Integrating Household Flexibility into Local Electricity markets: A market-Based Approach for Grid Stability and Demand Optimization

1 Abstract

The increasing need for grid stability and efficiency has led to a growing interest in integrating small-scale household flexibility into local electricity markets. In Switzerland, flexibility trading mechanisms primarily involve Distribution System Operators (DSOs), Balance Responsible Parties (BRPs), and Flexibility Service Providers (FSPs). While residential flexibility is often overlooked, its aggregated potential can substantially enhance market efficiency and support grid operations.

This study explores the integration of household flexibility through an aggregator and its impact on local flexibility markets. Using real-world transformer-level scenarios, we analyse bid structures while considering load profiles, headroom constraints, and buffer zones. The findings illustrate how aggregated residential flexibility can be effectively structured within market frameworks to optimize power flows, mitigate peak loads, and provide additional value to grid operators and market participants.

Furthermore, we demonstrate how a bidding platform for electricity markets can be systematically tested with realistic bidding structures that reflect the interactions between key stakeholders, including BRPs, DSOs, Transmission System Operators (TSOs), and FSPs. Additionally, we assess the extent to which power transformers approach their operational limits and explore strategies to alleviate constraints caused by peak loads. Finally, we examine the potential of existing flexibility in feed-in peaks and how it can be leveraged by market participants to enhance grid stability and overall efficiency.

Keywords Energy markets, Flexibility markets, Energy transition, Electricity grids, Prosumer

2 Introduction

As the global energy landscape transitions toward a low-carbon future, the increasing demand for electricity, coupled with the accelerated shift to sustainable energy systems, necessitates enhanced flexibility in power networks. Flexibility has emerged as a critical enabler of resilience and adaptability, ensuring the stability of evolving electricity markets. Effective flexibility mechanisms are essential for managing fluctuating renewable generation, optimizing power flows, and mitigating congestion at the distribution level.

Switzerland's national energy strategy for 2050 sets ambitious targets, aiming for a 90% reduction in greenhouse gas emissions and an almost complete transition to renewable energy sources [1]. A core component of this strategy is the decentralization of electricity generation, shifting from large, centralized power plants to distributed energy resources such as photovoltaic (PV) systems, heat pumps, and electric vehicles (EVs). The electrification of the heating and mobility sectors is further reshaping Switzerland's energy landscape, leading to increased variability in electricity consumption and feed-in. These changes impose new challenges on the Swiss distribution grid, particularly at the low-voltage level, requiring advanced grid management strategies to accommodate flexibility effectively.

As [2] highlights, integrating decentralized energy flexibility into electricity markets is gaining traction as grid operators seek innovative methods to manage network constraints and optimize power flows. However, key challenges remain, including market design complexities, regulatory barriers, and the need for advanced coordination mechanisms between Transmission System Operators (TSOs) and Distribution System Operators (DSOs). Addressing these challenges requires a comprehensive understanding of bid interactions at various grid levels and the development of strategies to aggregate and deploy residential flexibility efficiently.

Several studies have explored the potential of residential flexibility. The Research Center for Energy Economics (FfE) emphasizes the substantial flexibility potential of households through the utilization of flexible loads, proposing incentives such as dynamic tariffs to encourage consumers to adapt their energy consumption patterns [3]. Similarly, [4] analyzed how electric vehicles, heat pumps, and home storage systems could make 100 terawatt-hours of electricity demand flexible annually by 2035, while the German Federal Network Agency conducted a comprehensive examination of flexibility within the energy transition framework [**?**].

Despite these efforts, there remains a critical gap in research regarding the practical implementation of software-driven solutions that enable seamless flexibility trading. While [5] investigate stability and control schemes in active distribution grids, their work focuses primarily on control algorithms rather than the design of market-based flexibility trading mechanisms. Moreover, while international studies highlight various aspects of flexibility integration, the potential for small-scale flexibility from Swiss households remains largely untapped. By aggregating household flexibility, new market structures can emerge that enhance grid stability and efficiency while unlocking economic benefits for all stakeholders [6].

