comprehensive energy system test series. In these test series, setpoints are derived from model-based controllers executed in the cloud, enabling a sophisticated and interconnected approach to energy system testing. [8]

However, to effectively utilize this potential, automated, data-driven decision-making is required to determine when and how much of each form of flexibility should be used [3]. This decision-making process starts with internet of things (IoT)-based status monitoring of components in the smart area [26], which generates a rich data set to support demand forecasting. Based on this data, energy management systems coordinate the optimal use of waste heat in the low-temperature district heating network [32] and the optimal interplay of short-term and seasonal storage [14]. A variety of control strategies are used to support this process, ranging from rule-based control to model predictive control (MPC) [15]. The interoperability of components using different field-bus protocols is enabled by a FIWARE-based information and communication technology (ICT) platform [34], which facilitates local integration and interaction between LECs.

To support cross-regional coordination, geographically distributed co-simulations enable the assessment of LEC flexibility and their dynamic impact on system stability under realistic conditions [5,22]. At the Karlsruhe Institute of Technology (KIT), a FIWARE Context Broker is hosted to establish a network that connects research centers by exchanging energy data in real time. In collaboration with the German Aerospace Center (DLR) and FZJ, a simulation and testing process is underway for renewable energy generation and storage in future energy systems. This process utilizes real consumer data within the EnergyLab at KIT. In this study, the FIWARE-based data collection functionality was subjected to evaluation during a live test.

4 Methodology

This section delineates the fundamental components of the MASSIVE framework for decentralized coordination in LECs. The methodology is built around three core components. First, the agent architecture models components as autonomous units capable of local optimization and decision-making. Second, the market design facilitates coordination and interaction between agents through market-based mechanisms. Third, the ICT infrastructure provides the real-time communication backbone that connects agents and the marketplace, ensuring seamless data exchange and operational responsiveness. At the end, the setup of the experiment in this paper is explained.

4.1 Agent Modeling and Roles

In order to determine the offer of agents to purchase energy from the local electricity market, it is necessary for each agent to initially generate a power profile forecast of its component. Within the MASSIVE framework, the configuration of such simulation models is facilitated by the utilization of human-readable files, thereby enabling the instantiation of agents as digital twins when provided with real-time input data. The forecasts can be model-specific, as in the case of a photovoltaic (PV) system. For a campus agent, forecasts are derived from the aggregation of multiple simulation results.

Two types of agents are introduced in our architecture. The first type functions primarily as data analyzer, translating real-time environmental data (e.g., ambient temperature, solar irradiance, wind speed) from German Weather Service (DWD) into forecasts of building heat demand or renewable generation. This facilitates the capacity of agents to dynamically adapt to external conditions. The second type of agent not only forecasts their own demand, but also determines and utilizes the flexibility potential of its components (e.g., thermal storages, battery systems, controllable loads) by optimizing the their operation to minimize costs in response to local dynamic price signals. In doing so, they generate time-resolved power profiles that reflect the physical constraints of the system.

Agents are further classified into three categories based on their market behavior. Consumers, such as office buildings, cover their electricity demand exclusively by submitting bids to the marketplace, as power supply contracts are not considered in this study. The second group comprises pure generators, including renewable sources such as PV panels and wind turbines, as well as the public grid itself, which acts as a balancing source during periods of insufficient local generation. The third group is defined as "active prosumer", which is characterized by its dual capacity to consume and produce energy. These may operate energy storage systems (e.g. batteries or hydrogen storage systems) to engage in energy arbitrage, buying energy when it is cheap and selling it when prices are high.

4.2 Market Design and Clearing Mechanism

In our framework, agent coordination is enabled through market-driven scheduling that operates on a 15-min clearing interval, reflecting the structure of real-world intraday markets such as EPEX Spot Intraday. The market is cleared using the merit-order principle, in which bids are prioritized based on price to balance supply and demand [29]. For each clearing interval, the market compiles the bids from the agents, which represents the energy demand or supply for the subsequent 24 h. At the core of the market-driven scheduling is a linear optimization problem, which processes all collected bids to compute the optimal energy allocation for each clearing interval. Its objective is to minimize the overall operational cost of the LEC, while determining a corresponding market-clearing price for each timestep.

