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OPERA

Optimal use of renewable energy with Heat Pumps for renovated Multi-family houses

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Summary

Residential buildings are a key lever in the energy transition, yet their decarbonization remains a challenge—particularly for renovated multi-family buildings. In 2023, only 12% of such buildings were equipped with heat pumps (HPs), compared to 25% of single-family homes. Moreover, energy management solutions currently available on the market—often designed for individual housing—fail to significantly reduce operating costs when applied to collective buildings. For instance, systems that encourage HPs to consume available photovoltaic (PV) electricity can unintentionally degrade their energy performance, cancelling out the expected savings on the energy bill.

The OPERA project has shown that an intelligent, integrated approach can overcome these limitations. Deployed in a 20-apartment rental building in Neuchâtel renovated in 2024, the solution is based on the predictive energy management technology NRGMaestro®, developed by CSEM and used in the Soleco Optimizer product. This technology anticipates the building's energy needs based on weather and electricity pricing conditions, while optimizing the coordination between HPs and underfloor heating valves using temperature setpoint ranges instead of fixed values. The project's key innovation lies in the fine-tuned management of the building's thermal flexibility, without compromising occupant comfort.

The building was equipped with an advanced metering system, enabling a rigorous and reliable assessment of performance. By alternating between standard and optimized control strategies over a full heating season (2024–2025), the building recorded an 11.5% reduction in electricity costs for the HPs. In addition, a further estimated 11% reduction in costs was achieved through lower energy losses related to domestic hot water recirculation, resulting in total annual savings of at least CHF 1,500—with no additional hardware investment required.

The lack of standardized communication interfaces between equipment remains a major barrier to innovation in the field of energy management. We helped reduce this obstacle by collaborating with the SmartGridReady CH association to implement and promote an open and interoperable interface for heat pump control.

The solution is already operational, compatible with both new and renovated buildings, and offers significant potential for large-scale deployment. It supports a better return on investment for HP installations and provides a concrete contribution to removing key barriers to the decarbonization of Switzerland's residential building stock.

Zusammenfassung

Wohngebäude stellen einen entscheidenden Hebel für die Energiewende dar, doch ihre Dekarbonisierung bleibt eine Herausforderung – insbesondere bei der Sanierung von Mehrfamilienhäusern. Im Jahr 2023 waren nur 12 % dieser Gebäude mit Wärmepumpen (WP) ausgestattet, im Vergleich zu 25 % der Einfamilienhäuser. Darüber hinaus sind die derzeit verfügbaren Energiemanagementlösungen meist für Einfamilienhäuser konzipiert und können bei Anwendung auf grössere Gebäude die Betriebskosten nicht signifikant senken. Systeme, welche Wärmepumpen so steuern, damit diese den verfügbaren Photovoltaik (PV)-Strom nutzen, können sogar unbeabsichtigt deren Effizienz verschlechtern und so die erwarteten Einsparungen zunichtemachen.

Das Projekt OPERA hat gezeigt, dass ein intelligenter und integrierter Ansatz diese Grenzen überwinden kann. Die Lösung wurde in einem 2023 sanierten Mietgebäude mit 20 Wohnungen in Neuenburg implementiert und basiert auf der prädiktiven Energiemanagement-Technologie NRGMaestro®, entwickelt vom CSEM und eingesetzt im Produkt Soleco Optimizer. Diese Technologie prognostiziert den Energiebedarf des Gebäudes anhand von Wetter- und Preisinformationen und optimiert gleichzeitig die Regelung zwischen Wärmepumpen und Fussbodenheizungsventilen durch Solltemperaturbereich anstelle von festen Werten. Die zentrale Innovation des Projekts liegt in der präzisen Steuerung der thermischen Flexibilität des Gebäudes, ohne den Komfort der Bewohner zu beeinträchtigen.

Das Gebäude wurde mit einem fortschrittlichen Messsystem ausgestattet, das eine präzise und zuverlässige Bewertung der Leistung ermöglicht. Durch den Wechsel zwischen Standard- und Optimierungsstrategie über eine gesamte Heizsaison (2024–2025) konnte eine Reduktion der Stromkosten für die Wärmepumpen um 11,5 % erzielt werden. Hinzu kommt eine geschätzte Einsparung von weiteren 11 % durch die Verringerung von Energieverlusten bei der Zirkulation des Warmwassers, was zu einer jährlichen Gesamtersparnis von mindestens 1'500 CHF führt – ohne zusätzliche Investitionen in Hardware.