Swissgrid, in collaboration with Zurich's DSO ewz, launched a residential flexibility pilot utilizing blockchain technology to integrate household flexibility into the grid using large-scale battery storage. Similarly, platforms such as Tiko have been operational since 2014, aggregating behind-the-meter assets from Swiss households to provide primary and secondary balancing services to the Swiss TSO [7]. However, the implementation of such aggregation models at a neighborhood-wide level remains unachieved, and no standardized approach for remunerating household flexibility currently exists.

This study aims to bridge these gaps by analyzing the impact of household flexibility aggregation within Swiss electricity markets, focusing on the role of software-driven solutions for bid management and flexibility trading. By leveraging real-world data and assessing load profile variations and bidding behavior, this study explores how software platforms can optimize decentralized flexibility utilization without relying on battery storage. The findings contribute to the ongoing discourse on decentralized energy resources and their role in future electricity market designs, offering a pathway toward a more resilient, software-integrated, and efficient power system.

3 Materials and Methods

All values representing the pool of flexible loads integrated into the LocalFlex platform are derived from empirical data. The bidding process for day-ahead and intraday auctions was tested using 17 electrical boilers and 14 heat pumps. Bids were submitted at the medium-voltage (MV) level for Balance Responsible Parties (BRPs) and Transmission System Operators (TSOs) and at the transformer level for Distribution System Operators (DSOs). The analysis assumes the presence of both flexible loads, including heat pumps and electrical boilers, and non-flexible loads, such as household appliances, entire households, and photovoltaic (PV) systems. Notably, PV curtailment was not considered due to legal constraints.

3.1 General constraints

The pool of flexible loads connected to the transformer was configured to operate under specific constraints to effectively manage demand. The control mechanism remains active throughout the entire day, enabling continuous monitoring and regulation during platform testing. The amount of demand that can be curtailed in each period is determined by the blocking signal. Each activation is limited to a maximum duration of two hours, followed by a mandatory recovery period of two hours. Consequently, once the pool of flexible loads has been curtailed for one or two hours, it cannot be curtailed again until the subsequent two-hour interval has elapsed.

Furthermore, the total blocking time is constrained by a factor of four, ensuring that the system does not exceed two activations of two hours each or multiple shorter activations within the same overall energy limit. These operational constraints are designed to enhance energy efficiency while maintaining grid stability and ensuring the continuous functionality of heating and charging systems when required.

3.2 User Stories

Three different user stories were set for testing:

- **User Story 1 - Day ahead for cold winter day**. Assumption: High demand up to substantial overload of electricity for Head Pumps and not much sun.
- **User Story 2 - Day ahead for sunny spring day**. Assumption: Low demand of electricity for head pumps but lots of production due to mild temperatures and lots of sun.
- **User Story 3 - Intraday for sunny spring day**. Assumption: Low demand of electricity for head pumps but lots of production due to mild temperatures and lots of sun.

According to each User Story different results have been expected and hence were tested. TSO bids have been excluded for User Story 1 and 2 as they are not relevant for day ahead auction, as TSO bids are submitted later during intraday stage.

User Story 1 This scenario represents a cold winter day during the day-ahead auction, where the grid experiences high loads in the morning and evening. To alleviate congestion, it is essential to shift energy consumption from the evening to periods with lower electricity prices, following a downward direction scenario. In this context, the BRP aims to submit a sell order in the late evening, while the DSO intends to place a pay order during the same period. During the evening trading session, the DSO's downward bids between 21:00 and 23:00 are accepted, as they correspond to the highest price. However, only 10 kW can be traded due to the limited availability of flexibility offered by the Flexibility Service Provider (FSP). Conversely, the BRP's bids in the evening remain uncleared, as their prices are lower than those of the DSO, and the FSP enforces a mandatory two-hour recovery period, restricting additional activations.

User Story 2 This scenario represents a sunny spring day during the day-ahead auction, where PV generation and other inflexible sources exceed the current load demand, leading to grid congestion. To mitigate this issue, the TSO seeks to increase electricity consumption using flexible assets. In this context, the BRP intends to submit a sell order during midday, while the DSO aims to place a buy order in the same period.

