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# The role of local energy markets in low voltage networks: community-based approaches

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**Abstract:** *Rising adoption of distributed energy resources (DER) is bringing about significant transformations and challenges in future power systems. The main objective of a system operator is to optimize demand-side energy trading while reducing reliance on energy imports from the main grid. To address this, a trustworthy local energy market (LEM) trading system is suggested in this research, enabling consumers and prosumers to efficiently trade their own produced energy within a community-based market (CBM) structure, thereby achieving optimal energy balance. The primary aim of the suggested framework is to achieve cost reduction through equitable distribution of resources. Additionally, the model examines the Japan Electric Power Exchange market in Tokyo. Lastly, an assessment has been conducted on how the proposed markets affect low-voltage networks.*

**Keywords:** Local Energy Markets, Transactive Energy, Distributed Energy Resources.

**Nomenclature**

**Sets**

| | |
|---|---|
| e | Index of players |
| **Parameters** | |
| $L_e$ | Loads of each player |
| $G_e^{min/max}$ | Min/Max capacity og steerable generation of each player |
| $G_e^{n-ste}$ | Non-steerable generation of each player |
| $\pi^{import}$ | Selling price of upstream grid |
| $\pi^{export}$ | Purchasing price of upstream grid |
| $\pi^{ste}$ | Cost of steerable generation |
| $G^{Max}$ | Maximum capacity of steerable generation |
| $G^{Min}$ | Minimum capacity of steerable generation |
| $\alpha$ | Market participation fee |
| $cap^{export}$ | Maximum capacity for exporting energy to the grid |
| $cap^{import}$ | Maximum capacity for importing energy from the grid |
| **Variables** | |
| $P_e^{e-grid}$ | The quantity of energy being sold to the grid |
| $P_e^{i-grid}$ | The quantity of energy being purchased from the grid |
| $P_e^{e-CBM}$ | The quantity of energy being sold in CBM |
| $P_e^{i-CBM}$ | The quantity of energy being purchased from CBM |
| $G_e^{ste}$ | The generation of each steerable generator |
| $Cost$ | The proposed model's objective |

## 1. INTRODUCTION

### 1.1 Background

The global energy landscape has witnessed a remarkable shift towards decentralization and sustainable energy sources [1]. The growing penetration of distributed energy resources (DER) has sparked a paradigm shift in how power systems operate, presenting both challenges and opportunities. As the world seeks to transition to a greener and more resilient energy future, the concept of Local Energy Markets (LEMs) has emerged as a promising solution to address these evolving dynamics [1], [2].

LEMs represent a transformative approach to energy trading and consumption, enabling communities and stakeholders at the local level to actively participate in the energy ecosystem. By encouraging the fair and efficient exchange of energy generated through renewables and other distributed sources within a specific geographic area, LEMs promote a more equitable distribution of resources, reduce dependency on centralized grids, and foster community engagement in energy-related decisions [3], [4].

This paper aims to examine the notion of LEMs and their potential impact on the future of power systems due to their use. In particular, we delve into the design and mechanisms of a reliable LEM exchanging framework, which enable prosumers (those who both consume and produce energy) and consumers to engage in dynamic energy trading within a community-based market (CBM) structure. Through this, we aim to maximize the utilization of locally generated energy while minimizing energy imports from upstream grids, thus fostering energy self-sufficiency and enhancing overall grid resilience.

Drawing inspiration from various real-world examples and pilot projects, we seek to offer insights into the practical implementation and potential challenges associated with LEMs. Additionally, the paper investigates the implications of LEMs in the context of low-voltage networks, exploring the possible synergies and optimizations that can arise through their integration. Finally, we present a case study analyzing Tokyo's Japan Electric Power Exchange market, offering valuable lessons and comparisons with existing centralized energy systems. By doing so, we aim to shed light on the practical feasibility of LEMs in diverse urban settings.

### 1.2 Literature Review

Recently, Local Energy Markets (LEMs) have been under scrutiny with a focus on their architectural aspects. In line with customer preferences, two main types of LEMs have arisen: Community-Based Market (CBM) and Peer-to-Peer market (P2P). P2P markets facilitate direct interaction between energy sellers and buyers for negotiating electricity costs and volumes, while CBMs involve consumers and prosumers exchanging electricity under the oversight of a community manager. Further insights into CBM and P2P markets are extensively discussed in [5]. According to [6], CBMs are expected to become increasingly popular in the coming years because of the involvement of a third-party entity that streamlines market regulation and interactions with the system operator. Considering the advantages and limitations of both CBM and P2P markets and the growing potential for CBM expansion, this research introduces an innovative CBM model. Moreover, researchers have investigated various localized energy trading approaches, and a comprehensive review of LEM clearing approaches is proposed in [7].

