Data-driven Modeling of Grid-Support Services Provided by Heat Pumps in an Energy Community

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***Abstract*—This study develops a data-driven model of an energy community to represent the aggregated electrical behavior of residential heat pumps (HPs) and applies it to quantify their active and reactive power flexibility. High-resolution measured data spanning an entire year are utilized to assess the control of HP actions for the purpose of providing different grid services. Active-power flexibility exploits the thermal storage capacity of the buildings to redistribute demand, while reactive power flexibility regulates the community reactive power exchange by controlling the inverter-driven compressor of the HP. The results show that coordinated HPs operation enables measurable temporal load shifts, increases the utilization of locally generated photovoltaic (PV) energy, and enhances distribution-grid flexibility and renewable-energy integration without compromising user comfort.**

***Index Terms*—heat pumps, energy flexibility, energy community, demand-side management**

I. Introduction

The rapid electrification of residential heating, particularly due to the growing popularity of heat pumps (HPs), is transforming power demand throughout Europe. According to the European Heat Pump Association 2023 statistics report [1], European HPs sales grew by 38.9 % in 2022, reaching a record of three million units sold. This brings the cumulative installed stock to approximately 19.8 million heat pumps, of which 17.9 million are used for space heating. With around 120 million residential buildings in Europe, HPs now serve more than 16 % of the building stock. Germany is among the fastest-growing markets, reflecting national efforts to decarbonize the heating sector. However, this rapid electrification also introduces new operational challenges for distribution networks. Increased electric heating demand amplifies winter peak loads and daily load variability, requiring enhanced flexibility management in low-voltage grids [2].

In response, residential demand-side flexibility and energy community coordination have surfaced as viable solutions. Heat pumps provide significant flexibility thanks to their thermal storage capabilities; residential buildings and water tanks can store heat, enabling the deferral or pre-activation of electrical power consumption without compromising comfort [3], [4]. This inherent flexibility allows HPs to adjust how much electricity they consume over time, either to mitigate system peaks or to utilize local renewable excess. When implemented collectively, such as in an energy community or microgrid, coordinated HPs operation can adjust aggregated demand profiles in ways advantageous to the grid [5], [6]. Energy communities might thus evolve from passive consumers to active system participants, providing auxiliary services that conventionally required centralized resources.

Extensive simulation studies and field demonstrations have confirmed the grid-support potential of coordinated HPs operation. Prior work shows that aggregated control can mitigate feeder loading and enhance local renewable-energy use [7]. Field trials have demonstrated substantial demand reductions during peak periods without compromising comfort [8]. Similar findings were reported in [9], where customer-driven HPs flexibility was shown to support demand-side management in practical settings.

In addition to active power shifting, there is a growing interest in reactive power flexibility as an auxiliary grid service. HPs inverters can influence local reactive power flows, and modern variable speed units with power electronic interfaces are, in principle, capable of supplying both inductive (absorbing) and capacitive (injecting) reactive power to support power factor correction and voltage stability in low voltage networks [10]. However, empirical investigations of this capability remain scarce [11].

Overall, the literature is dominated by simulation-based studies, and only a small number of works have evaluated HPs flexibility using real high-resolution measurement data. This paper addresses this gap by providing a data-driven evaluation of HPs flexibility based on real-world measurements. It quantifies both active and reactive power capabilities, thereby complementing the predominantly model-based studies in the literature.

II. Methodology

This study develops a data-driven model of an energy community to analyse how energy flexibility from HPs can be used to provide grid services. The community is modeled as a single electrical node at its low-voltage transformer connection point, without representing individual low-voltage feeder sections between dwellings. A schematic of this configuration is shown in Fig. 1. The total demand and net power exchange with the distribution grid result from the combined operation of

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individual residential HPs and household loads. Grid-support actions are triggered by an external flexibility request issued by the DSO, and a community controller coordinates the individual HPs according to their available flexibility and inverter capability. The analysis relies on high-resolution measured data to drive the simulation rather than detailed physical models of buildings and heating systems.

A. Scope and Dataset Description

The data used in this research originate from the WPuQ project ("Wärmenetze mit einem Pufferspeicher und Quartiersregelung") described by Schlemminger et al. [12], which monitored an enclosed residential district near Hamelin in Lower Saxony, Germany. The real district is currently not operated as an energy community. It consists of 68 single-family houses built in the late 1990s and early 2000s, supplied by a cold local heating network with a typical supply temperature of 10-12,°C. Each dwelling is equipped with a HP connected to this network for space heating. The installed HPs have compressors with nominal electrical capacities of 1.9 kW or 3.0 kW and corresponding thermal outputs between 7.4 kW and 11.3 kW when the primary and secondary sides are at 10 °C and 35 °C, respectively. This setup is an example of a modern low-temperature district heating system that has been designed to be highly efficient and integrate renewable energy sources.

