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DECARBONISATION THROUGH INNOVATION

Field demonstration of a scalable predictive energy management approach for multi-family buildings with heat pumps and PV

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Abstract

The OPERA project demonstrates a predictive energy management strategy designed for multi-family buildings equipped with heat pumps (HPs) and photovoltaic (PV) systems. The project, implemented in a renovated 20-apartment building in Neuchâtel, Switzerland, aimed to develop, deploy, and validate a model predictive control (MPC) strategy that optimizes heat pump operation. It leverages the building's thermal inertia to minimize electricity costs while preserving comfort. Communication with the heating and domestic hot water (DHW) subsystems is standardized via SmartGridReady (SGR) functional profiles. Across a full heating season (2024–2025), the predictive control achieved an 11.5% reduction in HP electricity costs, primarily by shifting consumption to low-tariff periods and increasing self-consumption. The project confirms the technical and economic feasibility of predictive control for collective housing in a renovation context and puts a strong emphasis on replicability, by 1) providing a blueprint for replication to similar buildings with a communication and control approach relying on standardized interfaces to the heat pump and home automation system to control the valves, and 2) integrating in a commercial energy management system (EMS) with no additional hardware investment required; and 3) formulating recommendations related to design, control and operation drawn from that campaign.

Keywords: heat pump, energy management, MPC, PV, residential buildings, field deployment ;

1. Context and objectives

The decarbonization of residential buildings is a key component of Switzerland's Energy Strategy 2050. Buildings account for approximately 40% of total final energy consumption [1], primarily for space heating and domestic hot water (DHW). While significant progress has been made in electrifying single-family houses (SFHs) through heat pump (HP) adoption, the penetration of HP systems in multi-family houses (MFHs) remains comparatively low. In Switzerland in 2024, while 28% of SFHs were equipped with HPs, only 20% of MFHs were [2]. This disparity stems from multiple factors, including technical complexity, cost, and the organizational challenges of collective systems. Renovations in urban contexts bring additional complexity due to limited available space for indoor and/or outdoor units, noise requirements, and the need for multiple machines [3]. In addition, investment in HPs can still be perceived as risky because performance does not always reach expectations, as demonstrated by Brudermüller et al. [4].

Parallel to the electrification of heating, Switzerland is witnessing rapid expansion of building-integrated photovoltaics (PV). Switzerland's revised Energy Act promotes self-consumption and local energy communities, encouraging PV owners to consume their own generation. However, PV production and HP heating demand are temporally misaligned, particularly in winter. In addition, this same energy act also authorizes dynamic network tariffs which have recently become available to small consumers in Switzerland [5]. To enhance the economic viability and adoption of heat pumps (HPs), their operation must be optimized for efficiency and integration with other energy systems. A key aspect is synergy with PV production and varying tarrifs. Additionally, HPs should operate at good efficiency, making use, when possible, of low supply temperatures and advantageous outdoor conditions in the case of air-to-water systems. Finally, a crucial factor is to leverage the building's thermal inertia, as it has been shown that storing heat within the building mass is more effective than using small water buffer tanks [6].

Standard HP operating strategies typically fail to meet these objectives. Traditional control systems—originally designed for oil boilers—rely on static heating curves that set supply temperatures based solely on outdoor temperature, without considering solar production, tariffs or coordination with other subsystems. Emerging self-consumption strategies, which raise supply and storage setpoints to use more PV power, have been integrated into various commercial energy management systems (EMS). Yet, authors of study [7] have shown that while such approaches can increase self-consumption, they simultaneously reduce the seasonal coefficient of performance and overall system efficiency. In many cases, the resulting efficiency losses cancel out the economic gains from higher self-consumption, leading to no net financial benefit for occupants.

