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Sector-coupling in Renewable Energy Communities: Impact on Heat Pumps Providing Flexibility

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Abstract

Renewable energy communities enable local sharing of electricity and heat. This study evaluates the impact of sector-coupling in a rural Austrian housing cooperative transitioning to a renewable system with photovoltaic generation, a fifth-generation district heating and cooling network, borehole thermal storage, wastewater heat, and decentralized heat pumps. Using the open-source optimization tool *IESopt*, two scenarios are compared for one year: a baseline where heat pumps follow thermal demand, and a sector-coupled case where operation shifts to periods of surplus PV.

Both scenarios identify a large seasonal BTES (~120 MWh) as essential, covering over half of annual heat demand. The sector-coupled scenario reduces total system costs by ~10.5% through improved use of low-cost community electricity and coordinated flexibility. Heat pumps operate more dynamically—about 16% more activations with 15–20% shorter durations—and show reduced full-load hours due to higher installed capacity. Although sector-coupling increases peak electric demand, it substantially improves economic and operational performance. Overall, sector-coupling combined with moderate thermal flexibility provides an effective and cost-efficient pathway for decarbonizing community-scale energy systems supported by seasonal storage.

Keywords: district heating and cooling; low temperature network; flexibility provision

1. Introduction

Renewable energy communities (REC) according to the Renewable Energy Directive (REDII) [1] offer an organizational and legal framework for communities sharing their energy in the form of electricity, heat or even gas as long as its source is renewable. In Austria, REC are established in the electricity sector [2], [3], where participants give their surplus in generation, usually from photovoltaic (PV) systems, to participants with a demand. Since they still use the public electric grid, the benefit originates from price allocation: The surplus-participant sells for a higher price within the EC than to the electricity supplier while the demand-participant buys at a lower price.

An even greater benefit could be realized if participants had knowledge about the availability of surplus generation in the EC, resulting in cheap electricity. In homes with electrified heating, cooling and/or domestic hot water (DHW) systems, the effect is multiplied: Not only could EC-participants operate their electronic devices and household appliances to surplus-availability, but they could schedule their sector-coupling (SC) components accordingly, such as heat pumps or electric water boilers.

Sector-coupling and shifting demand to times of surplus availability positively impacts the electrical grid: Negative flexibility is made available from loading water storages or a seasonal storage, or preheating buildings. Positive flexibility arises through postponing or expediting of a demand. The thermal energy demands likely exceed the electric ones: While a typical single-person household likely will have a electricity

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demand of around 2000 kWh per year, the heating demand for a 50 m² home range from low values for a passive house standard, 500 kWh, to enormous amounts of 12500 kWh for old, non-thermally rehabilitated buildings [4]. Typical newly built structures should not exceed 100 kWh/m², resulting in 5000 kWh per year for the 50m² home.

An interesting option is to connect EC-participants via a local district heating network where participants also share energy in the form of thermal energy. Fifth generation district heating and cooling (5GDHC) networks promise many advantages [5], [6]: Bidirectional networks offer heating and cooling within one system; low temperatures allow the inclusion of low-temperature waste heat, result in very low heat losses, and allow to use the ground soil as storage[1] material; decentralized heat pumps, as a key technology, to elevate temperature levels for heating or DHW further enable sector-coupling.

Despite the great potential for their own economic benefit and grid stability, users of heat pumps might be sceptical about engaging in sector-coupling operation, related to degradation due to on-off operation. Studies have shown that different control strategies for heat pumps will become necessary to avoid energy losses at cycling or catch-up effects [7]. The current work studies the impact of applying sector-coupling and utilizing building flexibility on heat pump operation in comparison to a baseline, where heat pumps only operate according to heating demand.

2. Methods/Approach

Case study description

The current work focuses on a case study in rural Austria, where a housing cooperation is interested in switching their current heating supply to a sustainable system. Their system consists of: Eleven multi-apartment buildings, which would be refurbished with panel heating; solar PV generation on ten of these buildings; a bidirectional 5GDHC network featuring a BTES; low-temperature waste heat from a sewage treatment plant; and an additional “fallback” heat supply in the form of a community owned air-source heat pump.

Scenario approach

Two scenarios, baseline and sector-coupling, are examined, as presented in Tab. 1.

Table 1. Examined scenarios for case study.

