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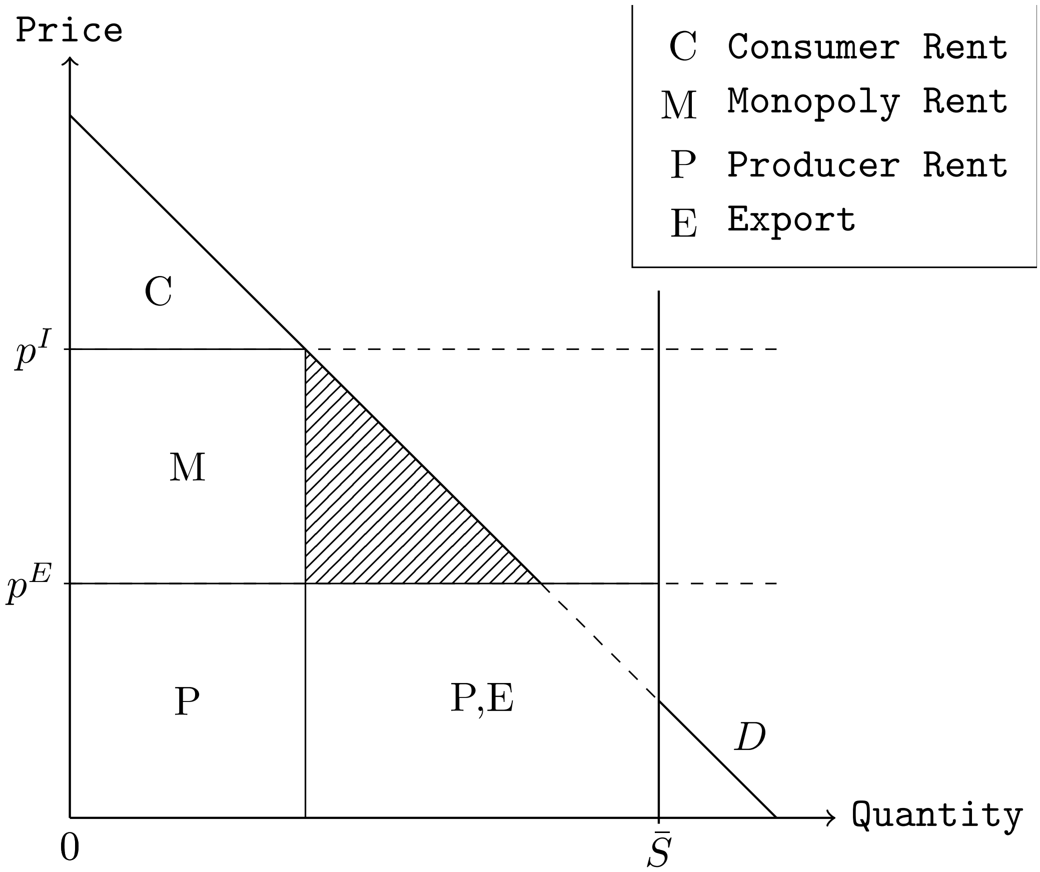
Interim report dated 14.10.2024

Charting energy platforms and market outcomes under varying policy measures



Source: Authors' model. Distribution of rents in a local energy market between consumers, producers, and a monopolistic platform with p^I as import electricity price and p^E as export electricity price and high exogenous supply.

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Zusammenfassung

Das Projekt befasst sich mit der Entwicklung einer simulationsbasierten Grundlage für die Regulierung von lokalen Energiemärkten. Ziel ist es, die Dynamik dieses neuen Markttyps unter verschiedenen regulatorischen Rahmenbedingungen zu analysieren und den Regulierungsbehörden eine "Kartographie" von möglichem volkswirtschaftlich schädlichen Verhalten der Marktteilnehmer und insbesondere Marktmachtmissbrauchs zur Verfügung zu stellen. Ein Schwerpunkt liegt dabei auf der Verknüpfung der ökonomischen Theorie von Energieplattformen mit wettbewerbspolitischen Erfahrungen im Bereich digitaler Plattformen sowie Modellen für mehrseitige Märkte.