Predictive control approaches, by contrast, use models to anticipate future conditions and make optimized decisions over a defined horizon, and are particularly appropriate to manage the trade-offs between the considerations listed above in a dynamic fashion. Specifically, MPC adjusts to changing boundary conditions, such as new tariffs, by design. See [8] for a recent overview of research on advanced control strategies in buildings, including MPC. Recent research has increasingly focused on applying Model Predictive Control (MPC) to heat pump systems under real operating conditions. Ham and al. [9] demonstrated a field implementation of MPC in a dual-fuel heat pump system for a small commercial building, achieving substantial cost and emission reductions. Betzold and al.[10] compared MPC with simpler predictive schemes in a building, confirming the potential of MPC to improve energy efficiency but also highlighting commissioning challenges. In the residential sector, a long-term field experiment [11] showed that MPC can enhance PV self-consumption and reduce operating costs compared to standard heat-curve control. Collectively, these studies confirm that MPC offers measurable benefits in real-world heat pump applications, though replicability and standardization remain key barriers to broader deployment. In a nutshell, MPC has been extensively studied in academic contexts and applied in laboratories and pilots, but large-scale validation in real *residential* buildings remains rare and cost-efficient replicability of MPC is often a concern, due to the higher complexity of the control strategy, as pointed by Sturzenegger et al [12].

The OPERA project fills this gap by demonstrating an integrated predictive control framework deployed in an MFH. The project's main objectives were:

- To develop and validate a predictive control strategy for HP-based systems in MFHs.
- To integrate PV generation, tariff optimization, and comfort preservation within a single framework.
- To deploy and test the system on a real renovated MFH over a full heating season.
- To evaluate the energy, cost, and comfort performance compared to baseline control.
- To address barriers to wide-scale adoption of advanced control strategies in buildings.

This paper summarizes the methodology and results of the OPERA project. Section 2 describes the pilot building and system configuration, including monitoring and control architecture. Section 3 presents the predictive control algorithm and data integration framework. Section 4 analyzes the field results, including performance, comfort, and operational efficiency. Section 5 discusses the findings and lessons learned.

2. Pilot description and Methodology

2.1. Description of the pilot site

The OPERA demonstration site is a six-story multi-family building located in Neuchâtel, Switzerland. Originally built in the 1960s, the building underwent complete energy renovation in 2023. The renovation included façade insulation, floor heating installation, and replacement of the fossil-fuel boiler with multiple HPs. The main buildings characteristics are listed in Table 1. The heating system has two air-to-water reversible HPs and a heat recovery HP for DHW production, connected to the building's mechanical ventilation exhaust, recovering low-grade heat from outgoing air. The HPs are equipped with inverter compressors, allowing modulated operation.

Figure 1: Test site before (left) and after (right) renovation

Table 1: Main technical characteristics of OPERA pilot building and systems

Characteristic	Value	Note
Location	Neuchâtel, Switzerland	Urban context
Total floor area	1,700 m²	20 apartments
Heating HPs	2 × 20 kW air-to-water	Reversible operation
DHW HP	1 × 10 kW heat recovery	Ventilation exhaust source
Heating buffer	800 L	
DHW storage	2 × 400 L	Parallel configuration
PV system	30kWp	21 kWp rooftop + 9kWp balcony
Heating distribution	Floor heating	Connected thermostats

2.2. Measurement concept for field tests

The monitoring system provides detailed measurement of thermal and electrical variables across the system. It combines data acquisition at several levels: (i) HP performance, (ii) DHW storage and circulation, (iii) space heating buffer temperatures, (iv) PV generation, and (v) indoor comfort conditions. All data are synchronized and recorded with a temporal resolution of five minutes. Figure 2 illustrates the sensor placement.

