Residential district heating network with peer-to-peer market structure: The case of Nordhavn district

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Abstract. Over the last decades, district heating has been under development, especially the technologies like heat pumps, solar thermal and cogeneration. However, there is still a long way to go regarding regulation, legislation and market liberalization, which varies across countries and regions. The objective of this work is to investigate the potential benefits of decentralized district heating systems in residential areas. By studying a case study of EnergyLab Nordhavn, a residential area in Copenhagen, Denmark, the paper compares the market outcomes of decentralized systems such as community markets to the centralized pool market currently in practice, under the EMB3Rs platform. The study focuses on key market outputs such as dispatched production, revenues, and daily consumption patterns. Additionally, the paper examines the impact of advanced features such as flexible heat consumption and network awareness in the market. The results of this research suggest that decentralized district heating systems have the potential to improve market outcomes and increase energy efficiency in residential areas.

Keywords: District Heating, Residential Heating, Decentralized Market Structures, Community, EMB3Rs.

1 Introduction

District Heating (DH) systems play a crucial role in meeting energy demand for heating and cooling, and it is important to consider viability in their planning and design. The research in [1] aims to examine the impact of integrated planning on the environmental and economic sustainability of DH systems. A decision tool for local authorities is developed based on a modified Vester system analysis and research in spatial, environmental, and energy planning. The main factors affecting DH feasibility include a mix of functions, density, building type, and heat source. Spatial planning policies must consider building density to ensure the long-term viability of DH systems. In [2] information is provided on how to design and plan DH systems in countries with low DH market share for heating and cooling supply. The article covers: building a heat atlas through essential techniques and methodologies for district thermal energy demand prediction and the integration of sustainable resources; Identifying technical barriers to the implementation of sustainable heat sources; Discussing technologies for the optimal planning of DH systems including current approaches, novel configurations, and upgrading measures for existing DH systems. Also, in [3] a novel 5th-generation DH model that implements the energy-prosumer concept of bilateral heat trading between the DH network and the building is proposed. The model utilizes the low temperature of the DH return pipe's water and its technical feasibility was evaluated through simulation analysis. Also, the replacement of old technology is assessed in [4] through the economic impact of converting six conventional DH systems in Poland to more sustainable and efficient systems. The new systems would include flat solar collectors, seasonal thermal energy storage, and gas heating plants as flexible heat sources.

Combined Heat and Power (CHP) plants can also play an important role in DH due to its flexibility. For instance, [5] presents simulations of a real CHP unit and DH network to show that this improves overall economic efficiency and increases the CHP unit's operating range in the electricity market. The proposed methodology provides logical results for calculating CHP efficiency indicators. While the work in [6] assesses the integration of pipeline energy storage in DH systems by adjusting CHP unit electricity production based on fluctuating electricity prices. However, the operational use of pipeline energy storage is challenging due to uncertainty, computational complexity, and limited sensors. To overcome these challenges, this study models CHP economic dispatch as a Markov decision process and uses reinforcement learning to estimate system dynamics.

The integration of solar energy into DH systems has become a crucial aspect in reducing greenhouse gas emissions and creating sustainable energy solutions for communities. [7] aims to determine the most cost-effective distribution system for a solar DH system by comparing the marginal life cycle cost of two systems. The simulations show that a novel distribution system with lower network temperatures and central domestic hot water preparation is the most efficient. The study found that the investment costs were more significant than operational costs in reducing life cycle costs. In [8] the use of solar energy transformation technologies in DH is also addressed. It examines the first year of operation of a large-scale solar collector field in the Baltic states. The study analyzes solar collector efficiency and factors such as temperature and flow. The benefits of optimal solar collectors’ placement, storage space, and demand for thermal energy for solar energy production are also highlighted. [9] provides a case study to include solar energy in cooling systems in the Middle East. The work concludes that the availability of installation area and electricity tariff play a significant role in the economic competitiveness of different solar-cooling configurations. The optimal solution is the photovoltaic district cooling system configuration, offering the lowest operating cost and the highest environmental performance.

Thermal energy storage can also be used to balance energy demand and supply, ensuring stable and efficient operation of the system. This is supported by the study in [10] showing that using thermal energy storage, specifically chilled water, in a community of 2000 buildings, can have a positive impact on reducing the need for electricity generation and storage. This can lead to a self-sufficient community powered by renewable energy. The simulations indicate that the use of thermal storage reduces the required photovoltaics rating and the electric energy storage system capacity during the summer. [11] also provides an overview of thermal communities’ research, but a lack of literature, directives and case studies is found. The authors state that further feasibility assessments of published studies are needed. Alternatively, [12] presents a model for assessing the economic viability of integrating a supermarket and power substation waste heat into existing DH systems.