User Story 3 This scenario represents a sunny spring day during intra day auction, where we are at 12.00pm and the TSO places a bid at 13.30. However, the recovery time from the day-ahead market does not carry over into the intraday session. At the same time, there is an active DSO bid in the opposite direction, and the available DSO headroom down remains at zero until 15:00. As a result, no intraday trading should take place before 15:00.

This scenario represents a sunny spring day during the intraday auction, where the system is at 12:00 pm, and the TSO submits a bid for 13:30. The recovery time from the day-ahead market should not extend into the intraday session. Simultaneously, a DSO bid should be active in the opposite direction, with the available DSO headroom in the downward direction remaining at zero until 15:00. Consequently, no intraday trading should occur before 15:00.

3.3 Headroom and Baseline

The DSO mimicking party sets the load forecast. It includes both, inflexible assets and the load profile of flexible assets. It in addition assumes no flexible activation. Only the remaining up and downwards Headroom was submitted to the localflex platform. The baseline for flex assets was calculated by LocalFlex based ion historic metering data.

4 Results

To assess whether the localflex platform accurately receives and processes bids from BRP, DSO, TSO and FSP correctly, two-week evaluation was conducted, involving daily offers and corresponding demands. The findings are presented below.

General Figure 1 displays for each User Story two graphs. The graphs in the upper line show the load profile for each User Story over a 24-hour period, with the x axis representing time in hours and the y axis representing load in kilovolt volts (kVA). All graphs share the same structural elements, including the load forecast represented by a blue line, the uncertainty shaded in light gray, the height of the head in blue, and the height of the head in orange. Additionally, all plots include red dotted lines that indicates the transformer size limits in kVA.

The graphs in the lower line show the given bids over a 24-hour period. The x-axis represents the time in hours from 0 to 23, while the y-axis represents power in kilowatts (KW). Each plot is divided into multiple horizontal sections, each representing a specific type of order or offer, including FSP offers, DSO orders, BRP orders, TSO orders. The bars within these sections indicate the presence and magnitude of power transactions at specific hours. The red dotted lines in the FSP offers section indicate critical thresholds.

Load Profile Analysis for Different User Stories The primary distinction among the load profiles depicted in Figures 1 (a) - (c) lies in the behaviour of the load forecast. The load remains relatively stable throughout a typical winter day. However, noticeable peaks occur during the morning and evening, bringing the load close to the transformer capacity limit. During the evening peak, when incorporating uncertainty, the load even surpasses this limit. Consequently, the available headroom up is significantly constrained.

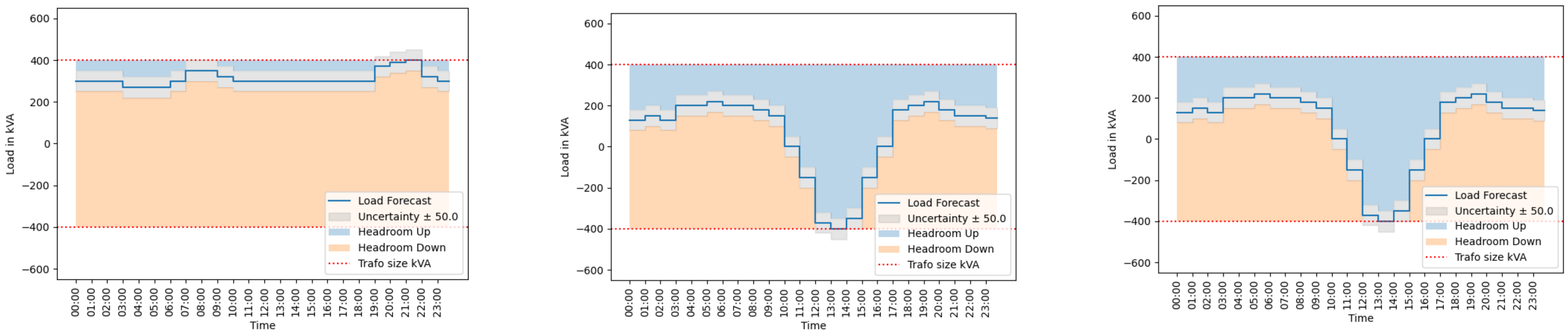
In Figure 1 (a), the load remains relatively stable throughout the day, fluctuating within a narrow range near the upper transformer limit. In contrast, Figure 1 (b) exhibits a more dynamic load pattern, characterized by a substantial decline between 10:00 and 15:00, indicating increased feed-in. During this interval, the load drops well below its typical range, approaching the lower transformer limit. This decline leads to a significant expansion of the headroom up area, which is considerably larger in Figure 1 (b) compared to Figure 1 (a).