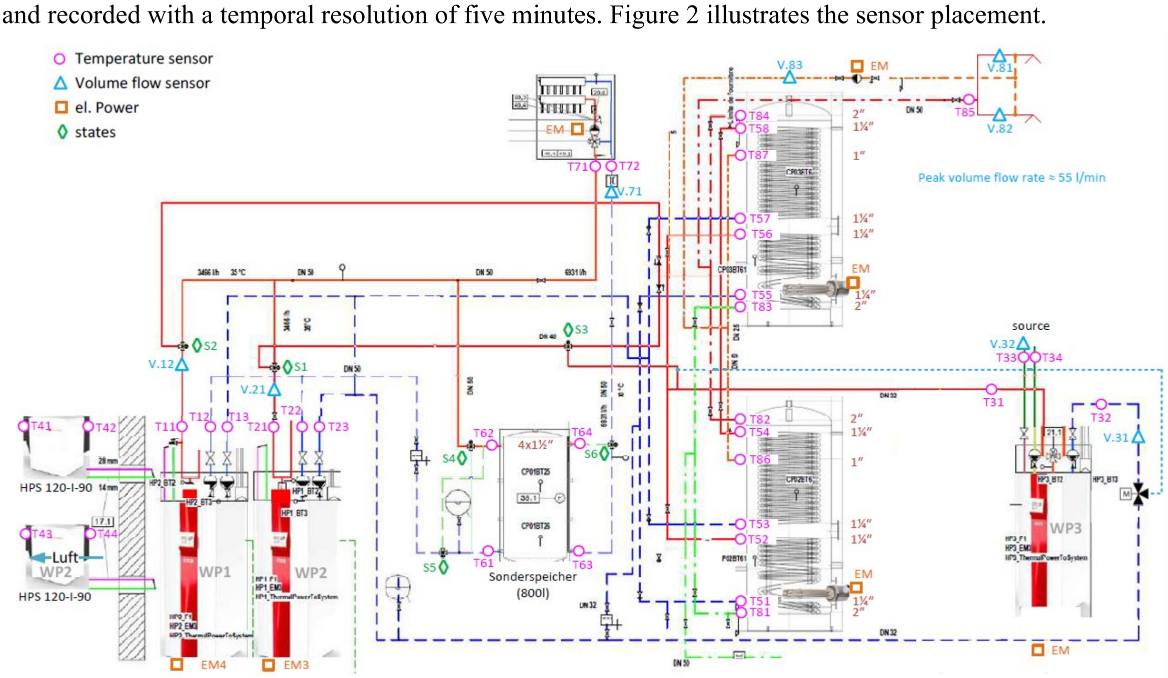

Figure 2: Technical system overview and monitoring concept

Each HP is equipped with a dedicated power meter. Temperature sensors record temperatures throughout the system. Flow sensors measure volumetric flow through the HPs, heating buffer, and DHW circuits. The DHW recirculation loop includes temperature sensors at the supply and return lines, enabling quantification of recirculation losses. The monitoring architecture was designed to provide a fine grain understanding of the system performance and to compute different indicators including HP coefficients of performance (COP), seasonal coefficient of performance (SCOP) and heating system performance factors (SNG+) .

$$SCOP = \frac{Q_{WP}}{E_{WP}}$$

$$SNG+= \frac{Q_f}{E_{tot}}$$

where Q_{WP} is the heat produced by the heat pump, E_{WP} the total energy consumption of the heat pump including compressor, evaporator, internal pumps and HP controller. Q_f is the useful energy used in the building / for hot water, respectively; and E_{tot} the total electricity consumption of the heating system including the heat pump, all circulation pumps and valves, and the heating rods (never used in this campaign). See [13, p.9] for further details. Note that since HP1 / HP2 are only used for heating and HP3 for DHW, it is possible in this case to calculate SNG+ for heating and DHW separately. To recap, SCOP focuses on the efficiency of the heat pumps while SNG+ considers the efficiency of the full heating system, hence including losses throughout the system, including tanks, circulation lines, etc.

Data are transmitted via Ethernet to a local data logger, which uploads measurements to a secure cloud platform for storage and visualization. It is noteworthy that the EMS does not have access to the full monitoring data. Hence this monitoring data is used solely for benchmarking.