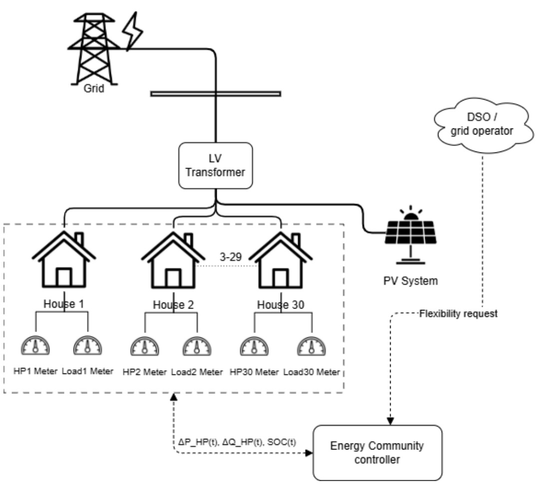

Fig. 1. Schematic representation of the modeled energy community.

Electrical measurements in each dwelling were obtained using two energy meters, one for monitoring the household load excluding the heat pump, and another dedicated to the heat pump electrical consumption. Local data loggers recorded measurements every 10 s, and the published dataset provides raw data and aggregated measurements at 1-minute and 15-minute resolutions.

The dataset includes active, reactive, and apparent power, voltage, current, power factor, and some thermal and environmental parameters, such as flow and return temperatures, ambient temperature, and solar irradiance.

To do a reliable analysis on flexibility over one year, thirty houses with complete and continuous electrical data for the whole year of 2019 were selected. The aggregated active and reactive power demand of the energy community is defined by:

$$P_{\mathrm{EC}}(t) = \sum_{i=1}^{N} (P_{\mathrm{HP},i}(t) + P_{\mathrm{House},i}(t)), \tag{1}$$

$$Q_{\mathrm{EC}}(t) = \sum_{i=1}^{N} (Q_{\mathrm{HP},i}(t) + Q_{\mathrm{House},i}(t)), \tag{2}$$

where $N = 30$ is the number of selected dwellings. An overview of the dataset is given in Figure 2.

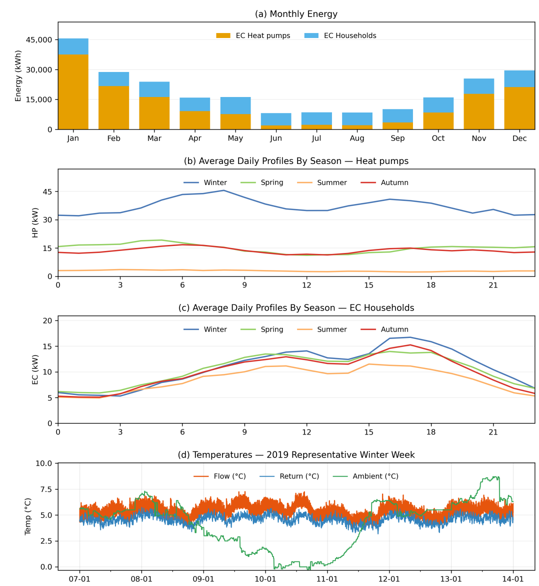

Fig. 2. Overview of the dataset.

B. Active-Power Flexibility Modeling

The energy flexibility in thermal systems contexts originates from the thermal inertia of the building and the domestic hot-water (DHW) storage, which enables the heating system to be switched off or reduced for a period of time without decreasing the comfort of the users. The possible duration of such a period depends on the thermal mass and heat losses of the buildings and can range from a few hours up to a couple of days [13], [14]. Rather than modelling the detailed thermal dynamics of each dwelling and its heating system, this study adopts a simplified energy-based formulation derived from the literature.

Negative flexibility refers to the ability to reduce the thermal energy of the building, while positive flexibility represents the ability to increase it within the limits of user comfort. The corresponding thermal flexibility is converted into electrical flexibility using the coefficient of performance (COP).