In this work, the aim is to compare and analyze market outcomes of centralized and community schemes. In particular, it is relevant to address the effects of the choice of market mechanism on parameters such as the price of heat, generation and consumption schedules and settlement. The second aim of this case study is to validate and test the EMB3Rs platform. This is done by running a full simulation including the Core functionalities (CF) module, Geographical Interface System (GIS), Techno-Economic (TEO), Market Module (MM), and Business Module (BM).

2 Market Structures and EMB3Rs Platform

In this section, the market structures are explored, as well as the main features and capabilities of the EMB3Rs platform.

2.1 Market Structures

The main purpose of this subsection is to provide a set of market structures capable of simulating existing and future markets for DH systems. More precisely, three different market designs are available: Pool, Peer-to-Peer, and community-based structures.

1. Pool: In this design, the merit order mechanism is used (similar to the electricity market) to determine the order in which producers and consumers will be dispatched. This mechanism prioritizes the cheapest producers, as well as the highest-bidding consumers, to ensure that the most cost-effective energy sources are used. The market clearing price is determined by the price bid of the marginal producer or consumer, which is the agent that is only partially scheduled. All participants in the market will pay and receive the same price per unit of energy, known as uniform pricing. The mathematical formulation for this market design can be found in [13];
2. P2P: This mechanism proposes that any pair of peers can trade heat on a bilateral basis, without third-party (coordinator) supervision. That is, each peer can exchange with another peer on an individual basis, defining the amount of energy to be bought or sold at a given price. Note that prosumers can trade with both producers and consumers, but such interaction is limited by the type of offer they submit on the market. The main advantage is that the privacy of peers is protected, as peers share limited information with those they want, taking full control of their facilities. A detailed description of this design can also be found in [13];
3. Community-based: The community-based market design intends to represent a more hierarchical structure of bilateral peer trades. In this semi-decentralized model, there is a community manager responsible for the community's energy management. In terms of privacy, it requires less exchange of information than the Pool market model but more than the P2P market

model. This system is often seen as a compromising solution between the centralized and decentralized approaches. The community manager supervises all the trading activities within the community, as well as works as an intermediary in the heating trade with the main heat supplier [13].

2.2 EMB3Rs Platform

The EMB3Rs platform is a tool for assessing the feasibility of exchanging excess heat and cooling in several sites, including industrial operations and DH systems. Through simulating various supply-demand scenarios, network configurations, and commercial and market frameworks, the platform can assist users and stakeholders in comprehending the economic viability of investing in recovering waste heat and cooling as an energy source.

The five modules of the platform work together to provide a comprehensive understanding of the possibilities for recovering excess heat and cooling in various situations. The CF module enables the identification of possible sources and sinks of excess heat and cooling, as well as the associated costs of recovery and utilization. The GIS module helps to find and evaluate potential solutions for connecting sources and sinks, taking into account factors such as losses, costs, network length, and available pipeline capacity. The TEO module helps to identify the most cost-effective solutions for utilizing excess heat, considering factors such as regulations, available heat, load profiles, and technical and economic characteristics of technologies. The MM enables users to simulate current and future trends in the heat and cooling markets and assess the economic potential and savings of their investments. Using the MM, users can choose the best market framework for their specific economic, environmental, and social interests, helping them to make informed decisions about their investments in recovering excess heat and cooling. The BM is designed to consider different ownership structures and market frameworks and evaluate key metrics such as net present value, levelized cost of heat, and internal rate of return.

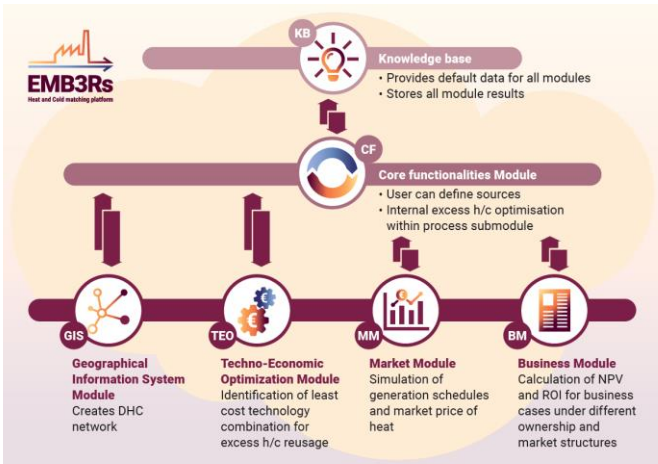

Fig. 1. EMB3Rs Platform modules functionalities.

3 Case Study Description

This section provides a complete description of the case study, including goals for simulation under the EMB3Rs platform, as well as the collected data used in the case study.