3. Predictive Control strategy

3.1. Control architecture

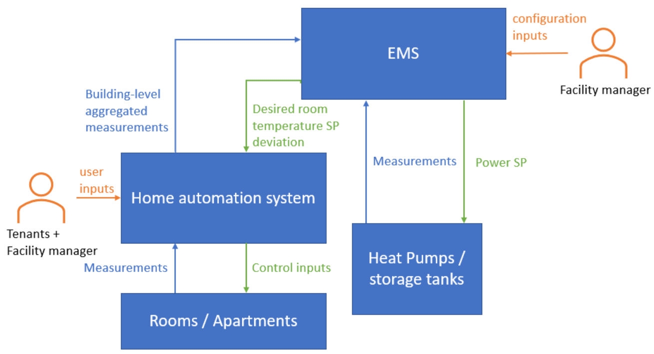

Figure 3: Control architecture overview

An Energy Management System (EMS) developed by company SOLECO AG acts as the central control unit. It is responsible for the coordination of heat production, heat distribution in the building and electricity production from the PV. It interfaces with a) the heat pump controller, b) the home automation system, and c) electricity meters measuring the consumption from each heat pump, the total consumption from the building and the electricity production of the inverter. In a typical MFH heating system setup, there is no communication between the heat pump control which operates based on a heating curve and the distribution valves. A key novelty of this work is to propose a simple reproducible interface to create the bridge between both, as illustrated in Figure 3. The home automation system (in this case a commercial Loxone setup) collects data from all individual room thermostats and valves in the building. This level of granularity is too high to be relevant from the point of view of the supervisory EMS because there is only one heating circuit and the MPC models the building considering one zone per heating circuit. Therefore, only aggregated values for the building (namely the weighted average measured temperature and setpoint temperature) are retrieved. Conversely, the EMS sends a desired setpoint deviation in a range of [-1°C, +1°C] that is used to shift all individual setpoint temperature in the building. The valve openings are still controlled based on the thermostat but with the shifted setpoint values. This allows the EMS to influence the valve openings and in turn the heat distribution in the building, without interfering with the low-level valve control. In this case, the aggregation and setpoint shifting is computed within the home automation environment.

3.2. HP communication with Smart Grid Ready Functional Profiles

Lack of standard data and control interfaces to HPs is a long-standing problem. To optimize electricity costs, direct power modulation of the heat pump is ideal, but this control input is not available in most cases. The approach proposed by SmartGridReady CH (SGR) was used to guide the HP interfacing efforts [14]. SGR defines so-called functional profiles (FPs) that define groups of read-write datapoints that allow management of devices of a class, such as HP, for specific use cases. In addition, interface to individual device model and brands are described with external interface description (EID), listing communication transport protocol and datapoints "addresses", e.g. Modbus registers or API endpoints.

An EID for HPs (of brand Heliotherm) in this pilot site has been created. It contains 9 functional profiles. For the deployment, the FP called *PowerCtrl* was used which specifies setpoints for compressor speed or direct power modulation of the heat pump. The EID drafted for the pilot has not yet been made public, pending administrative approval by the manufacturer, but a similar EID for a HP of brand Stiebel-Eltron [9] is added here for reference.

3.3 Model Predictive Control Framework

The EMS control algorithm is based on Model Predictive Control. At its core, MPC uses a mathematical model of the building and its subsystems to predict future behavior over a defined horizon. It then solves an optimization problem that minimizes a cost function subject to operational constraints. The first step of the optimal trajectory is applied to the system, and the process repeats periodically (receding horizon principle).

In this setup, the predictive optimization problem is formulated as a mixed-integer linear program (MILP) solved every 15 minutes with a prediction horizon of 72 hours. The system is described with few physical parameters for each element. In the model, this includes: the PV system, the 3 heat pumps, the storage tanks, the building, the uncontrollable electric power consumption and hot water consumption. See [15] for further details. We only recap here few key points about the approach.

The cost function is designed to reflect operating costs, which include electricity purchase and resell costs and peak power tariffs which are charged based on monthly peak power, as well as comfort penalties considering the aggregated temperature and setpoint for the building. The models used in optimization are simplified physical models whose parameters are physical values that need to be tuned. Some are fixed at commissioning while others are tuned continuously based on measurement, using a Kalman filtering approach.

The most important component of the model is the building model. The building is modelled as a single thermal zone whose average temperature evolves in response to:

- Estimated convective/conductive losses through the envelope.
- Solar gains that are computed based on a geometric model of windows and global irradiance forecast from a weather forecasting service.
- The thermal heating/cooling input from the heating/cooling system

The MPC code runs on the EMS, which is a Linux-based platform.