To focus the study on the coordination logic and flexibility aggregation, no bidding strategy is applied within the individual agents. Rather than implementing dynamic or strategic bidding behavior, each agent uses a fixed price for demand and supply. These values remain constant throughout the simulation. This simplification ensures that market outcomes solely reflect the effects of system-level optimization and agent coordination, rather than being influenced by complex or competitive bidding strategies. Despite the use of fixed prices, the market still produces dynamic clearing results, including fluctuations in market price that arise naturally from changing load and generation conditions. This demonstrates that the market design remains responsive and effective in coordinating distributed energy resources, even using simplified bidding strategies.

4.3 Agent Communication Framework

To enable structured and scalable communication within the LEC, a lightweight communication layer is used that is based on the MQTT protocol. In line with MQTT's publish/subscribe architecture, agents submit their bids by publishing to predefined topics. In order to protect the privacy of its users, agents are not able to communicate directly with each other or accessing data from other agents. Instead, all agent messages are routed exclusively through a centralized marketplace module that functions as the sole subscriber to agent outputs. At the end of each market-clearing interval, the marketplace publishes the resulting clearing prices and individual load profiles to agent-specific topics.

For direct communication between agents and the energy market, we rely solely on the MQTT protocol to minimize system complexity, reduce latency, and maintain high responsiveness, which are key requirements for real-time market interaction. Beyond the lightweight MQTT communication, we also enabled integration with a FIWARE-based ICT platform for data transmission from hardware to agent. FIWARE [10] offers advanced functionalities such as data contextualization, orchestration, security, and analytics. In the scope of this work, each campus operates its own instance of the ICT platform to collect sensor data from its assets.

In the initial version of the MASSIVE framework, a handshake mechanism was developed to support modularity and runtime flexibility. This mechanism enables agents to dynamically join the market [16]. Upon startup, an agent sends a registration message containing essential metadata to the marketplace that includes the agent in the upcoming market-clearing optimization. Similarly, a deregistration process allows agents to gracefully disconnect from the system. When an agent leaves, it sends a deregistration message, prompting the marketplace to remove its entry from the participant list, thereby ensuring that outdated or inactive agents do not affect future market rounds.

Furthermore, the agents were modularized and containerized using Docker, and each was deployed on an OpenStack-based virtual machine. This architectural shift enabled distributed and parallel execution, continuous runtime, and clear separation between agents and the marketplace instance, thereby supporting both scalability and realistic event-driven message exchange.

Together, these mechanisms enable plug-and-play functionality, allowing agents to be added or removed at runtime without restarting or reconfiguring the entire system. This real-time communication infrastructure provides a robust foundation for coordinating distributed components, and it also supports hardware integration, enabling direct control of physical devices using market-cleared setpoints.

4.4 Experimental Setup

The validation of the proposed decentralized, agent-based coordination framework was carried out in a hybrid experimental environment, combining purely simulative and real-world components. In the interest of simplicity, the grid constraints are not taken into consideration. Figure 1 illustrates the overall structure of the experimental setup.

At first, we established a setup of purely simulative component agents to the market environment. These components included an PV, electric vehicle (EV), building with heat pump, battery energy storage agent and a campus agent (FZJ Agent), which comprises multiple selected components of the FZJ campus. In agents such as the PV agent, bid generation is performed internally

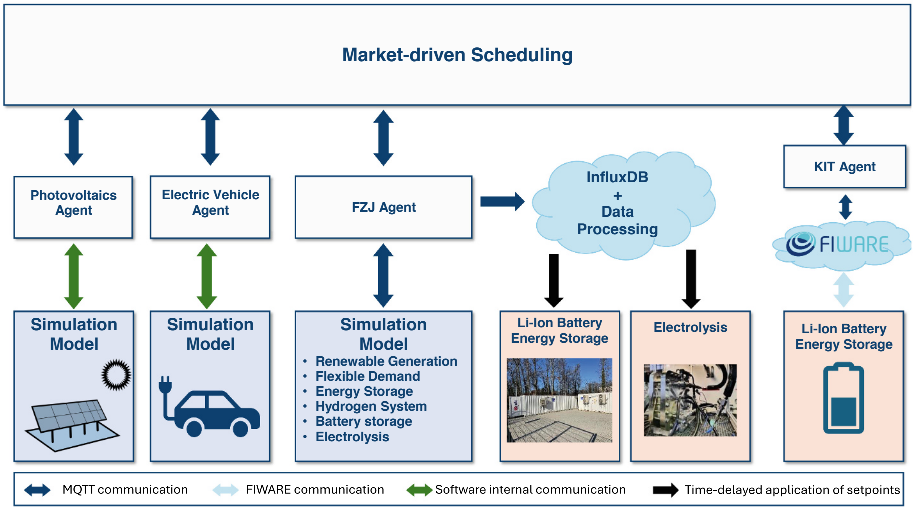

Fig. 1. Excerpt of experimental setup (not all simulative agents are shown)

and the resulting bids are communicated to the marketplace via MQTT. To reduce the solving time, the FZJ agent makes use of the controller as proposed in [15]. For bid generation, FZJ agent aggregates simulation results from multiple models using MQTT-based communication. A grid agent, representing a backup capacity (not displayed in the Fig. 1), is added to make sure that the market clearing is always solvable.

