Mitigating Supplier Pricing Power in Local Thermal-Electric Energy Markets with Welfare-Driven Storage

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***Abstract*—Local energy markets are a promising approach to promote the integration of renewable energy sources. As future energy systems are expected to intensify the electrification of the heat supply, local thermal-electric energy markets (LTEEMs) are of growing interest. Previous research highlights that a key challenge in LTEEMs is the risk of supplier market power abuse due to limited market participants. This study investigates whether welfare-driven storage assets can mitigate such pricing power. We extend an existing Nash-Cournot framework for local energy markets to analyze an energy market akin to a medium-sized city. Our results show that the introduction of welfare-driven storage assets redistributes welfare between suppliers and consumers while enhancing overall market efficiency. Furthermore, coupling multiple LTEEMs through the electricity grid benefits both the electricity and heat markets across regions, even when storage units are installed in only one region.**

***Index Terms*—energy storage, game-theory, local energy market, market power**

I. Introduction

Local energy markets are considered viable alternatives to traditional centralized energy trading, enhancing grid operation of electricity [1] and facilitating the integration of renewable energy [2]. Initially, the terms *local electricity markets* and *local energy markets* were used interchangeably in works that helped conceptualize these markets, such as [3] and [4]. Recent research has expanded to include multiple energy carriers, introducing local multi-energy markets. In particular, local thermal-electric energy markets (LTEEMs) have been introduced to address the increasing interdependence between the electricity and heat sectors, that combined heat and power (CHP) plants and heat pumps provide [5]. Most of these studies focus on the design and benefits of the markets, often assuming perfect competition.

In previous work [6], we show that perfect competition is not guaranteed in LTEEMs, as the local nature poses challenges to efficient operation. Profit-maximizing suppliers can exploit the pricing power to increase producer surplus at the cost of market efficiency.

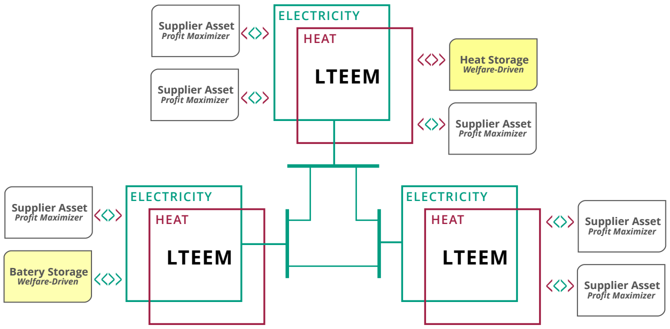

Fig. 1: Illustrative setup of local thermal-electric energy markets (LTEEMs), interconnected through the electricity grid. Participants are profit-maximizing agents.The impact of welfare-driven storage assets on market outcomes is studied.

Strategies to reduce imperfect competition can be grouped into two categories. The first involves direct market regulation, such as price caps or taxes. For example, the authors in [7] propose a clearing mechanism to mitigate allocation inefficiencies in local electricity markets. The second group consists of strategies that indirectly influence the market by encouraging the participation of more agents and the adoption of new technologies to improve market efficiency. We focus on this second group, specifically exploring whether welfare-driven storage assets can enhance market efficiency.

The use of electricity storage to improve market efficiency well-established, with numerous studies examining the impact of electricity storage on market outcomes. For example, the authors in [8], show that storage can improve electricity markets with locational marginal pricing, by alleviating grid congestion. Other studies explored the role of storage in local P2P electricity markets, focusing on maximizing owners' utility [9]–[12]. In contrast, research on heat storage is less developed, often addressing demand response potential's effect on system costs [13] or its influence on overarching (perfect) electricity markets [14]. To our knowledge, no study has yet evaluated the role of storage assets in a multi-energy imperfect local energy market.

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A. Scope and Contributions

This study explores how welfare-driven storage assets can mitigate supplier pricing power in LTEEMs. To this end, we extend our previous analysis [6], which focused on profit-maximizing suppliers, to include welfare-driven assets. The framework is also expanded to model interconnections between multiple LTEEMs, as illustrated in Figure 1, enabling an analysis of how storage capacity distribution across regions influences (or not) market efficiency.