As reported in [15], the downward (negative) electrical flexibility potential for buildings constructed in Germany between 1980 and 1995 and equipped with heat pumps is

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approximately: $E_{\text{neg}} = 26\ \text{Wh/m}^2$, which can be assumed for the buildings considered in this study. On the other hand, the upward (positive) flexibility is generally smaller because preheating is constrained by comfort boundaries and limited thermal storage capacity [15]. As stated in [13], upward flexibility is generally achieved during modest preheating periods of up to 6 hours. The current research adopts a conservative scaling factor of $\alpha = 0.7$ to correlate positive and negative flexibility, with a preheating duration of 3 hours.

$$E_{\text{pos}} = \alpha\, E_{\text{neg}}. \tag{3}$$

For each dwelling i with heated floor area A_i, the flexibility limits are given by

$$E_{\text{neg},i} = 26\, A_i, \qquad E_{\text{pos},i} = \alpha\, E_{\text{neg},i}. \tag{4}$$

The time-varying thermal state of each heat pump (HP) is represented by a simplified state-of-charge (SOC) variable that quantifies the cumulative energy shifted relative to the available thermal flexibility.

$$E_{\text{SOC},i}(t+\Delta t) = E_{\text{SOC},i}(t) + \Delta P_{\text{HP},i}(t)\,\Delta t, \tag{5}$$

bounded by

$$-E_{\text{neg},i} \le E_{\text{SOC},i}(t) \le E_{\text{pos},i}, \qquad E_{\text{SOC},i}(t_0) = 0. \tag{6}$$

The controlled HP electrical power is then defined as

$$P_{\text{HP}_{\text{ctrl}},i}(t) = P_{\text{HP},i}(t) + \Delta P_{\text{HP},i}(t) \tag{7}$$

Where $P_{\text{HP}_{\text{ctrl}}}$ is the controlled power of the heat pump, and ΔP_{HP} is the active control action constrained by the maximum power of the heat pump and the available negative or positive flexibility.

Different flexibility services can be characterized by the direction of $\Delta P_{\text{HP},i}(t)$. A negative $\Delta P_{\text{HP},i}(t)$ represents a decrease in load during times of high demand or network peaks, while a positive $\Delta P_{\text{HP},i}(t)$ represents an increase in load during periods of high generation to manage excess production. Following flexibility events, the SOC gradually decreases to zero, reflecting the recovery phase during which the HP reinstates the nominal thermal condition.

The total controlled community demand is derived by aggregating all controlled HPs loads and household base loads:

$$P_{\text{EC}_{\text{ctrl}}}(t) = \sum_{i=1}^{N} P_{\text{House},i}(t) + \sum_{i=1}^{N} P_{\text{HP}_{\text{ctrl}},i}(t) \tag{8}$$

C. Reactive-Power Flexibility Modeling

In addition to active power shifting, modern HPs can offer reactive power flexibility within their apparent power capacity. This functionality stems from the inverter-driven compressor and auxiliary electrical components, which maintain the instantaneous relationship between active power $P_{\text{HP},i}(t)$ and reactive power $Q_{\text{HP},i}(t)$. While HPs are not originally designed for reactive power control, their inverters can be deliberately operated to exchange reactive power with the grid. This study assumes that such control capability is available and can be coordinated at the community level.

The reactive power headroom of each HP is determined by the nominal apparent power S_{HP} and the instantaneous active power $P_{\text{HP},i}(t)$. The theoretical limits of the inverter are:

$$\begin{aligned} Q_{\max,i}(t) &= \sqrt{S_{\text{HP}}^2 - P_{\text{HP},i}^2(t)}, \\ Q_{\min,i}(t) &= -\,Q_{\max,i}(t). \end{aligned} \tag{9}$$

These limits indicate how much reactive power the inverter can handle. During normal operation, some of this capability is already being used to provide the reactive power that the compressor and other devices need. This is shown by the measured baseline $Q_{\text{HP},i}(t)$. The controllable reactive power headroom is the additional capacity that is not being used:

$$\begin{aligned} hQ_i^{+}(t) &= Q_{\max,i}(t) - Q_{\text{HP},i}(t), \\ hQ_i^{-}(t) &= Q_{\text{HP},i}(t) - Q_{\min,i}(t). \end{aligned} \tag{10}$$

This headroom can be used to regulate voltage, improve the power factor (PF) or to regulate the flow of reactive power at the grid connection point. Assuming each HP inverter is operating within its apparent power capacity, the regulated reactive power is presented as

$$Q_{\text{HP}_{\text{ctrl}},i}(t) = Q_{\text{HP},i}(t) + \Delta Q_{\text{HP},i}(t). \tag{11}$$