In the second step of the validation process, selected load profiles were applied to physical devices. These agents were modeled using physics-based simulations that closely reflected real hardware deployed on the campus. The application of setpoints was time-delayed, and there was no live connection between the market and the hardware. In our study, a PEM electrolysis system and a lithium-ion battery storage system were used to validate the feasibility of executing the market-cleared load profiles under real operational constraints. To ensure that the new legal requirements for cyber security (e.g. IEC 62443 series) are met as effectively as possible in the future, data transmission within the virtual local area network (VLAN) of the Jülich campus network was implemented and secured with a certificate.

In the third step, to demonstrate the validity of market derived load profile for hardware control, a live connection was established between the MASSIVE framework and a BESS located within the Energy Lab at KIT. The system under test consists of seven lithium iron phosphate battery modules, delivering a usable capacity of 15.4 kWh, and includes a battery management system, an energy management system, and an inverter.

The generation of bids for physical devices was accomplished through the utilization of a customized digital twin, which was configured using the configuration file embedded in the MASSIVE framework. The optimization process was extended to incorporate real-time feedback from the physical system, allowing MPC to respond dynamically to the battery's actual performance, while also accounting for both calendric and cyclic battery aging.

Once a schedule was determined by the market-clearing process, the load profile was translated into setpoints, which were periodically transmitted to the BESS via an MQTT–Modbus bridge developed at the Energy Lab. The agent and the adapter integrating the battery's measurements into the FIWARE-based ICT platform were both containerized using Docker and run in Kubernetes to ensure stability and deployability.

At the same time, using mainly MQTT for data transport, the current state of charge and active power measurements of the battery were used to update the corresponding battery entity in the FIWARE-based ICT platform, which also stores the data in an InfluxDB database. To ensure that the model of the battery and the physical system stayed in alignment, the state of charge was also fed back into the agent to update the battery model before each optimization.

5 Results

This section presents the results of a stepwise validation workflow designed to evaluate the real-world applicability of the proposed MASSIVE framework. The validation process is carried out across three stages of increasing system realism. First, we demonstrate real-time interaction among simulated agents connected via the ICT platform, validating the communication architecture and decentralized coordination mechanism over multiple weeks. Next, we evaluate whether market-cleared setpoint trajectories can be applied to real hardware components under controlled test conditions. Finally, we establish a live connection between market and physical devices, assessing the complete system in a field test.

5.1 Step 1: Simulated Agents

In this subsection, we evaluate the behavior of a simulated agent representing a PV system within our decentralized market framework. The PV agent offers its full generation potential based on the weather forecast to the market at each time step. Based on the agent's internal configuration and real-time weather data, it generates a 24-h forecast with a resolution of 15-min. The purpose of this test is to demonstrate the ability of the framework to handle intermittent renewable generation and apply curtailment when necessary through market-based coordination.

Figure 2 presents a comparison between the offered and realized power outputs of the PV agent over two consecutive days. The offered power (yellow curve) represents the maximum generation potential as the weather forecast, calculated using irradiance data and the technical capacity of the PV system. The realized power (green curve) shows the actual dispatched output as determined by the