	Scenario Baseline (BL)	Scenario Sector-coupling (SC)
Description	In the BL-scenario, participants do not engage in sector-coupling and do not allow deviations from their comfort temperature. They might be EC-participants which only impacts the price they pay for their used electricity, retrospectively.	In the SC-scenario, participants operate their sector-coupling components according to availability of surplus electricity from the EC, if possible. They allow short-term shifting of energy via postponing or pre-heating their homes.
Sector-coupling	Participants operate sector-coupling components (e.g., heat pumps for space heating) in the standard way, namely according to heat demand.	Participants know whether there is cheap electricity available from the EC and schedule their heat pumps for space heating accordingly.
Building flexibility	Participants dictate a set temperature in their homes and the heating supply system provides.	Participants allow a deviation of +/-2.5 K from the set temperature during heating periods.

Modeling

The system is modelled with *IESopt* [8], an open-source framework for energy system optimization problems, that has already been successfully applied to EC case studies [9], heat network design decisions [10] as well as decarbonization studies focusing on waste heat availability [11] in district heating. As often done with such optimization models, the model is solved over the full year (2023), in an hourly resolution, to find the overall optimal decision strategy, which entails perfect foresight onto all demand and generation time series. The modeling is done purely by energy carriers, as demonstrated in Fig. 1, but involves temperature dependent coefficients of performance (COPs), that are iteratively refined to match a realistic behaviour of heat assets. Tab. 2 provides a summary of the most important input parameters—further assumptions are listed on Zenodo [12][2].

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[1] A borehole thermal energy storage (BTES) shifts seasonal mismatches in heat demand and supply (cooling will feed into the thermal network).
[2] During review process available at Zenodo, will be published once accepted.

Electricity generated by PV is first used by the building it belongs to and covers its electricity demand and/or heat pump use. Any surplus after covering the internal demand can be sold to other EC-participants, handled for modeling via a "virtual" EC electricity grid that does not exist in reality, and the surplus is afterwards fed back into the grid—selling to the electricity supplier at a low feed-in remuneration.

Table 2. Annual range, and total, of values of the most important input parameters of the case study.

Asset	Parameter	Value	Total
Solar Photovoltaics	Annual availability	14.3-35.7 MWh	241.8 MWh
Annual Demand	Electricity	2.6-21.9 MWh	122.2 MWh
	Heating	10.3-24.1 MWh	155.5 MWh
	Domestic Hot Water	1.3-12.8 MWh	60.2 MWh
	Cooling	2.3-5.2 MWh	36.2 MWh
Waste Heat Source	Available Heat	77-250 kW	1.8 GWh
	Usable Heat	0-227 kW	78.6 MWh

On the thermal side, the low-temperature network is used as a source for the heat pumps for space heating and DHW. The network is coupled with a seasonal storage, a BTES operated between 5-25°C. As a simplification, we assume the network's temperature to always be equal to the BTES' temperature. The BTES temperature is modelled to be linearly correlated with the storage's charging level. With these temperatures and assumed supply temperatures of 35 and 60°C for space heating and DHW, respectively, variable COPs for the heat pumps are calculated via the Carnot-efficiency and an efficiency factor of 0.4.

Heat sources for the thermal system are 1) the cooling demand, which is supplied via active cooling (using the heat pump for heating with switched source and sink), 2) the waste heat potential, which can be utilized directly (via a heat exchanger) if the temperature level in the network is small enough, or 3) a fallback heat supply that is needed to fulfill the energy balance. This fallback heat supply could be realized, e.g., as an additional heat pump using either the waste heat potential or ambient air as a source.