Im zweiten Projektjahr wurde ein agentenbasiertes Modell erstellt, das modular ausgebaut werden kann. Die Simulation wurde in Python programmiert. Zusätzlich zu regelbasierten Agenten haben wir auch adaptive Agenten programmiert, die im sequenziellen Umfeld mithilfe von Neuronalen Netzen eine optimale Handelsstrategie finden.

In der aktuellen Phase testen wir die Simulation, während wir sie an spezifischen Stellen weiter ausbauen. Der nächste Schritt beinhaltet die Kalibrierung der Simulation mit Echtwelt- Daten, gefolgt von einer umfassenden Analyse der Simulationsergebnisse. Diese Ergebnisse werden mit den relevanten Stakeholdern diskutiert, um ein fundiertes Feedback zu erhalten.

Résumé

Le projet porte sur le développement d'une fondation basée sur la simulation pour la régulation des marchés locaux de l'énergie. L'objectif est d'analyser la dynamique de ce nouveau type de marché dans différents cadres réglementaires et de mettre à la disposition des autorités de régulation une « cartographie » des comportements potentiellement nuisibles pour l'économie nationale des acteurs du marché et, en particulier, des abus de pouvoir de marché. L'accent est mis sur la mise en relation de la théorie économique des plateformes énergétiques avec les expériences en matière de politique de la concurrence dans le domaine des plateformes numériques ainsi que sur les modèles de marchés multilatéraux.

Au cours de la deuxième année du projet, un modèle basé sur des agents a été créé, qui peut être développé de manière modulaire. La simulation a été programmée en Python. En plus d'un agent basé sur des règles, nous avons également programmé des agents adaptatifs qui trouvent une stratégie de négociation optimale dans un environnement séquentiel avec des réseaux neuronaux.

Dans la phase actuelle, nous testons la simulation tout en la développant à des endroits spécifiques. L'étape suivante comprend le calibrage de la simulation avec des données pertinentes, suivi d'une analyse complète des résultats de la simulation. Ces résultats seront ensuite discutés avec les parties prenantes concernées afin d'obtenir un retour d'information éclairé.

Summary

The project is concerned with the development of a simulation-based foundation for the regulation of local energy markets. The aim is to analyse the dynamics of this new type of market under different regulatory frameworks and to provide the regulatory authorities with a 'cartography' of possible economically harmful behaviour by market participants and, in particular, market power abuse. One focus is on linking the economic theory of energy platforms with competition policy experience in the area of digital platforms and models for multi-sided markets.

In the second year of the project, an agent-based model was created that can be expanded on a modular basis. The simulation was programmed in Python. In addition to a rule-based agent, we also

programmed adaptive agents that use neural networks to find an optimal trading strategy in a sequential environment.

In the current phase, we are testing the simulation while we continue to expand it in specific areas. The next step involves calibrating the simulation with relevant data, followed by a comprehensive analysis of the simulation results. These results are then discussed with the relevant stakeholders in order to obtain well-founded feedback.

Contents

Abbreviations

LEM	Local Energy Market
SCC	Self-Consumption Community
EV	Electric Vehicle
DNN	Deep Neural Network
LEG	Lokale Energiegemeinschaft
SDR	Supply-Demand Ratio
MMR	Mid-Market Rate

1 Introduction

1.1 Background information and current situation

Private households increasingly own photovoltaic systems and batteries (for example from electric vehicles), leading to a decentralization of energy production. In response, energy trading platforms have emerged that enable direct energy exchange between households and producers. Examples include Power Peers in the Netherlands, Sonnen Community in Germany, or the Lugaggia Innovation Community in Switzerland. Like digital platforms in other markets, such as Amazon and Airbnb, these energy platforms could significantly reshape the market by facilitating decentralized, peer-to-peer transactions. Recognizing the potential of SCCs and LEMs, a new law is currently in the post-parliamentary phase in Switzerland to permit the formation of local energy communities. Under this new legislation, residential agents could directly trade energy within their local communities, representing a transformation in the Swiss energy market framework (Abschnitt 2c, Bundesgesetz über eine sichere Stromversorgung mit erneuerbaren Energien vom 29. September 2023).