We model competition in LTEEMs using a Nash-Cournot approach, implemented as a complementarity problem. A case study is conducted using a reference market, representative of a medium-sized German city. The energy system includes gas power plants, gas and waste-to-energy CHP plants, heat pumps, heat-only boilers (HOB), and photovoltaic systems. Our findings reveal that adding welfare-driven electricity and heat storage assets in oligopolistic markets can improve market efficiency, with the greatest impact observed in the redistribution of welfare. Specifically welfare-driven storage assets help to restore consumer surplus that is lost due to the supplier pricing power. These effects are shown to influence not only the market where the storage asset is located but also neighboring markets.

B. Outline

The remainder of this paper is structured as follows: Section II provides a brief overview of market efficiency and competitive market equilibrium models, essential for understanding the problem and interpreting the results. Section III details the methodology used to model LTEEMs, emphasizing the extensions to the base framework. Section IV presents the experiments and discusses the results. Section V concludes.

II. BACKGROUND

A. Market (Allocative) Efficiency

In this work we use the term *market efficiency* to refer specifically *allocative efficiency*. However, it is important to note that market efficiency is a broader concept in economics, encompassing more than just allocative efficiency.

A market is considered allocatively efficient when goods are distributed in a way that maximizes social welfare. Let $SW(Q)$ be the social welfare of the market for a given quantity Q of goods. The efficient allocation is the quantity Q^* that maximizes the social welfare, i.e.,

$$Q^* = \arg\max_{Q}\{SW(Q)\}.$$

The market (allocative) efficiency η_Q for a given quantity Q is defined as the ratio of the social welfare at the current allocation to that at the efficient allocation, i.e.,

$$\eta_Q := \frac{SW(Q)}{SW(Q^*)}.$$

To assess the market efficiency of a competitive market, a benchmark model of a perfectly competitive market is required. Fortunately, the equilibrium of perfectly competitive markets can be formulated as a single optimization problem, solvable using standard optimization techniques. In contrast, imperfectly competitive markets do not allow for such direct optimization and require other methods, which we briefly discuss next.

B. Imperfect Market Equilibrium Models

Market equilibrium models are used when both the demand are endogenously determined. In perfectly competitive markets, the equilibrium corresponds to the efficient allocation and can be solved as a single optimization problem. However, for imperfectly competitive markets, methods capable of handling multiple agents with conflicting objectives are necessary..

One approach to model competitive markets is through a Nash-Cournot game, where consumers are price-takers and suppliers are profit-maximizers who can influence prices by controlling their supplied quantities. Let $P(Q)$ denote the market-clearing price function, where Q is the total quantity supplied to the market. Define $\boldsymbol{x} = (x_1, x_2, \ldots, x_N)$ as the quantities supplied by the N agents in the market, with $\sum_{i=1}^{N} x_i = Q$. The utility of supplier i is

$$u_i(x_i, x_{-i}) = x_i P(Q) - c_i(x_i),$$

where $c_i(x_i)$ is the supplier's cost function, and x_{-i} represents the vector of quantities supplied by all agents except i. A solution $\boldsymbol{x^*} = (x_1^*, \ldots, x_N^*)$ is a market (Nash) equilibrium if no agent can unilaterally improve its utility by changing its own decision variable, i.e.,

$$x_i^* = \arg\max_{x_i \in \mathcal{X}_i}\{u_i(x_i, x_{-i}^*)\}, \quad \forall i \in [1 \,..\, N].$$

where $\mathcal{X}_i$ is the set of feasible quantities for supplier i.

When the utility functions are concave and the constraints defining the feasible quantities are linear, the problem can be reformulated as a mixed complementarity problem (MCP). This reformulation enables the use of commercial solvers, such as Path, for efficient solution. For a detailed explanation of the MCP formulation process, refer to [15].