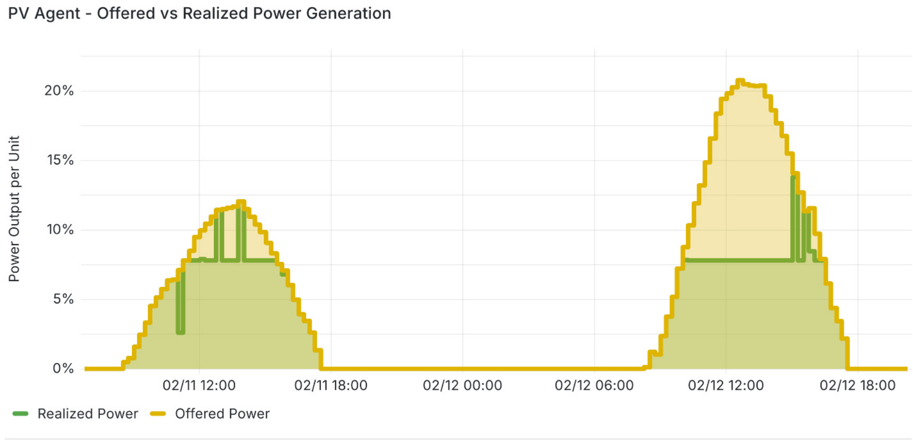

Fig. 2. PV power output - offered power (yellow) vs. actually used power (green) (Color figure online)

market-clearing process. While the offered profile follows the expected solar production curve, the realized output is frequently capped below the maximum, especially during midday peaks. This behavior is evident on both February 11 and 12, where flat-topped plateaus in the realized output indicate intentional curtailment initiated by the marketplace.

5.2 Step 2: System Response to Exemplary Market-Cleared Setpoint Trajectories

In this section, we focus on the evaluation of real-world hardware behavior. The objective of this stage is to determine whether physical components can accurately track market-cleared setpoints under real-time conditions while adhering to component-specific safety constraints.

Despite the utilization of a physics-based simulation model for signal generation, their execution was subject to stringent oversight, necessitating manual adjustment of load profiles to ensure adherence to operational constraints. This included ramp-rate smoothing and exclusion of restricted operating zones, depending on the device.

The initial live test utilized a PEM electrolysis apparatus with a commercial stack that was under development. As part of the assessment, a 9-h profile was applied, which was generated by FZJ agent following the market clearing process. In consideration of the device's operational requirements, particularly with regard to current ramp rates, the original market output was subjected to post-processing to ensure that the current gradient remained below a certain value.

Figure 3 illustrates the behavior of the electrolysis system during a live test conducted on February 6–7, 2025. The red markers represent the original setpoints issued by the market-based coordination framework, which were based on

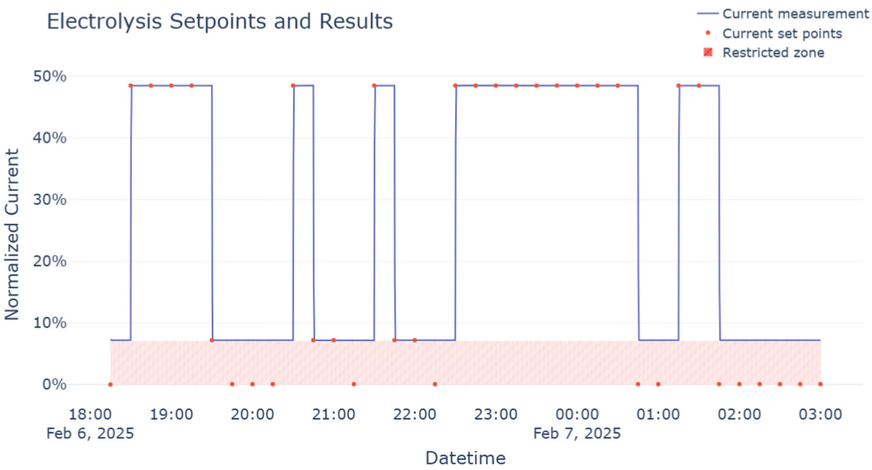

Fig. 3. Setpoints vs. system response of PEM electrolysis (Color figure online)

an optimization not including the minimal part-load, while the blue line shows the measured current response of the electrolysis. To reflect operational safety guidelines, a restricted operation zone (highlighted in red) was defined below a certain normalized current threshold.

A second live test was performed using a large-scale battery storage system (BESS) of LLEC, which was subjected to an excerpt of the power profile determined by the initial tests with the multiple agents. Although detailed technical specifications of the hardware systems cannot be disclosed, all evaluations were supported by a dedicated data acquisition pipeline based on the ICT platform. Measurements were recorded per second and stored in a cloud-hosted InfluxDB database for subsequent analysis.

5.3 Step 3: Real-Time Connection

In this section, the behavior of a second campus agent (KIT Agent), that was deployed to represent a battery system located at KIT, is evaluated. This agent was integrated into the existing setup, establishing a live connection between the market and the real hardware.