But the emergence of energy platforms also brings with it potential policy concerns. In markets dominated by digital platforms such as Amazon or Airbnb, network effects have lead to market concentration, where a few dominant players control access and set the terms of participation. Energy platforms may face similar challenges, raising various questions about the role of market power in decentralized energy markets. The critical importance of energy infrastructure requires a well-coordinated and predictable transition towards digital platforms that avoids many of the pitfalls observed in other sectors. A solid understanding of the behavior of prosumers and platforms, especially regarding potentially harmful behavior and market power abuse, is an important element for a smooth transition to decentralized energy production and a prerequisite for establishing a reliable regulatory framework.

1.2 Purpose of the project

In this project, we investigate the behaviour of prosumers and electricity trading platforms in detail. For electricity trading platforms, there is neither a widely accepted economic model nor sufficient real-world evidence for analysis. We therefore use both a theoretical model and an agent-based simulation to investigate agents' dynamics and interactions within this new market structure. Within this model, we analyze the potential of a platform or individual market participants to acquire market power and their potential for abuse. Since this type of market is also prone to using artificial intelligence for optimization (either as an intermediary agent for all prosumers or individually), we will integrate reinforcement learning techniques, reflecting expected trends in this industry. We validate the outcomes with available data from LEMs and feedback from an advisory board.

The project provides Swiss policymakers with a conceptual framework for setting up regulations of electricity trading platforms and for the creation of an appropriate monitoring framework. We will design and test regulations to address and mitigate market failures or market power abuses. Our work serves as a benchmark for energy platform regulation by highlighting harmful strategies of market participants operating under different regulatory constraints.

1.3 Objectives

Despite the ongoing legal processes and the significant opportunities within this domain, a comprehensive analysis of the long-term effects of the operation of Local Energy Markets (LEMs) on social welfare remains incomplete. By understanding the economic dynamics governing LEM markets and identifying the key drivers of adverse market behavior, we can proactively address challenges that may arise, such as antitrust cases and monopolistic tendencies, within existing regulatory constraints (even though there will be no full liberalization in CH). Our primary aim is to elucidate LEM markets' economic dynamics and identify the key drivers of adverse market behavior. Specifically, our research questions are as follows:

- What are the specific vulnerabilities with respect to the creation and abuse of market power of local and interregional energy markets and platforms?
- What regulatory measures can be implemented to mitigate such behavior effectively?
- What is the influence of artificial intelligence on the functioning in LEMs?
- How does the presence of LEMs impact the overall systemic stability of energy provision?

2 Procedures and methodology

Our methodology includes the development of an economic model and a simulation environment that reflects the practices of state-of-the-art energy platforms. We characterize energy platforms as multi-sided games with different actors and incentives. We analyze agent behavior under different scenarios and policy constraints, ranging from simple rule-based agents to more complex learning agents.

Key steps in our methodology include:

1. Evaluation of existing platforms and literature review. The literature review and assessment of existing platforms have been completed. Data analysis of user behavior on existing energy platforms is ongoing.
2. Design of the economic model and analysis of its results. The design of the economic model of work package 2 is finalized.
3. Develop a simulation engine based on the economic model, validated with real-world data. The simulation engine has been implemented in Python, with data from CKW and Renewables.ninja integrated and prepared for use.
4. Establish a monitoring process involving market experts, energy providers, and regulators to ensure the plausibility of the results. An advisory board has been established. The initial workshop to discuss simulation results is yet to be scheduled.

3 Activities and results

1. *Dataset on existing electricity platforms*

   We have expanded our dataset of energy trading platforms, including commercial platforms and pilot projects, to 54 projects. This dataset serves as the foundation for our analysis, ensuring that our simulations accurately represent prosumer platforms.

2. *Compilation of effects that could lead to winner-takes all dynamics of electricity trading platforms*

   Our analysis of the economic effects on energy trading platforms has been expanded to include mechanisms that operate at the intermediary level, others at the system-wide level, and yet others at the market level. Each level captures dynamics that shape platform performance and prosumer incentives.

   - Intermediary Level: Effects at the intermediary level benefit prosumers connected to the same intermediary, even if they are in different local markets. This creates unique advantages and synergies within the intermediary's network. For example, sharing data for demand management allows intermediaries to aggregate information to more effectively balance peak loads and improve energy efficiency for all users, regardless of their specific local markets.