III. METHODOLOGY

For our analysis, we model LTEEMs as a Nash-Cournot game, formulated and implemented as a mixed complementarity problem (MCP). We extend the open-source framework for modeling local multi-energy markets from [6] to include welfare-driven assets and the simultaneous modeling of multiple regions. While our focus is on the specific case of LTEEM, the extension is designed with the framework's generality in mind, ensuring it remains applicable to other types of multi-energy markets.

A. Base Framework

The base framework consists of a abstract set of equations that can be used to model a local multi-energy market in a single region. It defines energy carriers $c \in \mathcal{C}$, supplier assets $a \in \mathcal{A}$, and time steps $t \in \mathcal{T}$. Consumers are modeled as price-takers, with utility given by a quadratic function of energy demand:

$$U_{c,t}(D_{c,t}) = a_{c,t} D^0_{c,t} D_{c,t} - \frac{1}{2} a_{c,t} D^2_{c,t}, \tag{1}$$

where $D^0_{c,t}$ is the base demand for carrier c at time t, and $a_{c,t}$ is the demand elasticity.

Suppliers are described using a general supplier model (GSM), which consists of linear conditions capturing costs and operational constraints. The GSM can represent various technologies, such asCHPs, heat pumps, and battery storage. The GSM interacts with the market through the variable $P^M_{a,c,t}$, denoting the power supplied to the market by asset a of carrier c at time t. As we do not modify the internal structure of the GSM, we refer to its equations as *GSM conditions* and direct the reader to [6] for the detailed equations.

B. Welfare-Driven Assets Extension

We introduce a second type of supplier asset in the framework, aimed at maximizing social welfare rather than individual profit. These welfare-driven assets use the same generalized supplier model (GSM) as in the base framework but differ in their objective function.

Profit-maximizing agents aim to maximize utility as follows:

$$\begin{aligned} \max_{P^M_{a,c,t}} & \sum_{c \in \mathcal{C}} \sum_{t \in \mathcal{T}} \left(P^M_{a,c,t} P(P^M_{a,c,t}) - C_{a,c,t}(P^M_{a,c,t}) \right) \\ \text{s.t.} & \\ & \text{GSM Conditions}, \end{aligned} \tag{2}$$

where $P(P^M_{a,c,t})$ is the price function, and $C_{a,c,t}$ is the cost function representing the costs incurred to supplier a to generate supply the energy commodity c.

In contrast, welfare-driven agents aim to maximize the social welfare, i.e.,

$$\begin{aligned} \max_{P^M_{a,c,t}} & \sum_{c \in \mathcal{C}} \sum_{t \in \mathcal{T}} \left(U_{c,r,t}(D_{c,r,t}) - C_{a,c,t}(P^M_{a,c,t}) \right) \\ \text{s.t.} & \\ & \text{GSM Conditions}, \end{aligned} \tag{3}$$

where r denotes the region where the welfare-driven agent is located, as we will discuss in the next subsection. Although total social welfare includes contributions from all regions and suppliers, for the welfare-driven agent, terms related to other agents and regions appear as constants and can be omitted from the objective function.

To ensure non-negative energy demand, we introduce the concept of a must-supply price $\pi^L_{c,r,t}$ and the corresponding supply amount $P^L_{c,r,t}$. The must-supply price equals the marginal utility of the consumer when demand is zero,i.e.,

$$\pi^L_{c,r,t} = a_{c,r,t} D^0_{c,r,t}. \tag{4}$$

This condition is added to the MCP formulation through the complementarity condition

$$0 \leq P^L_{c,r,t} \perp D_{c,r,t} \geq 0. \tag{5}$$

This condition is necessary because storage agents may buy energy at low-demand times to resell it when demand is higher. Although it indirectly limits prices by defining a point where demand is zero, this is not a regulatory price cap, as it does not restrict the price consumers may ultimately pay; consumer demand at this price remains zero.

C. Multi-Region Extension

We consider that local multi-energy markets can be interconnected for certain energy carriers but remain isolated for others. In the case of LTEEM, regions are interconnected through electricity, as electricity transport is significantly more efficient than heat transport, and the necessary grid infrastructure already exists.