Bidding Analysis for Different User Stories The graphs in the lower row illustrate the output of the LocalFlex platform in relation to the bids submitted by all participants during the two-week testing phase. The primary objective was to assess whether the platform correctly processes these bids, performs accurate matching, and adjusts them in accordance with the available headroom—both upward and downward.

The bars in the low graphs are colour-coded to represent different types of bids and indicate the magnitude of each submitted bid. By comparing these results with the corresponding load curve in the upper row, it is possible to evaluate whether the platform correctly assessed the existing load and effectively utilized the available flexibility to shift adjustable loads.

The structure of the FSP offers remains largely consistent across all three scenarios, as evidenced by a continuous dark blue band, indicating a stable offering pattern. Similarly, the DSO orders section displays a comparable trend across the figures, with coloured bars appearing at specific time intervals, signifying scheduled power transactions. The BRP orders section also exhibits analogous activity, with hatched bars appearing at different time slots in each plot.

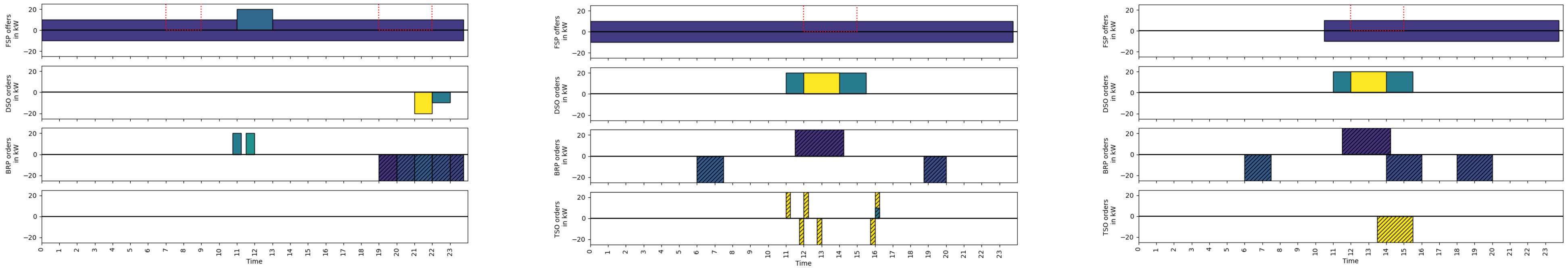
However, in Figure 1 (c), the FSP submits offers during midday, a feature absent in the other two scenarios. Furthermore, in Figure 1 (d), the DSO orders emerge only in the late hours, whereas in Figures 1 (e) and 1 (f), these orders appear earlier and span a broader time range. The TSO orders are exclusively present in Figures 1 (e) and 1 (f), comprising both negative and positive orders. Finally, the BRP orders section exhibits variations in timing, magnitude, and frequency of the hatched bars across Figures 1 (d) - (f), indicating scenario-dependent bidding behaviors.



(a) Load profile of User Story 1.

(b) Load profile of User Story 2.

(c) Load profile of User Story 3.



(d) Bids of User Story 1.

(e) Bids of User Story 2.

(f) Bids of User Story 3.

Figure 1: **Visualisation of load profile and Bids of all three User Stories.**
(a) - (c) Depicted are the load profiles of a Transformer. On the x-Axis one can see the time in hours for one day and on the y-Axis the Load in kVA. The forecasted load is depicted with a blue line and a buffer in grey. The Headroom Up is shown in blue, the Headroom down in orange. The size of the Transformer is shown as a dashed red line.
(d) - (f) Depicted are the submitted Bids to the market. On the x-Axis one can see the time in hours for one day and on the y-Axis the offered Bids in kW for FSO, DSO, BRP and TSO (top to bottom).