- System-Wide: System-wide effects impact all prosumers, independent of their intermediary or local market affiliation. These effects include broad effects such as the Utility Death Spiral and Learning Effects. In Switzerland, for instance, prosumers on LEGs can enjoy up to 60% reduction in grid fees, increasing platform appeal. However, as prosumers contribute less to network costs, fees for non-participants rise, potentially leading to a Utility Death Spiral. The Learning Effect further amplifies general platform value by attracting new participants as the total, system-wide prosumer base grows. Studies by Basu et al. (2011) and Bollinger & Gillingham (2012) support this trend for PV installations, demonstrating that a higher number of existing PV installations increases the likelihood of new installations.
- Market Level: Market-level effects are specific to prosumers within the same local market, influencing dynamics and benefits that are unique to that setting. For example, the expected profit for a flexible prosumer in a flexible pricing market is heavily influenced by the presence of other flexible prosumers and the total supply-demand balance in that market. Flexible prosumers face negative in-group effects due to increased competition, while flexible and inflexible prosumers positively impact each other. The effect between inflexible prosumers, on the other hand, varies based on the similarity of their consumption or production patterns. Further analysis of these market-level effects is currently underway.

3. *Development and implementation of an agent-based model for electricity trading platforms*

We have advanced the implementation of our agent-based model significantly and implemented the simulation in Python, allowing us to investigate the dynamics of electricity trading platforms in a modular and flexible framework. Below, we present our approach.

Our agent-based model consists of a set of prosumers, $P = 1,2, \ldots, N$ each with unique demand, supply, and prosumer parameters over a defined time horizon $T = 1,2, \ldots, T$. Prosumers operate within a structured environment where they can buy or sell electricity, influenced by external market prices (e.g., feed-in tariffs or day-ahead prices) and internal platform prices that depend on the platform internal pricing mechanism. They can be equipped with batteries, allowing them to optimize their net import/export by charging and discharging based on real-time price signals and platform rules.

Model Setup and Agent Dynamics

The model captures each prosumer's demand and supply through exogenously defined sequences, $d_i = (d_i^1, d_i^2, \ldots, d_i^T)$ and $s_i = (s_i^1, s_i^2, \ldots, s_i^T)$. Some prosumers are equipped with a battery, where b_i^t represents the battery charge or discharge level at time t for prosumer i. This variable is bounded by the minimum and maximum capacity limits

$$b_i = (b_i^1, b_i^2, \ldots, b_i^T);\; b_i^t \in \left[-B_i^t, \overline{\overline{B}}_i - B_i^t\right],$$

and includes inefficiencies in charging and discharging to reflect real-world energy losses[1]. Prosumers adjust their net import

$$x_i^t = d_i^t + b_i^t - s_i^t$$

over the time horizon, adjusting battery usage dynamically to respond to shifting market prices and optimize costs.

[1] If the hours during which the electric vehicle (EV) is connected to the home network and EV usage are specified, this part of the simulation can be easily adjusted to represent bidirectional charging. This formulation is based on the state-of-charge (SoC) bookkeeping model (e.g. see Korpas et al. 2006, Zhao et al. 2013).

The pricing mechanism on the platform plays a central role in the model, as it determines the cost and revenue for each prosumer based on their net import or export. This function is defined as

$$(p_c^t, p_p^t) = f\big((x_1^t, \dots, x_N^t), p^E, p^I\big),$$

where p_c^t and p_p^t represent the buying and selling prices, respectively, and are influenced by the aggregate import and export levels of all prosumers. The function is modular, allowing us to test various pricing mechanisms, including supply-demand ratios, mid-market rates, and a discriminative double auction currently under development[2]. This flexible approach enables us to assess how different pricing schemes impact prosumer profitability, platform dynamics, and potential for market dominance.

Household costs are calculated per period as

$$c_i^t = \begin{cases} x_i^t(p_c^t + \tau_c) & if\ x_i^t > 0, \\ x_i^t(p_p^t - \tau_p) & if\ x_i^t < 0, \end{cases}$$

where transaction costs τ_c and $\tau_p$can be set by the intermediary (reminiscent of the modeling of transaction costs in the platform literature by e.g. Rochet and Tirole (2003)). The total profit over T periods of a household is

$$C_i = \sum_t^T \mathrm{c}_i^t + m_i$$

where m_i represents the membership fee from the platform. The total cost over T periods can be expanded to include a term representing a higher valuation for local electricity[3], simulating a preference for energy sourced from within the platform over grid-sourced alternatives.