This experiment was carried out over several days. The power measurements and the battery's state of charge over the course of 14 h can be seen in Fig. 4 alongside the schedule that the agent received from the marketplace. Here, the active power measurement as well as the scheduled setpoints are displayed in Watt, with negative values indicating charging, and positive values indicating discharging of the battery system.

At the start of the experiment the battery's SOC was 38 %. After a period of neither charging nor discharging, it was then charged with up to 1 kW starting at 7 pm, and then discharged continually during most of the night, with up to

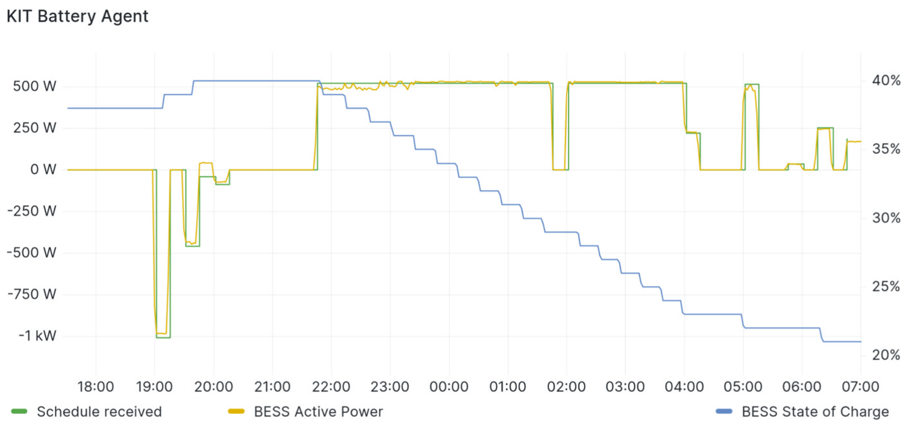

Fig. 4. Active power and state of charge of BESS, alongside the load schedule received from MASSIVE's marketplace.

500 W. In the morning, periods of inactivity widen and it is only discharged sporadically with 250 W and less. This leaves the BESS with a SOC of 21 % at the end of the experiment.

The measured power values follow the determined schedule closely with a deviation around 35 W occurring only in one timestep in this time frame, and smaller deviations occurring shortly after the battery received a new set-point. Some deviations were expected using this BESS, and overall the observed response was reasonably precise and timely.

As can be seen in this graph, the battery is charged in the evening, when there is still some PV production, just before sundown, and discharged during the night. This results in a reduction of the time between charging and discharging, thereby minimizing losses due to self-discharge over time. In this time frame, the battery is charged up to only 40 % of its total capacity. Charging unnecessarily, which can lead to battery degradation and potential loss of capacity was avoided. This is consistent with the optimization we used, which incorporates parameters such as self-discharge, charging losses and battery aging.

6 Discussion

In this section, the results of the three validation steps will be interpreted and discussed. Additionally, we explore the practical considerations involved in hardware integration, with a particular focus on safety and operational constraints.

6.1 Interpretation of Results

In step 1 (Simulated Agents), the behavior of simulated agents within our decentralized market framework was observed, including varied agents representing

PV and wind systems, battery storage and heat pump-controlled buildings as well as an aggregate agent representing a selected section of the LLEC setup at FZJ. An experiment including an agent representing a PV system shows the offered profile following the PV forecast with most capping occurring around midday, as can be seen in Fig. 2. Thus the capability of the framework to actively curtail PV output when required by system-level constraints or market conditions was demonstrated. Furthermore, the ability of the agent-based market mechanism to integrate fluctuating renewable energy was confirmed.

In step 2 (Hardware reply to predefined load profile), real-world hardware was included and its behavior within our simulated agent framework was observed. In order to ascertain the viability of physical devices in adhering to market-cleared setpoints, a 9-h profile generated by an agent was applied to a PEM electrolysis. The results demonstrate that the electrolysis system is capable of accurately tracking discrete setpoint changes, maintaining stable operation during activation phases and returning to baseline output during inactive periods. The findings indicate that market-based control signals generated by the MASSIVE framework can be effectively followed by relatively slow-responding hardware, such as the electrolysis system, while adhering to safety constraints. However, it also highlights the importance of incorporating such safety restrictions during the design and calibration of the simulation model to ensure realistic and executable control behavior. A second live test using a battery storage system also demonstrated stable and accurate tracking, indicating that market-cleared dispatch signals can be executed reliably by storage assets.