To that end, we define a set of regions $r \in \mathcal{R}$. Each region r has its own set of supplier agents $\mathcal{A}_r \subseteq \mathcal{A}$. Importantly, each supplier agent belongs to only one region, meaning:

$$\mathcal{A}_r \cap \mathcal{A}_{r'} = \emptyset, \quad \forall\, r, r' \in \mathcal{R},\, r \neq r'.$$

For transportable commodities, we define $P^I_{c,r,t}$ as the power injected by region r into the transport network of carrier c at time t. The local power balance for region r is given by

$$\sum_{a \in \mathcal{A}_r} P^M_{a,c,t} + P^L_{c,r,t} - P^I_{c,r,t} - D_{c,r,t} = 0. \tag{6}$$

Note that the demand $D_{c,r,t}$ is now indexed by region r. We assume the transport network is lossless and has infinite capacity, meaning it is sufficient to ensure that the total power injected into the network across all regions is zero, i.e.,

$$\sum_{r \in \mathcal{R}} P^I_{c,r,t} = 0. \tag{7}$$

The power injection variable $P^I_{c,r,t}$ is managed by the grid operator, a new agent type. The grid operator is assumed to be social welfare driven, meaning they optimize social welfare by solving the following problem:

$$\begin{aligned} \max_{P^I_{c,r,t}} & \sum_{r \in \mathcal{R}} \sum_{c \in \mathcal{C}} \sum_{t \in \mathcal{T}} U_{c,r,t}(D_{c,r,t}) - \sum_{a \in \mathcal{A}_r} C_{a,c,t} \\ \text{s.t.} & \\ & \text{Eqs. (6)-(7)}. \end{aligned} \tag{8}$$

Note that the optimization problem for the grid operator, as defined in (8), has a convex quadratic objective function with linear constraints. As a result, the Karush-Kuhn-Tucker (KKT) conditions are both necessary and sufficient for optimality. These KKT conditions can be incorporated into the MCP formulation of the base framework.

IV. EXPERIMENTS AND DISCUSSION

In this section, we evaluate the impact of welfare driven storage assets and the coupling of multiple LTEEMs on market efficiency and welfare distribution. Two experiments are conducted using an illustrative case study. The first investigates how storage assets affect the market efficiency of a single oligopolistic LTEEM. The second examines how coupling multiple LTEEMs through the electricity grid impacts market efficiency across regions and how the distribution of storage capacity among regions influences regional efficiency.

A. Base LTEEM

We base our experiments on a fictitious LTEEM with supply and demand characteristics akin to a medium-sized German city. The market includes six types of suppliers: gas power plants (Gas PP), gas CHPs, waste-to-energy (WtE) CHPs, heat pumps (HP), heat-only boilers (HOB), and photovoltaics (PV). Technical parameters, such as efficiency and costs, were sourced from the Danish technology catalog [16] and are detailed in Table I. We assume a constant demand elasticity of 0.85 for electricity [17] and 1 for heat. Load profiles are generated using the *demandlib* module from the Open Energy Modeling Framework [18], based on an annual energy demand of 960 MWh for heat and 740 MWh for electricity.

B. Single Node: Impact of Storage Assets in LTEEM

To assess the theoretical impact of storage assets on market outcomes in a single LTEEM, we simulate four scenarios: *Perfect Competition*, *Oligopoly*, *Selfish Storage*, and *WD Storage*. Each scenario runs on a representative day of each season—winter, spring, summer, and autumn. Unless stated otherwise, the results are averaged across these seasons.

The *Perfect Competition* scenario serves as a benchmark, representing the maximum achievable social welfare and defining 100% market efficiency (see Section II). The *Oligopoly* scenario models the base case, where all suppliers are profit-maximizing agents and no storage is available. We then introduce storage assets, distinguishing between *Selfish Storage*, which maximizes individual profit, and *WD Storage*, which maximizes social welfare. We consider a single agent owning both heat and electricity storage assets.