Modularity and Flexibility of the Model

The modular design of the agent-based model allows us to modify multiple dimensions of the simulation environment. Key adjustable components include:

- Pricing Mechanisms: The model supports a range of pricing schemes, from basic tariffs to more complex, dynamic price-setting mechanisms based on supply and demand ratios.
- Prosumer Characteristics: Prosumers can be configured with different net-demand patterns. In addition, they may possess rooftop PV systems and batteries, enabling them to store surplus energy or purchase from the grid during low-cost periods.
- Intermediary Pricing Schemes: Intermediaries on the platform can implement diverse cost structures, such as transaction-based or membership fees, allowing us to examine the effects of different business models on prosumer actions and revenue.
- External Market Prices: The model currently incorporates feed-in tariffs and electricity prices. Future iterations will allow integration with day-ahead markets, enabling real-time trading simulations with more volatile external market prices.

Rule-based agent

A rule-based agent has been implemented to optimize self-sustainability. By managing its battery charging and discharging, the agent minimizes reliance on external energy, serving as a baseline for self-sufficient behavior in decentralized energy markets.

[2] In the discriminative double auction, the agents not only set the net import but also choose a bid. A double auction was for example implemented in Quartierstrom 1.0. (Ableitner et al. 2020)
[3] This term depends on self-sufficiency of the platform.

4. *Adaptive agents in the simulation setup*

In our model, the prosumers navigate a complex, dynamic environment. While rule-based decision-making can capture basic behaviours, it can fall short in accurately modelling the adaptive strategies needed in decentralized energy markets, where prices, supply, and demand fluctuate continuously. Given this complexity, computational approaches are essential to enable agents to dynamically adjust their actions and optimize their performance over time. By employing advanced algorithms, agents can identify optimal strategies based on both historical and real-time data, maximizing their utility within the market context.

Computational optimization allows each agent to make decisions that account for the stochastic nature of energy demand and supply, battery states, and varying market prices. Rather than following fixed rules, agents learn adaptive strategies that maximize their assigned values, such as payoff or utility. This adaptability is crucial in our model, as it enables agents to anticipate market conditions, respond to price signals, and engage in actions that optimize their energy use and financial outcomes.

We employ deep neural network (DNN) techniques, similar to those in Krabichler et al. (2023), to simulate agent adaptivity and optimize decision-making. The DNN framework enables us to design agents that dynamically learn optimal control strategies based on historical and simulated market conditions.

Each prosumer's DNN takes a set of features as input at each time step:

- The net electricity demand (calculated as the difference between demand and supply),
- The time step (normalized within the simulation's total duration),
- The demand-supply ratio (an aggregate measure of demand relative to supply),
- The battery's state-of-charge from the previous time step,
- The market buy price from the previous time step,
- The market sell price from the previous time step.

Using these inputs, the DNN outputs a decision on how much to charge or discharge the battery, constrained by the battery's capacity and state-of-charge. This action aims to optimize the agent's net position based on market prices, minimizing reliance on external electricity when prices are high and maximizing sales when prices are favorable.

Centralized Optimization

In the centralized optimization setup, a central aggregator optimizes energy resources across all agents to maximize overall platform revenue. This approach assumes complete information, where the central entity has access to all prosumer data and determines the optimal allocation of resources to achieve the best collective outcome.