4. Results

4.1. Experimental Protocol

To evaluate the benefits of the control strategy, a comparison against a "standard" management was needed. To this effect a baseline operating mode (BL), in which HPs were operated with fixed supply temperature heat curves, without self-consumption or tariff consideration. Predictive control (OPT mode) alternated with baseline control every two to three weeks to ensure comparable boundary conditions. Each phase covered complete heating cycles under similar weather and occupancy profiles.

The key performance indicators (KPIs) include electricity consumption, heating system performance factors, PV self-consumption, thermal comfort metrics, and net electricity cost. To control for variations in weather conditions and building use, outside temperature, irradiance, rest electricity consumption (from appliances other than the heat pump) are also reported.

Results with 66 days in baseline operation and 56 days in optimized operation were collected and analysed. This covers the period starting on October 1st 2024 and ending on February 28th 2025. Transitions between BL and OPT were performed at noon every two to three weeks, and the days of transition were excluded from the analysis. Finally, a few days had to be eliminated from the analysis due to data collection issues. Starting in March 2025, the alternation between OPT and BL was stopped and the building was operated in OPT mode with targeted optimization measures (heat pump internal parameter tuning and pump flow tuning) to improve the overall system efficiency. The KPIs reported in section 4.2 are based on the period October to February (without optimization measures) The effect of the efficiency measures is reported in section 4.5.

4.2. Results from strategy comparison

Table 2 reports the main KPIs as daily sums (cost, energy) or averages (temperatures)

Table 2: KPIs for validation campaign

KPIs	Outdoor temperature	Indoor temperature	PV production	Self-Consumption	HP Electricity	Rest electricity	Cost (real)	Cost (adjusted)
Unit	°C	°C	kWh	%	kWh	kWh	CHF	CHF
BL	5.97	20.98	38.31	72.4%	125.22	78.52	64.13	64.13
OPT	6.06	21.08	35.15	78.5%	124.16	78.69	61.21	59.99
delta	*0.1*°C	*0.1*°C	*-9.0%*	*7.9%*	*-0.9%*	*0.2%*	*-4.8%*	*-6.9%*

Two cost KPIs are reported: **real cost** (electricity bought minus electricity sold) and **adjusted cost**, which corrects for external factors such as temperature, solar radiation, and uncontrollable consumption.
Since indoor/outdoor conditions and consumption were similar across periods, the main difference arises from **9% higher solar production** in the BL days. Each additional kWh of PV power (valued at approximately 0.39 CHF/kWh considering the average self-consumption rate of 75%) reduces the net energy cost, so the adjusted cost corrects for this advantage. Note that this adjustment is conservative, as greater solar radiation also should lower heating needs.

On average, **the estimated cost saving in optimized mode is 7% compared to the baseline mode**. Looking specifically at the electricity used by the HPs, the share originates either from the local PV, from the grid during low-tariff (LT) periods or high-tariffs (HT) can be calculated, and in turn an equivalent unit cost of energy for the electricity of the heat pump as a weighted average can be computed, as shown in this table:

Table 3: Origin of energy for HPs

KPIs	HP energy from PV	HP energy from LT	HP energy from HT	Avg Unit cost
Unit	%	%	%	CHF/kWh
BL	11.6%	46.3%	42.0%	0.33
OPT	13.1%	63.9%	23.1%	0.29

HT and LT are based on the actual supplier tariffs in 2024 and are 0.46CHF/kWh and 0.29CHF/kWh respectively. HT apply from 6am to 23pm on weekdays (except holidays) and from 6am to 2pm on Saturdays.

The table clearly shows two effects: 1) The optimization shifts a large portion of the demand to low tariff periods; 2) The optimization manages to increase the PV electricity consumed by the heat pump, even in a context where the PV energy available is 9% lower. This effect remains small due to the low volume of PV power.

Figure 4 depicts the daily average consumption and production over baseline days and optimized days. It shows how the optimizer shifts consumption (on average) for the heat pumps away from evening and early morning hours towards midday and low-tariff periods.