In reference [8], the focus is on examining the notion of trading DERs for cooperative neighborhoods to lower the community's social living expenses. The study demonstrates that the cooperative electricity trading approach offers more favorable economic advantages when compared to non-cooperative methods. Ref. [9] develops and centrally clears the proposed P2P market. Additionally, [10] proposes a two-stage framework, supporting prosumers as key players to share electricity both within the community and with the grid.

The examination of vulnerable consumers' and prosumers' behavior is conducted by evaluating a CBM model that was introduced in reference [11]. Moreover, the study by [12] employs a modified auction-based approach to optimize the sharing of community energy storage and minimize the expenses associated with storage installation. The approach presented in reference [13] suggests an iterative clearing strategy for maximizing profits through the integration of energy and hydrogen transfers within a community. The article [14] investigates many models pertaining to community energy storage operators, including non-cooperative, cooperative, and competitive approaches. Nevertheless, to the best of the authors' knowledge, there is currently no existing work on analyzing the role of CBM in the distribution network.

## 2. SUGGESTED CBM ARCHITECTURE

The suggested Community-Based Market (CBM) architecture presents an innovative design to establish an efficient energy trading system within local communities. This framework enables equitable energy exchange among consumers and prosumers, all under a designated community manager (CM) supervision. The CBM architecture addresses the challenges of the evolving energy landscape by promoting renewable energy adoption and reducing reliance on centralized grids. Consumers and prosumers actively participate in energy trading, negotiating energy cost and volume, thus optimizing the local energy balance.

## 3. THE PROPOSED FORMULATION

In this model, each community manager assumes the crucial responsibility of gathering data from the community members. Once the data from the market participants is collected, the community manager proceeds to clear the market with the primary goal of minimizing overall costs within the community, while simultaneously ensuring the efficient allocation of resources.

$$Cost = \sum_{e} \big( P_e^{i-grid} \pi^{import} - P_e^{e-grid} \pi^{export} + \alpha ( P_e^{e-CBM} + P_e^{i-CBM} ) - G_e^{ste} \pi^{ste} \big) \quad (1)$$

The objective function for this proposed market is articulated in equation (1). The objective function consists of four primary components. The initial part, represented as $P_e^{i-grid}\pi^{import}$, reflects the costs incurred from importing energy from the upstream grid. The second part, denoted as $P_e^{e-grid}\pi^{export}$, represents the revenues generated by exporting excess energy back to the upstream grid. As per this second part, if the community produces more energy than it consumes, the community can reap benefits from this surplus. The third component of the objective function represents the costs associated with participating in the market, denoted by the parameter $\alpha$. This cost, $\alpha$, is relatively smaller compared to $\pi^{import}$ and $\pi^{export}$. Finally, the last component is related to the cost of steerable generation.

$$P_e^{e-grid} - P_e^{i-grid} + P_e^{e-CBM} - P_e^{i-CBM} + L_e - G_e^{ste} - G_e^{n-ste} = 0 \quad (2)$$

Equation (2) illustrates the overall power equilibrium within the community. This equation ensures that the sum of purchased and sold prices to/from the grid of each player is equivalent to the energy demand and generation of the player. Additionally, the duality variable associated with this equation corresponds to the Community-Based Market (CBM) pricing mechanism. Equation (2) encapsulates the interplay between energy transactions and CBM pricing, ensuring a balanced energy distribution that meets the community's needs and aligns with the CBM market dynamics.

$$\sum_{u} ( P_e^{e-CBM} - P_e^{i-CBM} ) = 0 \quad (3)$$

Equation 3 represents a crucial power balance constraint within the community, highlighting the need for equilibrium between the energy purchased and the energy sold within the constrained environment. This equation serves as a fundamental guideline, ensuring that the energy transactions within the community remain in balance, and any energy acquired through purchases must be equal to the energy being sold. This equation serves as a safeguard against market intermediaries, ensuring that participants cannot buy high from the high-demand market and subsequently sell it in the local market. By implementing this measure, the system aims to maintain transparency and fairness, preventing unfair advantage or exploitation of price disparities between markets by individual players.