The energy community level reactive power is obtained by aggregation:

$$Q_{\text{EC}_{\text{ctrl}}}(t) = \sum_{i=1}^{N} Q_{\text{HP}_{\text{ctrl}},i}(t) + \sum_{i=1}^{N} Q_{\text{House},i}(t). \tag{12}$$

and the resulting PF at the community level is computed as

$$\text{PF}_{\text{EC}_{\text{ctrl}}}(t) = \frac{P_{\text{EC}_{\text{ctrl}}}(t)}{\sqrt{P_{\text{EC}_{\text{ctrl}}}^2(t) + Q_{\text{EC}_{\text{ctrl}}}^2(t)}}. \tag{13}$$

III. Simulation Scenarios Results

Based on the methodology described in the previous section, the study simulates the modeled energy community across an entire year to assess its active and reactive power flexibility. Each simulation scenario demonstrates a particular grid-support functionality accomplished by the coordinated operation of HPs, with household demand profiles remaining constant. Grid support is provided through the thermal flexibility of the HPs, and no additional storage or controllable devices are assumed.

A. Active-power flexibility scenarios

Two representative scenarios are simulated to quantify active-power flexibility:

- *Load-Shifting Scenario:* This scenario examines the potential of the energy community to regulate electricity demand temporally through the coordinated operation of

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HPs. The control strategy adjusts HPs operation within the constraints of thermal storage, facilitating the redistribution of energy across different time periods without altering total daily consumption or compromising user comfort. Each HP starts preheating in the morning (09:00-12:00) to accumulate thermal energy and progressively reduces operating during the afternoon (14:00-18:00) when the stored heat is discharged. The results in Fig. 3 illustrate this behavior.

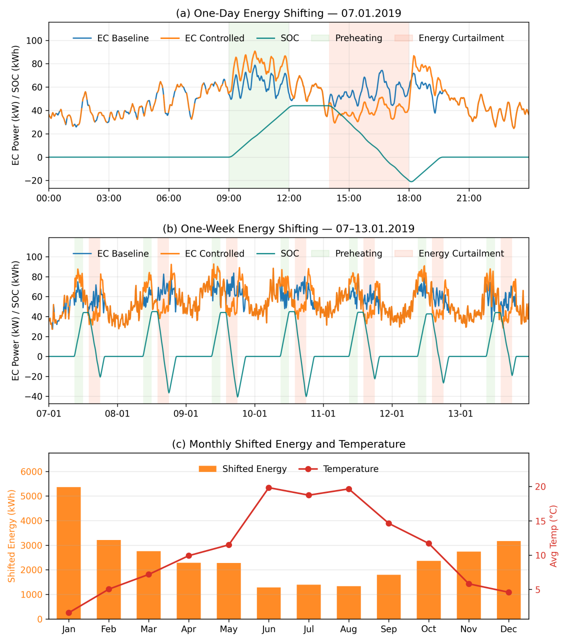

Fig. 3. Active-power flexibility results for the Load-Shifting Scenario.

The controlled power profile shows individual preheating and reduced operational intervals, while the SOC validates the associated storage dynamics. The pattern persists over extended periods, demonstrating stable control performance. At the annual level, the amount of shifted energy varies based on the demand for heating, being higher in the winter and lower in the summer. The resulting aggregated controlled community demand is then compared to the baseline to illustrate how much energy was shifted.

- *PV-Absorption Scenario:*
In this scenario, a photovoltaic (PV) system is assumed to be installed within the community and simulated over the same period as the measured data. The objective is to determine how coordinated HP control may improve local PV self-consumption by ensuring that energy demand matches solar generation during the day. The control strategy distributes part of the HPs load to daylight hours, transforming any extra PV generation into stored heat. Each HP increases its operation during the absorption window (09:00–18:00) and later reduces consumption when PV output declines. This behavior is illustrated by the results shown in Fig. 4.

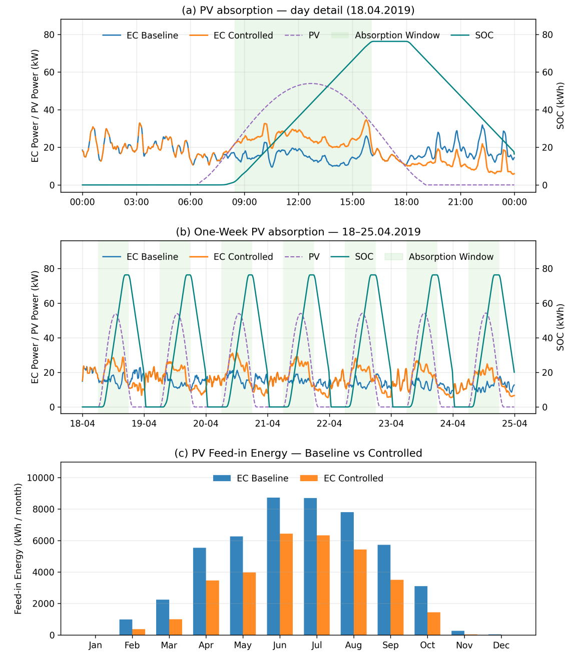

Fig. 4. Active-power flexibility results for the PV absorption scenario.