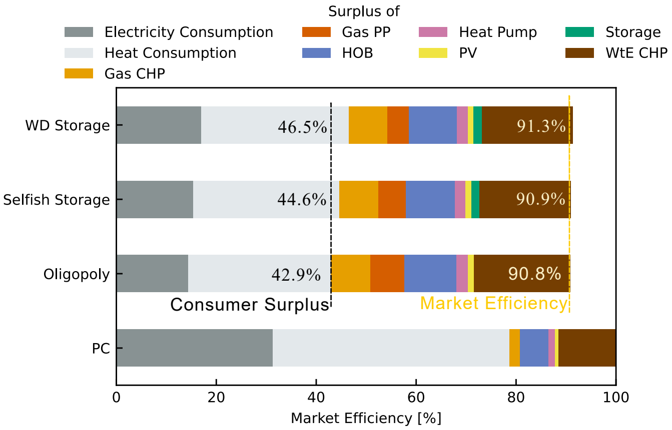

Fig. 2: Market efficiency of the four scenarios. Gray bars represent consumer surplus, while colored bars indicate producer surplus.

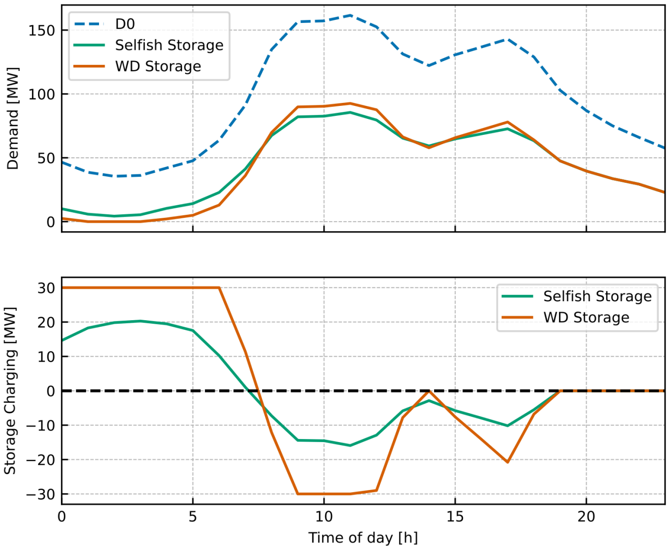

Fig. 3: Comparison of selfish and welfare-driven electricity storage operations on a typical winter day. The top panel shows the cleared demand over time compared to the base demand (D^0). The bottom panel illustrates the corresponding storage charging and discharging behavior.

Figure 2 illustrates consumer and producer surplus across all scenarios. The *Oligopoly* scenario results in a 9% reduction in market efficiency compared to the perfect competition benchmark. Additionally, welfare distribution shifts significantly: in the *PC* scenario, the consumer-to-producer surplus ratio is 3.7, whereas in the *Oligopoly* scenario, it drops to 0.89. Introducing storage assets improves market efficiency in both scenarios, with welfare-driven storage showing a greater impact. These assets also help restore consumer surplus, with welfare-driven storage doubling the effectiveness of selfish storage, increasing consumer surplus by 3.6%.

Figure 3 illustrates the operational differences between selfish and welfare-driven electricity storage on a winter day. Both charge during low-demand periods, when prices are lower, and discharge during high-demand periods, when prices are higher. This behavior enhances social welfare by redistributing energy supply over time. While charging raises prices and benefits producers, the subsequent discharging offsets this effect and increases consumer surplus by supplying energy when consumer utility is higher. This behavior also boosts traded energy volume, improving market efficiency.

The key difference between selfish and welfare-driven storage lies not in timing but in capacity utilization. Welfare-driven storage maximizes capacity use, enhancing the load-shifting effect and further improving efficiency.

TABLE I: Techincal Parameters of the base LTEEM

Asset	Parameter Unit	Free cooling cost[1] [EUR/MWh]	Generation Cost [EUR/MWh]	Installed Capacity [MW]	Storage Capacity [MWh]	Other	Value
Gas CHP	Electricity	–	100	20	–	Heat Production to Electricity Ratio	1.4
	Heat	20	–	30	–		
WtE CHP	Electricity	–	40	15	–	Heat Production to Electricity Ratio	2.5
	Heat	20	–	40	–		
Gas PP	Electricity	–	67	100	–		
HOB	Heat	–	40	100	–		
PV	Electricity	–	–	5	–		
Heat Pump	Electricity → Heat	–	–	10	–	COP	3
Storage[2]	Electricity	–	–	30	200	Efficiency	85%
	Heat	–	–	20	300	Efficiency	95%

[1] When produced heat is not feed into the grid. [2] Only for the scenarios with storage.