$$G^{Min} \leq G_e^{ste} \leq G^{Max} \tag{4}$$

Equation (4) represents the constraints on the steerable generation capacity. This equation ensures that the output of the steerable generators does not exceed their designated capacity. In other words, it restricts the steerable generators from producing energy beyond their specified limits. This constraint ensures that the energy generation from these sources remains within their operational boundaries, preventing overutilization and ensuring the reliable and safe operation of the steerable generators.

$$P_e^{e-grid} - P_e^{i-grid} \leq cap^{export} \tag{5}$$
$$P_e^{i-grid} - P_e^{e-grid} \leq cap^{import} \tag{6}$$

Following the outlined in (4) and (5), community members are entitled to export and import power from the upstream grid within the specific capacity.

## 4. DATA

This paper focuses on a market comprising a single community, which consists of three key players ( $e_1, e_2, e_3$ ). Each player has distinct responsibilities within the community. Firstly, player $e_1$ is tasked with consolidating the demand data from various sources within the community. Secondly, player $e_2$ takes on the responsibility of integrating the data related to non-steerable generation (solar) within the community. Lastly, the third player is entrusted with the crucial role of gathering and managing the data concerning steerable generation sources. Together, these three players play integral roles in efficiently coordinating the community's energy demand, non-steerable generation, and steerable generation data, ensuring the smooth functioning of the community-based energy market.

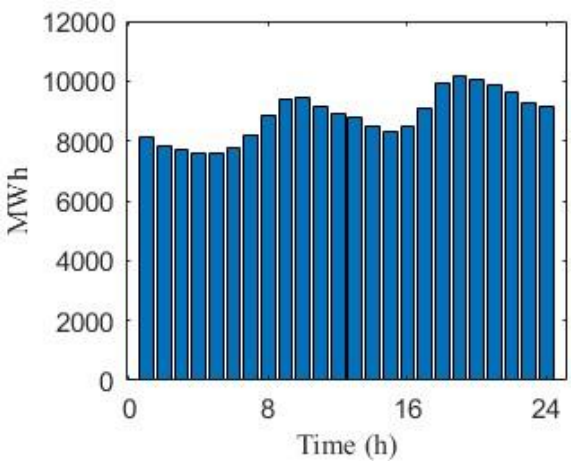


Figure 1. The Demand Data

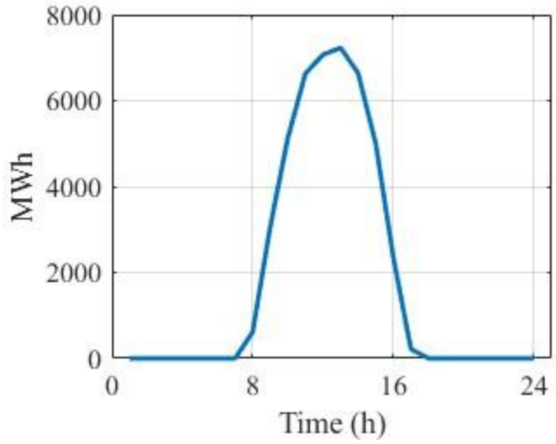


Figure 2. The Solar Generation

Furthermore, comprehensive data, encompassing the load and non-steerable generation specifics for December 31, 2022 can be sourced from the Tokyo Electric Power Company [15]. Figure 1 depicts the demand, while Figure 2 represents the non-steerable generation. The prices for energy imports from the upstream grid were collected from JEPX (Japan Electric Power Exchange) on December 31, 2022 [16]. Additionally, for the purposes of this study, it is assumed that the export price is equivalent to 50% of the import price. Cost of steerable generation is extracted from [1]. Figure 3 demonstrates the export and import prices. Finally, additional data are extracted from [1] and [3].

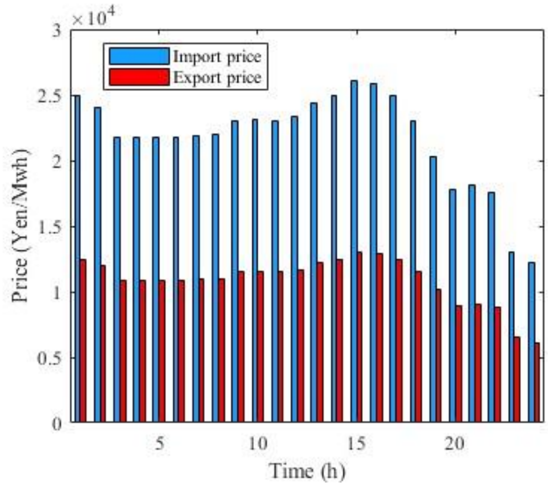


Figure 3. The Import and export prices.