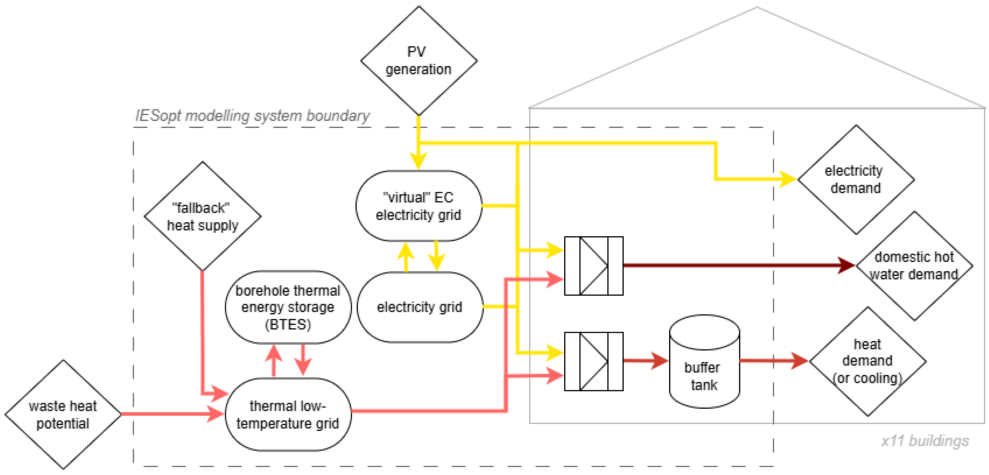

Figure 1. Scheme of components for modeling approach, direction of arrows shown for heating periods. For cooling, the heat demand feeds into the buffer tank, and the stream is heated up via the heating heat pump and fed back to the thermal network ("active cooling").

Demand and generation data is an input to the model and was modelled separately. Space heating and cooling demands were calculated using the City Energy Analyst [13] for the ambient temperatures of 2023 with inputs about the buildings obtained from a Google Street View examination. The electricity and DHW demands were based on assumptions about diverse residents, number and family structure, in the respective apartments and their load profiles [14], [15]. PV generation considers the available roof area, its orientation and the roof pitch and was generated using PVGIS [16]. The available waste heat potential and its temperature levels are based on real world measurements, which resulted in distinctive values for the four seasons and day/night differences (refer to Tab. 3). Smoothing was applied to not have jumps in the available temperatures.

Table 3. Temperature thresholds for the thermal network, above which the waste heat source can be utilized—accounting for a lower limit for return temperature at 10°C. Utilization during winter times is not feasible due to the low temperature of the waste heat. Note that values given here are rounded for confidentiality reasons.

Season	Max. Thermal Network Temperature at which waste heat can be used	
	During day	During night
Spring	14.0 °C	13.5 °C
Summer	16.0 °C	15.5 °C
Autumn	15.5 °C	14.5 °C
Winter	-	-

As the optimization problem does not involve temperatures, the COP calculation is performed as preprocessing and treated as an input to the optimization. Since the optimizer then changes the operation of the heat pump and waste heat feed-in in the sector-coupling scenario to low-electricity price times, an iterative approach is necessary for stable solutions where input COPs fit to resulting temperatures (derived from the BTES charging level).

3. Results and Discussion

Both scenarios were simulated on an Intel(R) Core(TM) i7-1185G7 running at 3.00GHz, with each iteration being solved using HiGHS [17] taking between one and two minutes. A total of 25 iterations were run for each scenario, with convergence already happening considerably earlier for the baseline scenario.

General Results

In both scenarios, the necessary size of the BTES to obtain an optimal operation of the overall system is roughly given as 120 MWh. This corresponds to around 77% of the annual direct heat demand, or around 56% of the overall annual heat demand (including domestic hot water). Fig. 2 shows the optimal operation of the storage to supply heating and cooling, considering the availability of waste heat and an additional freedom provided by the air-source heat pump feeding into the low-temperature grid.

The EC, in the sector-coupled scenario, shows a total amount of electricity exchanged[3] of 12.3 MWh, which amounts to 7.1% of the total annual electricity consumption (including the electricity that buildings use for heat pump operation). The possibility to utilize within-EC electricity at prices that are favorable for both sellers and buyers—compared to the tariffs offered by the energy supplier—results in a decrease of total (system-wide) costs by around 10.5% compared to the baseline scenario.

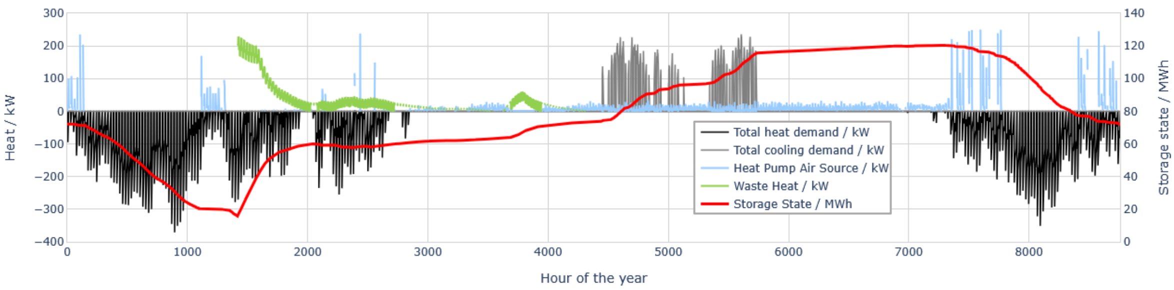

Figure 2. Storage state over the year in respect to current heating demand, and heat input in the form of cooling demand, waste heat, and an air-source heat pump.