C. *The impact of spatial distribution of storage assets*

This experiment evaluates how coupling LTEEMs and storage placement affect social welfare. We model three interconnected regions (A, B, and C), each with its own base LTEEM, identical supplier assets, and demand profiles. While electricity can be transported between regions, heat cannot. First, we compute the oligopolistic equilibrium for each region in isolation as reference. Next, we calculate the market equilibrium with interconnected regions but no storage. Then, we add storage to region A only, followed by adding storage everywhere.

Figure 4 shows the impact of infrastructure and storage distribution on social welfare across regions. Coupling the electricity markets increases competition, significantly raising consumer surplus from electricity demand, with heat markets also benefiting. Adding storage to region A increases consumer surplus by 7.2%, while producer surplus decreases by 0.5%. This storage also affects other regions, though less significantly. When storage is added everywhere, consumer surplus outside region A more than doubles, reaching a 16.3% increase. This effect is consistent across all regions due to system symmetry.

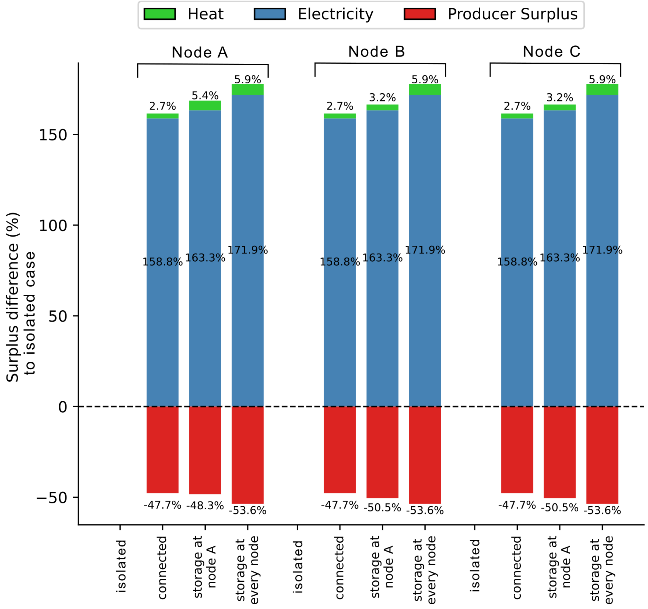

Fig. 4: Changes in producer surplus (red), and consumer surplus from electricity (blue) and heat (green) relative to the benchmark scenario with isolated regions.

V. Conclusion

We analyzed the impact of welfare-driven storage assets on market efficiency and welfare distribution in local thermal-electric energy markets (LTEEMs), extending a Nash-Cournot modeling framework for multi-energy local markets to incorporate welfare-driven storage and multi-region coupling. This enabled the evaluation of storage's role in mitigating supplier pricing power and how its effect on market efficiency.

Our approach has limitations, such as grid model simplifications and the assumption of perfect information, but it lays a foundation for further research. Results based on a system comparable to a medium-sized German city show that storage improves market efficiency, mainly affecting welfare distribution. We show that storage assets can wield market power, making welfare-driven storage critical for maximizing the benefits of storage integration. Our findings also highlight that LTEEMs benefit from existing electricity grid infrastructure. Connecting markets through the grid enhances competition and restores consumer welfare, not only for electricity but also for heat. Additionally, storage placed in one region positively affects other regions, but to a lesser degree, with heat markets also benefiting despite being unconnected by heat transport.

Given the demonstrated potential of welfare-driven storage, the next step is to enhance the model with a more detailed grid model. would enable a deeper investigation into how storage can reduce grid congestion and allocation inefficiencies in competitive local energy markets.

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