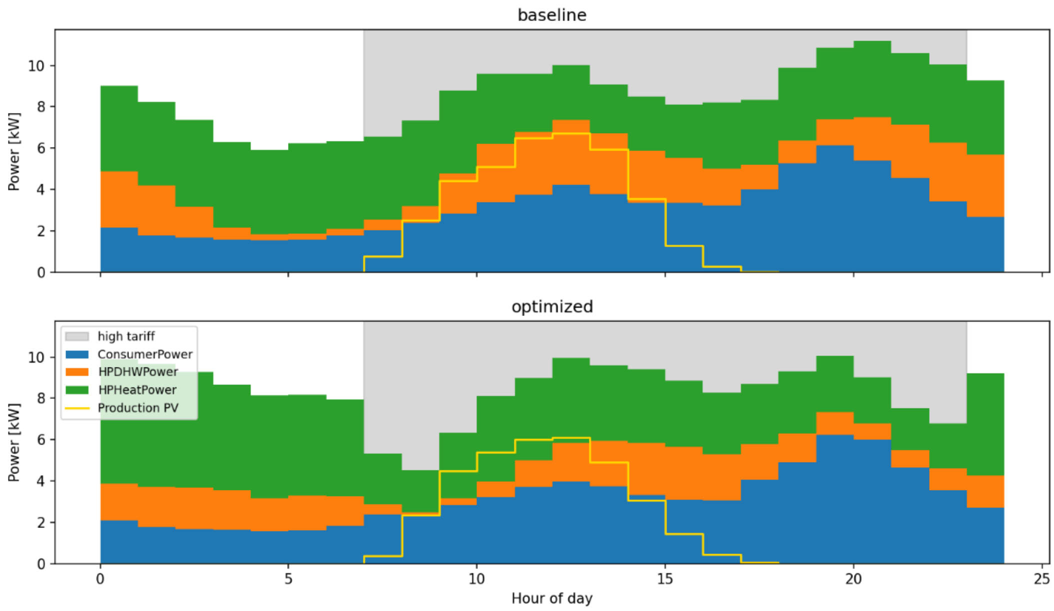

Figure 4: Average hourly consumption over test periods. Grey shaded area show high-tariff period

Regarding comfort, the average indoor temperature was slightly higher in optimized mode than in baseline mode. Looking at individual temperatures throughout the building, the trend is similar. We calculated the total average cumulated deviations outside of the desired comfort band of [-1°C, +1°C] around room setpoints over all rooms, and we report a decrease of 10% of negative excursions, meaning periods of time where the temperature was more than 1 °C below the setpoint was reported. That is evidence that the overall comfort was similar if not superior in optimized mode.

4.3. Focus on DHW

Table 4 displays the KPIs focusing on the production of hot water (reported as per day quantities)

Table 4: DHW KPIs:

KPIs	Electricity for DHW	HP heat	DHW consumed	DHW circulation losses	DHW SCOP	Heating losses	SNG+ - DHW
Unit	kWh	kWh	kWh	kWh	-	%	-
BL	48.1	126.1	65.8	60.0	2.9	47.7%	1.37
OPT	38.4	108.2	61.1	49.5	3.2	43.6%	1.59
delta	-20.0%	-14.2%	-7.2%	-17.4%	+9.5%	-8.9%	+8%

In the optimized mode, overall efficiency improves notably, with electricity use for domestic hot water reduces by 20% despite a much lower gap in DHW demand (7%). This gain is due to a higher heat pump COP and lower system losses. The hot water heat pump uses exhaust air as a heat source, making it fairly weather independent. In optimized mode, it operates at lower average supply temperatures, as the optimizer avoids reaching the maximum 62 °C of the hysteresis controller at every DHW production cycle, further enhancing efficiency. However, we report significant heat losses since the ratio of final consumed heat to produced heat by the heat pump is 47%. This is largely caused by excessive recirculation. The authors refer to section 4.5 for further discussion.

4.4. Focus on space heating

Table 5 reports on the main KPIs for space heating. Calculations are based on measurement of HP1 and HP2 which only produce heat for space heating.