5 Discussion

The integration of household flexibility into local electricity markets presents both opportunities and challenges for grid stability, market efficiency, and flexibility aggregation. Our findings demonstrate that flexible assets, such as heat pumps and electrical boilers, can be aggregated and strategically utilized to alleviate grid congestion and optimize power flows. However, bidding strategies, operational constraints, and market coordination mechanisms must be carefully considered to ensure effective implementation and maximize the potential benefits of residential flexibility.

In this study, we have taken a step beyond many previous approaches. Firstly, we successfully tested a software solution that enables the automated trading of aggregated household flexibility, allowing DSOs, BRPs, and TSOs to place bids that dynamically adjust to available grid capacity. Secondly, we demonstrated that flexibility can be utilized effectively without the integration of batteries as storage, instead relying on demand-shifting mechanisms and bid structuring. Furthermore, our study presents a solution that differs from the approach of the FfE study [3], as it does not require active consumer participation in the bidding process. Instead, consumers only need to make their flexible assets available, enabling seamless integration into market structures while aligning with existing Swiss flexibility initiatives, such as Swissgrid's pilot projects and Tiko's demand-side aggregation model.

The analysis of load profiles and bidding behaviour across different user stories provides insights into how flexibility assets interact with market mechanisms, revealing critical implications for Grid stability and flexibility trading. The findings demonstrate that variations in load patterns influence available headroom, impacting how DSOs, BRPs, and TSOs place their bids and how effectively flexibility is utilized.

A key observation across the analysed scenarios is the presence of morning and evening peak loads, which push transformer capacity toward its operational limits. The available headroom up is significantly constrained during these peaks, limiting the ability of flexibility markets to absorb additional energy. Under uncertainty, the transformer even surpasses its operational threshold, reinforcing concerns raised by previous studies on distribution grid stress due to increased electrification ([5], [2]). However, a notable midday decline in load (Figure 1 (b)) provides opportunities to shift flexible demand to off-peak periods, reducing congestion and optimizing grid utilization. Similar strategies have been highlighted in studies advocating for demand-side flexibility to balance renewable energy fluctuations ([4], [8]).

The bidding patterns of market participants further illustrate the platform's ability to process and match bids based on grid constraints. The stability of FSP offers, indicated by the continuous dark blue bands, suggests that the LocalFlex platform effectively maintains consistency in processing flexibility bids. However, scenario-dependent variations in DSO and BRP orders highlight that market participants dynamically adapt their bidding strategies based on real-time grid conditions. This aligns with existing research on flexibility market efficiency, which underscores the need for bid structuring that responds to local congestion levels ([6]). Differences in bidding behaviour also reflect unique operational strategies across grid participants. The emergence of FSP offers during midday in Figure 1 (c) indicates increased flexibility activation opportunities during surplus PV generation. Meanwhile, the late-hour concentration of DSO orders in Figure 1 (d) suggests a preference for activating flexibility during peak evening loads, contrasting with the broader time range of DSO orders in Figures 1 (e) and 1 (f).

These findings underscore the importance of advanced forecasting models for market optimization. The ability of BRPs and DSOs to place bids efficiently depends on accurate load predictions, emphasizing the role of AI-driven forecasting models in improving bid placement accuracy and overall market efficiency ([5]). Furthermore, the lack of standardized remuneration mechanisms for household flexibility remains a challenge, limiting consumer participation in Swiss flexibility markets ([7]).

The findings reinforce that software-driven platforms such as LocalFlex can effectively manage bid interactions and optimize flexibility utilization. However, future research should focus on enhancing coordination between DSOs and TSOs, improving aggregation models for household participation, and integrating AI-based forecasting to improve bidding accuracy. Developing automated bidding frameworks that dynamically adjust to real-time grid signals would further enhance local flexibility market efficiency.

In summary, the integration of software-based flexibility trading mechanisms is essential for maximizing the value of decentralized household flexibility in Switzerland. While the LocalFlex platform successfully processes and matches bids, further refinements are needed to ensure that aggregation models, real-time forecasting, and coordination between grid operators evolve alongside increasing flexibility participation. These findings contribute to the ongoing transition toward a more resilient, software-integrated, and consumer-inclusive energy market.

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