Das Fehlen standardisierter Kommunikationsschnittstellen zwischen den Geräten stellt weiterhin ein wesentliches Innovationshindernis im Energiemanagement dar. Im Rahmen des Projekts haben wir dazu beigetragen, dieses Hindernis zu verringern, indem wir mit dem Verband SmartGridReady CH zusammengearbeitet haben, um eine offene und interoperable Schnittstelle zur Steuerung von Wärmepumpen zu entwickeln und zu fördern.

Die Lösung ist bereits im Einsatz, mit neuen wie auch sanierten Gebäuden kompatibel und bietet ein hohes Potenzial für eine breite Anwendung. Sie verbessert die Rentabilität von Wärmepumpeninstallationen und trägt konkret dazu bei, zentrale Hindernisse bei der Dekarbonisierung des Schweizer Wohnungsbestands zu überwinden.

Résumé

Les bâtiments résidentiels représentent un levier essentiel de la transition énergétique, mais leur décarbonation reste un défi, notamment pour les immeubles collectifs rénovés. En 2023, seuls 12 % d’entre eux étaient équipés de pompes à chaleur (PAC), contre 25 % des maisons individuelles. Par ailleurs, les solutions de gestion de l’énergie disponibles sur le marché, souvent pensées pour l’habitat individuel, échouent à réduire significativement les coûts d’exploitation lorsqu’elles sont appliquées aux bâtiments collectifs. Par exemple, les systèmes qui incitent les PAC à consommer l’électricité photovoltaïque (PV) disponible peuvent involontairement dégrader leur performance énergétique, annulant les bénéfices attendus sur la facture.

Le projet OPERA a démontré qu’une approche intelligente et intégrée permet de surmonter ces limites. Déployée dans un bâtiment locatif de 20 appartements à Neuchâtel rénové en 2023, la solution repose sur la technologie prédictive NRGMaestro®, développée par le CSEM et utilisée dans le produit Soleco Optimizer. Cette technologie anticipe les besoins énergétiques du bâtiment en fonction des conditions météo et tarifaires, tout en optimisant la coordination entre les PAC et les valves du chauffage au sol via des plages de consigne de température plutôt que des valeurs fixes. L’innovation clé du projet réside dans la gestion fine de la flexibilité thermique du bâtiment, sans compromettre le confort des occupants.

L’immeuble a été équipé d’un système de mesure avancé permettant une évaluation rigoureuse et fiable des performances. En alternant les stratégies standard et optimisée sur toute une saison de chauffe (2024–2025), le bâtiment a enregistré une baisse de 11,5 % des couts de l’électricité pour les PAC. À cela s’ajoute une réduction des couts estimée à 11 % grâce a une reduction des pertes liées à la recirculation d’eau chaude sanitaire, pour une économie annuelle minimale de 1 500 CHF – sans coût matériel supplémentaire.

L’absence d’interfaces de communication standardisées entre équipements reste un frein majeur à l’innovation dans le domaine de la gestion d’énergie. Nous avons contribué à réduire cet obstacle en collaborant avec l’association SmartGridReady CH, afin de déployer et promouvoir une interface ouverte et interopérable pour le pilotage des pompes à chaleur.

La solution est déjà opérationnelle, compatible avec les bâtiments neufs ou rénovés, et offre un potentiel de déploiement à grande échelle. Elle favorise un meilleur retour sur investissement lors de l’installation de PAC et contribue concrètement à lever les freins à la décarbonation du parc résidentiel Suisse.

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API	Application Programming Interface
BL	Baseline
BWP	Bundesverband Wärmepumpe
COP	Coefficient of performance
DHW	Domestic hot water
DHW	Domestic Hot Water
EID	external interface description
EMS	Energy management system
FPs	functional profiles
GFH	Ground Floor Heating
HP	Heat pump
HT	High Tariff
JAZ	Jahres-Arbeits-Zahl (Annual performance factor)
LT	Low Tariff
MFH	Multi-Family Housing
MPC	Model Predictive Control
PV	Photovoltaics
SC	Self-consumption
SFH	Single family Housing
SFOE	Swiss Federal Office of Energy
SH	Space Heating
SNG	Systemnutzungsgrad (System utilisation factor)
SNG+	System performance factor
TMY	Typical Meteorological Year
WNG	Wärme-Nutzungs-Grad (Heat utilisation factor)

1 Introduction

1.1 Context and motivation

The transition to sustainable energy systems is a pressing global challenge. In Switzerland, like many other countries, the adoption of renewable energy technologies remains a critical goal. This report focuses on the integrated management of heat pumps (HPs), PV systems, and buildings—a holistic approach that promises significant benefits in terms of energy efficiency, cost savings, and environmental impact.