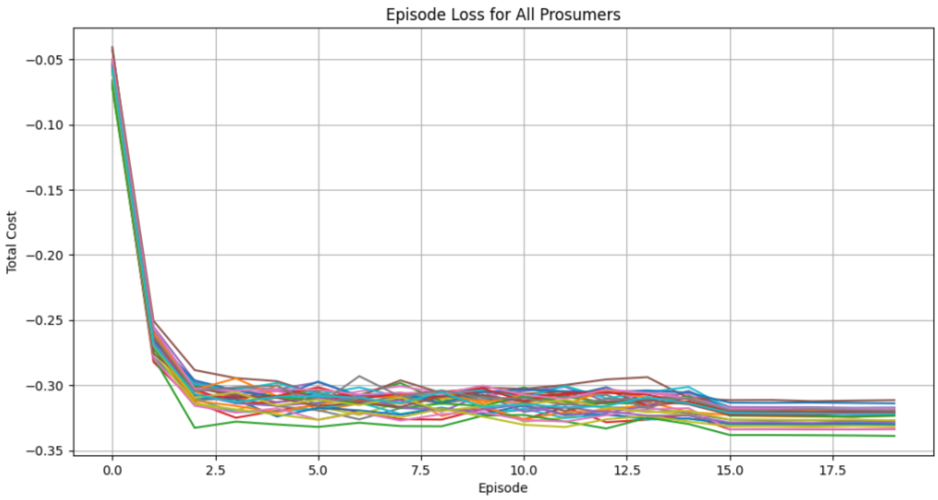

Figure 1: Episode Loss for 30 homogeneous Prosumers in an MMR Market.

Notes: Each prosumer learns optimal trading strategies across episodes, resulting in a gradual decrease in total costs per prosumer with each learning iteration. Noise injection is applied during training until episode 14, after which it is removed. This reduction in noise stabilizes learning outcomes, as seen in the convergence of total costs in later episodes.

5. *Simulation Test Phase and Preliminary Results*

In line with the schedule, the simulation engine is currently being tested. Initial, preliminary results have emerged, highlighting some key hypotheses that will be explored in more detail over the coming months:

- Centralised optimisation outperforms decentralised optimisation in pricing schemes where prices depend on supply and demand. Decentralised optimisation in turn outperforms the rule-based strategy in these settings.
- Pricing schemes with prices depending on supply and demand yield a higher utility for prosumers than the feed-in tariff scheme.
- Utility per agent increases marginally with the number of prosumers in the market under optimization and variable pricing schemes.

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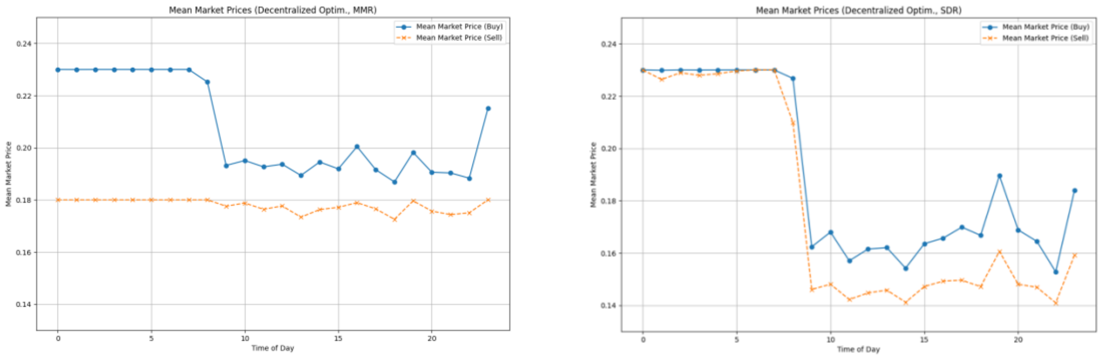

Figure 2: Mean market prices for 30 homogeneous prosumers in an MMR market and in an SDR market.

Notes: Both graphs display results with decentralized learning. While the left graph shows prices resulting from mid-market rate, the left graph shows prices resulting from supply-demand ratio. Both simulations use a feed-in tariff of 0.13 and an electricity price of 0.23. The mean market prices are determined by the net import and export activity of the 30 prosumers per period.

6. *Policy Design Space*

   A fist selection of policy interventions that should be analysed has been proposed to SFOE. The final selection is still to be decided.

4 Evaluation of results to date

Our project has made significant progress by establishing a modular agent-based simulation framework tailored for energy trading platforms and markets. To the best of our knowledge, this project is among the first to explore winner-takes-all dynamics in prosumer-based platforms by modelling heterogeneous agents with adaptive decision-making. The future integration of real-world data ensures that our simulation captures a high degree of realism and relevance. Early simulations have demonstrated the model's flexibility and capacity to test various market scenarios, providing insights into platform attractiveness and competition among prosumers with differing needs and behaviours.

As we continue to refine the simulation and implement additional mechanisms we anticipate that the project will yield valuable insights into decentralized energy markets and inform the design of effective policy instruments.

5 Next steps

We will continue testing the simulation engine and calibrating it with real-world data. In parallel, we are implementing the discriminatory double auction mechanism. The next step includes a workshop with energy experts to review the simulation setup and potential policy interventions

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