Table 5: Heating KPIs

KPIs	HPs Electricity	Heat to building	HP1 heat	HP2 heat	HP1 SCOP	HP2 SCOP	SNG+ - heating
Unit	kWh	kWh	kWh	kWh	-	-	-
BL	81.9	285.3	93.3	167.4	3.2	3.5	3.5
OPT	89.5	295.9	109.4	152.5	3.0	3.4	3.4
delta	9.2%	3.7%	17.3%	-8.9%	-8.1%	-3.7%	-2.8%

Overall, the optimized mode uses more electricity than the baseline mode. This comes from a combination of higher overall heat to the building (+3.7%) and lower overall efficiency (SNG+ about -2.8% on average). This is expected as the optimizer heavily shifts consumption from high to low-tariff periods (see Figure 4) which can deteriorate overall efficiency. Nevertheless, this deterioration is small and does not offset the cost benefits gained from that consumption shift. Moreover, the higher heat demand partly reflects more favorable conditions during the baseline period due to higher radiation and is not fully attributable to the optimizer.

Second, an experimental gap in performance of heat pumps between HP1 and HP2 can be noticed although they are supposed to be identical and are operated in the same way. Further investigation did not allow us to identify the root cause of this difference, and it is suspected that it could be related to the HP hardware itself. Coincidentally, this proves slightly detrimental to the optimizer which uses HP1 more than the standard control, relative to HP2.

4.5. Additional efficiency measures

Based on a first analysis of the data, efficiency measures were identified to reduce losses and enhance overall efficiency. These measures consist of tuning the heat pump and valves and require manual intervention. They could not be implemented through the EMS remotely. Hence, they were implemented once starting in March 2025 for the rest of the heating season.

For **domestic hot water**, excessive recirculation was addressed by scheduling recirculation pump interruptions during low and high demand periods. This increased DHW heat consumption to production ratio from **34.6% to 40.1%**, cut electricity use by **14%**, and achieved annual savings of about **700 CHF**, with no loss of user comfort (no complaints about DHW temperature from occupants were reported over a three-month period). Note that the saving is based on a comparison against the preceding period, considering only OPT mode operation so this savings comes **on top** of savings already reported in section 4.2

For **space heating**, flow imbalances caused recirculation through the buffer tank and mixing warm water from the HP with recirculated cold water. The heat pump temperature delta setpoint was reduced, and distribution flow rates in the building were lowered by 20%. Although this seemed to improve efficiency of the system, the gain could not be rigorously confirmed due to relatively milder weather conditions after implementing these corrective measures, compared to before.

5. Discussion

5.1. Recommendations drawn from the project

From the experience of the project, the following list of recommendations destined to stakeholders in the design, commissioning, and operation of heat pumps and MFHs have been compiled.

Prioritize System Efficiency and Tariff Variations Over Self-Consumption: In collective residential buildings, self-consumption is naturally high during the heating season. In this pilot, it rose from 70% in BL to 78% in OPT, but that accounts for only about 1–2% cost savings. Because production-to-consumption ratios are small, increasing self-consumption bring little net benefit in MFHs. Greater cost reductions come instead from improving overall efficiency and shifting energy use to low-tariff periods, which proved the main driver of savings in this study.

Utilize Building Thermal Mass for Energy Storage: Storing energy within the building's thermal mass, rather than in water tanks, enhances the efficiency of heat pump systems. The authors' concrete recommendation is that EMS that manage heat pumps should operate with temperature setpoints bands for the thermal zones, not with fixed setpoints. A replicable and simple approach to integrate room setpoint management for an MFH is proposed here.

Focus on Global Efficiency Beyond Coefficient of Performance (COP): While the COP reflects a heat pump's performance, true efficiency depends on overall system design, integration, and operation. In this study, significant DHW recirculation losses have been observed, a problem also noted in other monitored systems [17, 18]. Such inefficiencies often go unnoticed due to limited sensor data or inadequate monitoring. Indicators like large temperature gaps between heat pump output and heating inputs can reveal issues. The authors recommend auditing available energy data after a few months of operation and/or installing heat meters for DHW and building-level consumption—an investment that quickly pays off by identifying major energy losses.