## 5. RESULTS AND DISCUSSIONS

This section conducts a numerical analysis of the proposed method on the CBM to assess its feasibility and effectiveness. The aim is to investigate how well the method performs and whether it is a viable and efficient approach for the given context.

In the initial phase, the performance of the proposed CBM is evaluated by comparing it with a scenario where the CBM is not available. In the absence of the CBM, market players have limited options and can only trade energy with the upstream grid based on the bids and offers presented by the grid.

However, with the CBM in place, market players gain the advantage of conducting energy trades within their own community. If they possess surplus or deficient energy, they can engage in internal energy transactions before resorting to trading with the upstream grid. This prioritization signifies that the primary focus of market players lies in trading energy within their community, and turning to the upstream grid for energy transactions becomes secondary.

By conducting this comparison, the feasibility and effectiveness of the proposed CBM are thoroughly assessed, aiming to determine the extent of improvement it brings in terms of enabling community-based energy trading and optimizing energy flow within the system.

Table 1. Comparison of CBM with and without its Availability

| | CBM | Grid |
|---|---|---|
| *Costs (M)* | 1847.962 | 3536.204 |
| *Exported (MW)* | 70717 | 282044 |
| *Imported (MW)* | 226 | 211881 |
| *Traded (MW)* | 211655 | 0 |

Table 1 presents a comprehensive analysis of the impact of the Community-Based Market (CBM) on the distribution level, comparing its availability with a scenario where it is not accessible. Implementing CBM within the distribution network has shown remarkable cost reductions, signifying its efficiency and effectiveness.

Based on the optimization process results, the costs associated with energy distribution are significantly reduced by an impressive 47 percent. Furthermore, the total energy export from the community experiences a substantial decrease of 75 percent, while a remarkable 98 percent notably reduces the total energy import. These findings underscore the pivotal role of CBM in the distribution network, emphasizing its ability to reduce dependency on the upstream grid.

As a result, the analysis reveals that with the CBM in operation, market players can successfully meet a substantial portion of their energy demands within the community, enhancing self-sufficiency and minimizing reliance on external sources. The study highlights the crucial importance of CBM in empowering communities to manage their energy requirements efficiently, fostering a more sustainable and independent energy ecosystem.
Based on the findings in Table 2, the prices within the CBM exhibit fluctuations between the purchasing and selling prices of the upstream grid. When CBM prices fall below what the upstream grids pay for electricity, all participating players and communities take the opportunity to sell their electricity directly to the upstream grids. On the other hand, when the CBM prices align between the purchase and sale prices of the upstream grid, electricity transactions occur within the CBM.

Table 2. CBM Prices

| Time | CBM Prices | | |
|---|---|---|---|
| | U1 | U2 | U3 |
| t1 | 15250 | 12450 | 12450 |
| t2 | 14800 | 12000 | 12000 |
| t3 | 13695 | 10895 | 10895 |
| t4 | 13695 | 10895 | 10895 |
| t5 | 13695 | 10895 | 10895 |
| t6 | 13695 | 10895 | 10895 |
| t7 | 13730 | 10930 | 10930 |
| t8 | 13775 | 10975 | 10975 |
| t9 | 14300 | 11500 | 11500 |
| t10 | 14335 | 11535 | 11535 |
| t11 | 14330 | 11530 | 11530 |
| t12 | 14450 | 11650 | 11650 |
| t13 | 14965 | 12165 | 12165 |
| t14 | 15300 | 12500 | 12500 |
| t15 | 15815 | 13015 | 13015 |
| t16 | 15700 | 12900 | 12900 |
| t17 | 15245 | 12445 | 12445 |
| t18 | 14300 | 11500 | 11500 |
| t19 | 18250 | 15530 | 15530 |
| t20 | 17790 | 14990 | 14990 |
| t21 | 11845 | 9045 | 9045 |
| t22 | 11560 | 8760 | 8760 |
| t23 | 11530 | 8730 | 8730 |
| t24 | 11530 | 8730 | 8730 |

The significance of the CBM model becomes evident for market players as it allows them to optimize their profits and significantly reduce costs. By offering more competitive prices, the CBM facilitates efficient energy trading, providing an advantageous platform for market players and DER owners. In contrast, without joining the CBM, market players are compelled to exchange electricity with the upstream grid at fixed selling and purchasing prices, which may not be as beneficial.