The case study area is located in the Nordhavn neighbourhood in the city of Copenhagen. The area is linked to the EnergyLab Nordhavn (ELN) project [14]. It is composed of 30 residential consumers and a local supermarket. The residential buildings are supplied by the DH network operated by HOFOR. Note that the DH network in this area is already in place. Furthermore, the area is connected to the greater Copenhagen DH Network. The local supermarket from the chain Meny can provide excess heat that could inject back into the Nordhavn DH grid. The company Danfoss owns the heat recovery unit (HRU) of the Meny supermarket.

From this project, the total hourly heat consumption of 30 consumers is available. This consumption includes domestic hot water (DHW) and space heating (SH). Also, for the supermarket, the heat consumption is available, as well as an hourly production profile. In addition to the collected data, several open data sources have been used to simulate a price signal from the grid connection. The procedure for simulating this price signal can be found in [15]. Among others, electricity spot prices for DK2 are used, obtained from Nord Pool open data.

4 Results

In this section, the different agent behaviour is analyzed through different market mechanisms and features. Note that due to the limited number of pages, it is not possible to show all the results and functionalities from the EMB3Rs platform.

4.1 Consumption flexibility

The simplest simulation of the Pool market is used, with and without the energy budget bidding format, to see the effect of flexible consumption on different market outcomes: the load profiles, the generation profiles, and the market prices. The scheduled load for each hour of the day averaged over the full simulated period is shown in **Fig.** ***2***. The solid red line shows the average pattern in the total scheduled load when there is no energy budget, so the load is more inflexible. The dotted line shows the effect of this energy budget, which allows the load to be shifted from one hour to another hour during the same day. It can be seen that a large share of the load during morning and evening hours is shifted to the night, and some of it is shifted to mid-day. This is the result of electricity prices normally being higher in the morning and evening so that the supermarket heat is more expensive there. To minimize cost, the load is scheduled to avoid those expensive periods of the day.

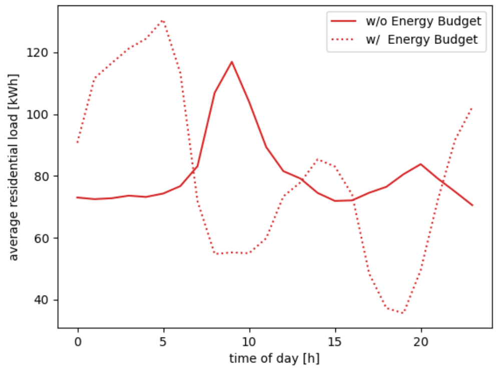

Fig. 2. Energy Budget effect on the Pool Market consumption pattern.

4.2 Network-aware mechanism

Generally, the different market designs are network agnostic. That is, the physical constraints to heat transport resulting from the district heating or cooling network layout are not considered. However, in the short-term pool market, there is an option to take network directions into account. As a result, the generation and consumption are scheduled such that the flow directions in the network are respected.

Fig. ***3*** shows the effect of adding those network constraints on the scheduled generation of the supermarket (yellow) and grid (blue). The average daily generation pattern in a pool market without network (solid line) is compared with the network-direction option (dotted line). It can be seen that the supermarket is, on average, consistently scheduled less, and this is offset by increasing the grid import. The reason is that due to the network constraints, there are now several residential consumers that cannot be served by the (generally cheaper) supermarket excess heat. These consumers have no choice but to import heat from the grid instead.

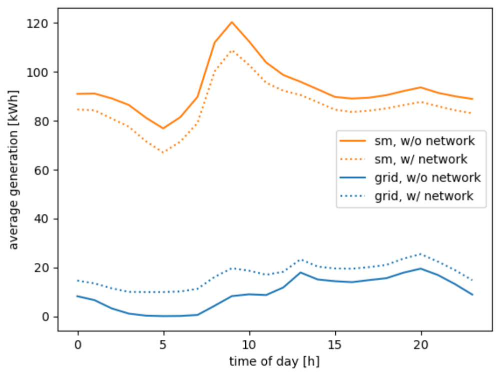

Fig. 3. The effect of network constraints on the daily generation patterns of the supermarket (sm) and grid.

4.3 Community Markets (Peak Shaving)

For the community market, the user must choose an objective for the community. The short-term MM provides two options for this: peak shaving and autonomy. For this market type, the user needs to define which agents are in the community, and which agents are not. In this case study, we consider that all agents except the grid connection are in the community. Energy Budget feature is activated in all simulated markets in 4.3 and 4.4.