Heat Pump KPIs

Tab. 3 shows the detailed results for full load hours, number of activations, and mean duration of each activation, averaged across all eleven buildings.

The effects of active sector-coupling show a considerable impact on the reported KPIs, mainly:

1. A shift of activations from autumn (and a bit of spring) into the winter, with around 16% more activations during the winter season with sector-coupling compared to the baseline.

[3] Here meaning a total annual sale of 12.3 MWh surplus, matched with a total consumption of 12.3 MWh, varying between buildings and hours depending on the internal generation and demand.

2. A further decrease in the mean duration of these activations, between 15-20% across all seasons—highlighting a more flexible operation of heat pumps. Especially during peak heating season (winter) where high amounts of heat need to be supplied this evenly offsets the aforementioned increased number of activations (+16%), with shorter periods (-15%) of heat pump operation.
3. A reduction of around 25% in full load hours (so utilization), which is however mainly linked to increased heat pump capacities (see below).

The increasingly flexible operation of heat pumps in the sector-coupled scenario is linked to an increase in necessary peak power: While the baseline utilizes around 8 kW of rated power (electricity) on average per building, with a total of 86 kW, the sector-coupled scenario can utilize close to 34% more heat pump capacity, averaging 10.5 kW per building (a total of 115 kW). Testing the effect of this increase was done by limiting the sector-coupled scenario to the exact amounts of rated power for the heat pump of each building as resulting from the baseline scenario. This results in an increase of operating costs by 2.4% (and in subsequence similarly high full load hours as in the baseline scenario), still being cheaper than the baseline scenario by about 9.4%, showcasing the positive impact of the sector-coupled approach.

Table 3. Heat pump related KPIs, comparing the baseline (BL) and sector-coupled (SL) scenarios across all four seasons. All values are mean results over all eleven buildings.

Season	Full load hours per season (h)		Number of Activations		Mean Act. Duration (h)	
Scenario	BL	SC	BL	SC	BL	SC
Spring	50.0	66.5	74.5	75.5	8.6	10.1
Summer	0.0	0.2	0.0	0.3	0.0	0.5
Autumn	21.3	28.2	34.5	38.9	10.6	13.3
Winter	162.4	215.5	42.8	36.9	38.9	45.8

4. Conclusions and Outlook

This study examined the operation of a renewable energy system for a rural Austrian housing cooperative, comparing a baseline configuration with a sector-coupling scenario that activates flexible heat pumps as part of an energy community. The results demonstrate that even in a small community system, flexibility and coordinated operation can deliver significant system-level benefits.

In both scenarios, the optimization consistently identifies a large seasonal storage (approx. 120 MWh borehole thermal storage) as essential. Its capacity—equivalent to more than half of the annual heat demand—underlines the critical role of long-term thermal shifting in systems relying on low-temperature sources and variable renewable electricity. This storage enables effective use of waste heat outside of the winter period and supports favorable COPs throughout the year.

The sector-coupling scenario shows clear economic advantages, reducing total operating costs by 10.5%. This is primarily enabled by intra-community electricity exchanges and the ability to shift heat pump operation to periods with low-cost surplus PV generation. Demand flexibility, implemented as short-term thermal comfort deviations, results in more dynamic heat pump behavior: 16% more frequent but between 15-20% shorter activations, a partial seasonal shift toward winter, and overall reduced full-load hours.

These findings highlight three broader insights. First, integrated operation of electricity and thermal sectors, combined with moderate building-level flexibility, provides tangible economic and operational value for community-scale systems. Second, the presence of seasonal storage and low-temperature waste heat can be leveraged effectively, but only when the system has sufficient flexibility to align heat production with renewable availability. Third, flexibility comes with trade-offs—namely, increased peak power requirements—which must be recognized in investment planning.

Future work should explore: (1) the robustness of these results under imperfect foresight or uncertainties in load and generation; (2) broader socio-technical aspects of occupant comfort and acceptance; and (3) alternative operational strategies for exploiting waste heat during the heating season, such as hybrid sources or dynamic network temperature control, and (4) an increased level of detail in the modeling of complex, non-linear effects of the BTES charge/discharge capacities. Overall, the case study reinforces that sector-coupling is a promising and cost-effective pathway supporting the electrification and decarbonization of rural residential energy systems when supported by appropriate storage and flexible control strategies.

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