Minimize Recirculation and Mixing to improve efficiency: Recirculation and mixing in heating and DHW systems can cause major energy losses by lowering water temperature and heat pump efficiency. While Swiss sanitary norms require DHW recirculation to ensure fast hot water delivery, excessive flow rates lead to unnecessary heat loss. In this case, targeted recirculation control measures implemented in the site achieved 14% electricity savings for DHW preparation (~700 CHF/year), comparable to the gains from optimized control. See [17] for an extensive discussion of DHW preparation. Similarly, the architecture of the heating circuit caused significant remixing of warm and cold water, that is clearly detrimental in a heat pump-based heating system.

Lower DHW Temperature Setpoints for Enhanced Efficiency: Reducing the setpoint temperature for DHW can lead to significant efficiency gains. Savings of approximately 20% of electricity with optimized management of DHW production was demonstrated. Lowering the temperature reduces the temperature lift required by the heat pump, thereby improving its performance and reducing energy consumption, and also reduces losses which are significantly here since losses are quite large. However, it is essential to ensure that the set temperature complies with health and safety standards which can tend to be very conservative.

Implement Predictive Control Strategies for Optimal Management: Predictive control algorithms effectively manage trade-offs between energy consumption, cost, and comfort. The authors recommend to require EMS's to implement a predictive management strategy such as MPC.

5.2. Replicability

One of the primary goals of this project was to tackle the barriers to hinder the adoption of predictive control and other advanced energy management strategies in buildings. Different areas that touch on replicability in this work are discussed here:

- Integrated management of heat production and heat distribution: the authors already argued that synchronizing heat distribution and heat production is primordial to allow shifting heat consumption periods while maintaining high efficiency of the heat pump. However, this is not straightforward in a standard MFH because HP control and the valve management are managed by independent subsystems, usually based on separate off-the-shelf products with no mutual integration. As deep integration is not realistic nor necessarily desirable, the authors have proposed a simple integration approach where setpoints in the building are shifted, based on inputs from the centralized optimization. This allows minimal changes to the system and the appropriate input/output requirement for the home automation can be implemented by standard product installers (this was the case here)
- The strategy proposed does not rely on costly hardware for measurement. The extensive monitoring system deployed is used for advanced performance analysis here and the EMS does not rely on or have access to that data. The only hardware that a typical installation may not have are heat pump meters, which are fairly cheap, and which may be present anyway for billing purposes.
- The Energy Management System (EMS) requires the presence of connected thermostats that can provide aggregated data and allow adjustment of setpoints. Such thermostats are now standard in most renovations, and while aggregation and control may need some custom implementation, these tasks can be handled by installation technicians during home automation setup, as was the case here. The EMS must also be able to communicate digitally with the heat pump, a feature that is now common in modern installations. Although individual metering of the heat pump and PV inverter is not strictly necessary, it is recommended to enable precise responses to power fluctuations. The software has already been integrated into a commercial EMS running on an on-premises gateway device, with modest computing requirements—comparable to those of a Raspberry Pi—thanks to the use of lightweight optimization models.
- Interfaces to HPs: this remains a hurdle despite various ongoing efforts towards standardization. The authors follow an open model based on SGR profiles that provide public descriptions of interface

descriptions. Progress in this domain is in large part in the hands of manufacturers, and it is noteworthy that several have joined the SGR initiative already.

6. Conclusion

This field demonstration validated the feasibility of predictive energy management for multi-family buildings with heat pumps and PV. The model predictive control strategy achieved 7% electricity cost savings by shifting operation to low-tariff periods and improving self-consumption, without compromising comfort. Using standardized SmartGridReady interfaces and commercial EMS components, the approach proved replicable and cost-effective, requiring no additional hardware.

The project emphasized the importance of system design and operation—particularly minimizing DHW recirculation losses and leveraging building thermal mass for storage for cost-efficient HP operation, as well as the importance of standard interfaces to be offered by heat pump manufacturers to allow the integration of HP with future-proof and flexible EMS's. These findings provide a practical foundation for wider adoption of predictive control in collective residential buildings.

7. Acknowledgements

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