First, the community market is compared with the peak-shaving penalty to the pool market. The daily scheduled generation patterns for the grid and the supermarket are shown in **Fig.** ***4***. Here, the average generation for each hour of the day is plotted, for different market types. It can be seen that the low peak-shaving penalty does not have a visible effect on these schedules. However, for the higher penalty, the import from the grid is affected, as shown by the blue dashed line. The import profile from the grid becomes more constant during the day, with a lower peak. To compensate, supermarket production is increased for several hours of the day, mostly during low-price hours in the night and the middle of the day.

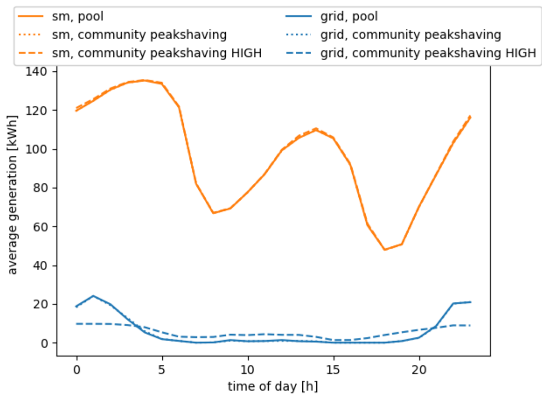

Fig. 4. The effect of peak-shaving objective on the average daily generation patterns.

Next, it is investigated how the community peak-shaving objective affects the settlement. From the form of the corresponding optimization problem, it is to be expected that prices increase as a result of this penalty, compared to the pool market. **Fig.** ***5*** shows that in the high-load winter months from October to February, the high penalty on peak import leads to increased revenues for both the supermarket and the grid. The increased revenue is most significant for the supermarket.

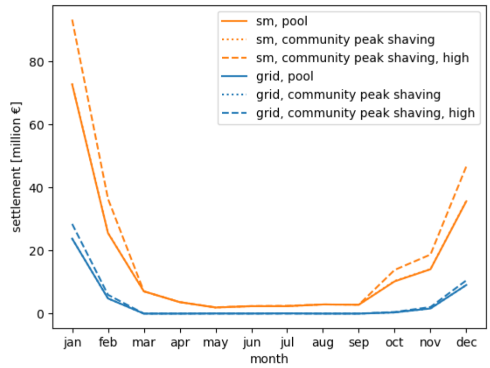

Fig. 5. The effect of a community with the peak-shaving objective on total settlement per month.

4.4 Community Market (Autonomy)

In **Fig. *6*** the effect on the average daily generation pattern of the grid and supermarket is visualized. Again, the effect is very small for the low penalty. For the higher import penalty, the effect is still rather small. The only change is that the supermarket production increases in some hours, whereas the grid import on average is decreased in some hours of the day. In all, this means that the community has become more autonomous.

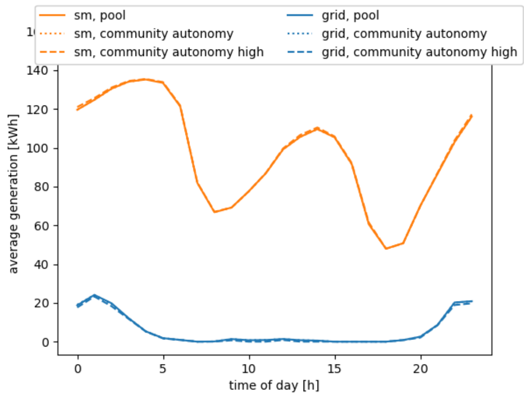

Fig. 6. The effect of a community market with autonomy objective on average daily generation profiles.

Regarding the settlement, the main effect is that the supermarket is earning more from October to February, because the supermarket is scheduled more, as **Fig. *6*** shows.

4.5 Investment in a supermarket heat pump

Here, the goal is to investigate if the community of residential consumers and the supermarket together would benefit from investing in the supermarket heat pump. To analyze this, the pool market with Energy Budget is compared in two cases: 1) with the supermarket excess heat included and 2) without the supermarket excess heat. The average price per unit of heat without the supermarket excess heat is 784 DKK/MWh = 105 EUR/MWh, and 313 DKK/MWh = 41.7 EUR/MWh with the supermarket excess heat. Comparing the total settlement for the group of 30 consumers with and without the excess heat from the supermarket, the total savings in heat cost for one year is 675.000 €. This means that the consumers could invest this amount in the installation of the supermarket heat pump and earn their investment back within a year.

5 Conclusion

This work intended to show how different market mechanisms can affect the performance of certain agents, regarding both heat dispatched and economical benefits, under the EMB3Rs platform. The flexibility on the consumer side was also explored by the energy budget feature, as well as autonomy and peak-shaving on the community side.

Another finding was the monetary benefits that decentralized structures can bring and how a possible investment in this sector can come up with short payback periods, as demonstrated by the profits from the supermarket allowance to participate in the market.

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