In step 3 (Real-time connection), a physical system was included in real-time, controlling a BESS in a live connection within the MASSIVE framework. A live connection between geographically distributed agents and physical devices was successfully established, confirming the feasibility of the complete system in a field test. Through this experiment, which was running over multiple days with timely and correct responses from the BESS to the scheduled setpoints, it was demonstrated that the resulting control signals are adequate to apply on real-world hardware. Furthermore, the load schedule as an optimization result was reasonable and well-suited for the battery system, taking into account the system's specifications. While this demonstrates the feasibility of using this framework in a live connection, this validation step was only done using a single component. To further validate it, this experiment should be expanded to include more both real-world and virtual components over a longer time-span.

Overall, the outcomes of this research have demonstrated the applicability of the proposed framework. Not only were we able to demonstrate real-time interaction among simulated agents connected via the ICT platform over multiple weeks, validating the communication architecture and de-centralized coordination mechanism. By establishing a live connection between geographically distributed agents and physical devices, we confirm the feasibility of the complete system. It has been demonstrated that market-cleared setpoints derived from optimization can be followed by real hardware components.

Given the prototypical configuration of the framework, the present outcome merely substantiates the feasibility of implementing an ICT-connected MAS for LECs.

6.2 Practical Challenges of Hardware Integration

Maintaining the safety of energy systems such as electrolysis, which pose explosion and pressure risks, is a challenge when developing integrated energy systems. It is important that the developers of the software and the system technology work well together to ensure compliance with safety-relevant and operationally limits, even during operation via the ICT platform. For the electrolysis, these requirements have been jointly integrated into the communication protocols by hardware operator and software developer, and then implemented by the manufacturer in the PLC's MQTT interface program.

It is also imperative to implement additional safety limitations in future developments. For example, configurable limits for electrolysis can be specified within the test stand, customized to the specific stack installed. It is important that these limits should not be override via the MQTT interface. Furthermore, the automation of start-up and shut-down processes, in conjunction with the behavior of the electrolysis with respect to current changes, should be considered in subsequent development.

6.3 System-Level Considerations

This study substantiates the viability of coordinating LECs through market-cleared load profiles and the adaptability of these profiles to physical hardware. However, the validation remains constrained in scope. The evaluation was conducted on a standalone basis, encompassing a single BESS and electrolysis, and the outcomes were applied exclusively over brief time frames. Consequently, the system's behavior concerning larger-scale participation and seasonal dynamics remains to be explored. To address this, future work should expand the number of simulated agents. The efficiency of the central market instance in MASSIVE ensures the computational tractability of simulations involving thousands of agents [11]. Additionally, the incorporation of supplementary real hardware will introduce realistic uncertainty and facilitate the testing of agents with more complex optimization strategies, such as MPC.

A further crucial constraint lies in the utilization of a simplified grid model, which assumes unrestricted power flows. To capture grid constraints, the MASSIVE framework's multi-round clearing feature can be adapted to account for capacity prices [11]. An additional clearing round could reflect distribution limits, with the grid agent raising capacity prices during congestion to influence market outcomes accordingly.

Adopting these measures will enable the system to evolve in a more realistic direction, thereby ensuring its applicability for broader implementation in future smart energy infrastructures.

7 Conclusion

Increasing penetration of renewable energy sources necessitates the provision of flexibility, which can be offered by energy communities and smart areas. In this work, we propose a decentralized agent-based control framework using a market-driven scheduling, powered by a lightweight ICT platform. Its applicability under close-to-real conditions in smart energy system laboratories is validated, establishing a testbed for future exploration of interacting local energy communities.

Overall, the feasibility of the overall system is confirmed in a field test. We are able to show that market-cleared setpoints derived from simulated digital twins can be safely applied to real hard-ware components within Living Lab Energy Campus at Forschungszentrum Jülich and Energy Lab at Karlsruhe Institute of Technology. Furthermore, we validate the framework's suitability using geographically distributed agents and physical devices. Autonomous agents ensure the scalability of the system.

This successful validation of a decentralized, market-based MAS demonstrates the potential of this concept for the coordination of smart energy areas, addressing a possibility for the provision of flexibility in future energy systems.

Future research could integrate more components and smart areas, exploring the framework's scalability and suitability for more diverse components and participants. Furthermore, the incorporation of distribution-grid constraints through the multi-round clearing functionality of the MASSIVE framework is expected to enhance the realism of the simulation. In the subsequent phase of the study, the economic and environmental impact of agent-based flexibility coordination will be examined, with the incorporation of factors such as wholesale electricity prices and carbon taxes.

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