The annual decrease in PV feed-in energy in the controlled scenario suggests that a larger share of locally produced electricity is used within the community instead of being transmitted to the grid. The total photovoltaic feed-in decreases from 49,387.1 kWh in the baseline to 32,001.4 kWh under control, indicating a reduction of 17,385.7 kWh or 35.2 %. The highest impact occurs between April and September, when solar generation and local absorption capacity reach their maximum.

B. Reactive-Power Flexibility Scenarios

This scenario builds upon the previous scenario, where a PV system with a unity power factor is introduced into the energy community and examines how the HP inverters regulate the reactive power exchange with the grid. The analysis assesses the ability of HP inverter units to dynamically modify their reactive power output within apparent power constraints while maintaining the baseline active power operation. In the presence of PV generation, the active power drawn from the grid decreases, while the reactive power demand remains relatively constant, resulting in a reduction of the total PF at the grid connection point. A coordinated reactive power control method is implemented to sustain the energy community power factor at 0.95 during daytime operations. The results of this scenario are shown in Fig. 5.

The available inductive and capacitive headroom are significant relative to the reactive power adjustments made by the control, showing that the inverters remain within their apparent-power limits. Throughout the year, the applied reactive power control sustains a steady daytime power factor of 0.95, despite fluctuations of the PV generation. Over shorter time periods, reactive power is in line with the PV profile,

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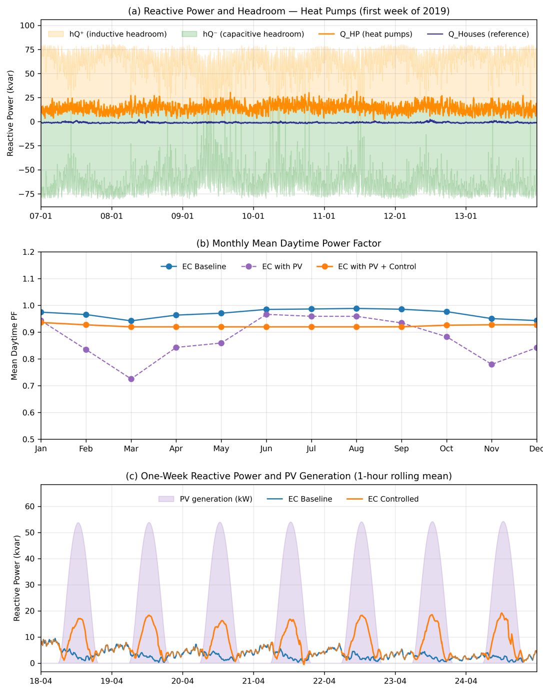

Fig. 5. Reactive-power flexibility results for the PF regulation scenario.

increasing during daylight as HPs offer reactive power support and reverting to baseline levels after sunset. These results show that HP inverters can deliver stable, controllable reactive-power behavior under real operating conditions and maintain a predefined PF target using only the available HP flexibility.

IV. Conclusion and Future Work

This paper presented a data-driven framework to assess the active and reactive power flexibility of an energy community composed of residential heat pumps using high-resolution measured data. Instead of relying on detailed building and grid co-simulation, the proposed approach combines mathematical flexibility formulations with real operating profiles to evaluate grid-support services at the community level. The results demonstrate that coordinated control of aggregated heat pumps can provide meaningful active power flexibility through load shifting and PV absorption, while inverter-based operation enables controllable reactive power support within apparent power constraints. Future work will consider additional flexibility scenarios, larger communities, network constraints, and real-time validation with DSO-oriented control signals.

Acknowledgment

We express our gratitude for the financial assistance provided by the Federal Ministry for Economic Affairs and Climate Action (BMWK), promotional reference 03EI4081A. This research received financing from CETPartnership, the Clean Energy Transition Partnership, as part of the 2022 joint call for research projects, co-financed by the European Commission (GA N°101069750), with funding organizations detailed at https://cetpartnership.eu/funding-agencies-and-call-modules.

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