The proposed CBM model enables market players and DER owners to engage in hourly electricity trading, offering greater flexibility and potential for higher profits. This differs from Japan's wholesale market, which operates under the feed-in-tariff (FIT) systems, where DER owners are obligated to export their power to the upstream grid at fixed rates, often lower than what can be obtained through the CBM. Consequently, the CBM structure emerges as a more profitable option for owners of DERs compared to the FIT scheme, emphasizing its potential to boost economic returns for participants in the energy market.

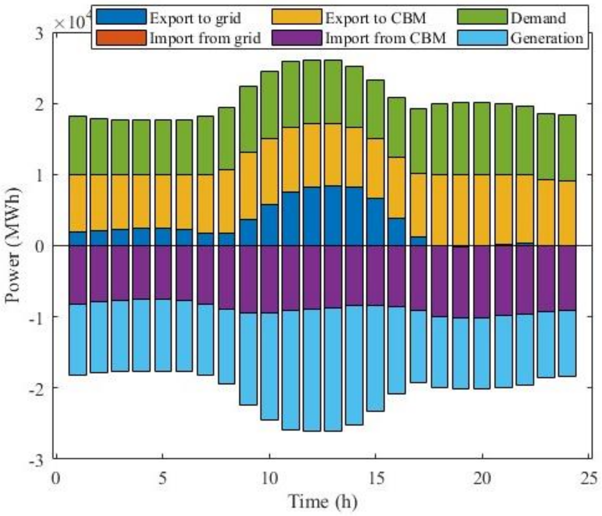


Figure 4. The power balance in the proposed market.

In Figure 4, the comprehensive power balance is visually presented. Positive values in the figure represent the total demand, which includes the sum of electricity sold to the upstream grid and the electricity traded within the Community-Based Market (CBM).

On the other hand, negative values in the figure depict electricity purchases from the upstream grid, electricity purchases made within the CBM, as well as non-dispatchable and dispatchable generation. These negative values signify the amount of electricity acquired from external sources to meet the community's energy requirements.

The visual representation in Figure 4 offers a clear overview of the energy flow within the system, showcasing the interplay between electricity demand, supply, and trading activities both with the upstream grid and within the CBM. By considering the overall power balance, stakeholders can gain valuable insights into the efficiency and effectiveness of the proposed modeling approach, providing a comprehensive view of energy management and distribution within the community.

## 6. Conclusion

With the growing installation of DERs and an increasing number of prosumers, CBMs are perceived as a promising evolution in the future energy landscape. In this research, a novel CBM structure was introduced, designed to minimize total costs within the energy market.

To assess the viability and effectiveness of this novel CBM structure, the developed model was implemented and evaluated in the context of the Japan Electric Power Exchange (JEPX). The analysis utilized real-time wholesale electricity prices and demand load data from Tokyo, considering the anticipated rise in RES penetration in Japan in the coming years.

The comparison was made between the proposed CBM structure and a scenario where trading solely with the upstream grid is the sole option available to market players. This comparative study aims to demonstrate the advantages and benefits of implementing the CBM, especially in terms of cost optimization and improved energy trading options for market participants. The results of this study are expected to shed light on the potential of CBMs as a forward-looking solution to accommodate the increasing use of DERs and prosumers, paving the way for a more efficient and sustainable energy market in the future.

The comparative analysis between the CBM implementation and the exclusive reliance on the upstream grid yielded significant findings:

- Reduction in Total Export Energy: By employing the CBM, the total energy export to the grid experienced a substantial decrease of 75 percent. This result indicates that the community-based market allows for more efficient utilization of locally generated energy, reducing the need to export excess electricity to the grid.
- Decrease in Total Import Energy: Implementing the CBM led to an impressive reduction of 98 percent in the total energy imported from the grid. This outcome highlights the ability of the CBM to facilitate effective energy exchange within the community, diminishing the reliance on external sources and optimizing energy distribution locally.

These primary results demonstrate the significant advantages of the CBM approach in enhancing energy self-sufficiency and reducing both energy export and import dependencies on the grid. By empowering communities to trade energy within their own network, the CBM fosters a more sustainable and resilient energy ecosystem, benefitting both market players and the broader energy landscape.

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