Context and Challenges

1. Photovoltaic (PV) Installation Gap:
   - The federal law on safe energy supply based on renewable energy stipulates binding targets of 35TWh from non-hydro renewables in 2035 and 45TWh in 2050 [1]. The bulk of this should be obtained from PV systems. In 2022, PV systems produced 64% of the 4.4TWh of non-hydro renewable energy. The majority of PV installation is expected to happen on buildings due to the limited potential for field systems in Switzerland. The untapped potential, estimated at around 67 TWh, underscores the urgency to accelerate PV adoption.
   - Switzerland's aging multi-family housing (MFH) stock, predominantly built before 2000, presents a unique opportunity. These buildings, with surfaces exceeding 200 m², can accommodate PV systems ranging from 20 to 30 kW_p. Thus, targeting MFH renovations becomes crucial.
2. Heat Pumps in Multi-Family Housing:
   - In 2022, 19% of buildings had heat pumps, a fourfold increase since 2000. Newer buildings (built in the last ten years) have had a 75% adoption rate while it is much lower in buildings built prior to 2000. That shows that renovation is crucial to reaching decarbonization objectives. In 2019, HP sales outpaced traditional gas and oil burners, signaling a shift toward cleaner and more efficient heating solutions.
   - While Switzerland has successfully deployed heat pumps in single-family houses (SFH) with 23% overall penetration, their adoption in MFH lags behind at only 12% [2]. However, recent evidence suggests that HPs can thrive in multi-unit buildings. Nevertheless, it is important to acknowledge that HP installations in MFH are typically more complex than in SFH for the following reasons
     - Need for multiple heat pumps: it is typical to have 2 or in the case of our pilot site 3 HPs to meet the need of the building
     - Significant space limitation: As oil burners are more compact than heat pumps, it is typical to have to deal with small available footprint for HPs in the context of renovations. This was the case in the pilot site
     - Noise: MFH in Urban environment need to deal with noise level restrictions for evaporators which can be challenging to meet: this was also a concern for the pilot site

3. Optimizing Heat Pump Control:
    - To enhance economic viability and in turn adoption, HPs must be operated efficiently:
        - **Synergy with PV:** Coordinating HP operation with PV production is essential, as tariffs generally favor self-consumption.
        - **Efficiency:** HPs should run at peak efficiency, leveraging favorable outdoor conditions and low supply temperatures as much as possible.
        - **Synergy with building thermal inertia:** It is now understood that it is more beneficial to store energy in the building mass than in water buffers which are generally too small [3].
    - Standard HP operating strategies fail at those objectives:
        - Traditional control is similar for oil burners and relies on heating curves which dictate supply temperatures as a function of outside temperature. The management of the HP is done with no knowledge of solar production, nor any coordination with the distribution system. This means that it is sub-optimal with respect to all three aspects listed above
        - Self-consumption strategies based on increasing supply and storage setpoints have started to appear in a variety of commercial EMS. It has already been shown [4] that those approaches increase self-consumption increase but decrease the seasonal COP of heat pumps, and hence the overall system efficiency. Furthermore, it has been demonstrated that [4] losses in efficiencies tend to offset gains for self-consumption increases from an economic point of view, leading to no net saving for the building occupants!

1.2 Project objectives

The purpose of this project is to promote and demonstrate the scalable integrated management of HPs, PV systems and buildings heat demand in multi-family residential buildings. This will be done thanks to improved HP and building control. To that purpose, the following steps will be taken:

1.2.1 **Objective 1:** Model predictive energy management

- Considering that the ultimate objective of the energy management strategy is the reduction of costs, it is important to acknowledge that it needs to arbitrate between multiple trade-offs, namely:
- Potential gains in self-consumption versus potential increases in losses and/or reduction in efficiency
- Potential gains in selling PV power vs savings in storing it which is dependent on tariff levels
- Optimization against varying tariffs, for example day / night

Model Predictive Control (MPC) has gained significant attention in energy management for buildings due to its ability to address multiple conflicting objectives and consider constraints.

- Predictive Capabilities: MPC integrates weather forecasts and thermal models of the building. It predicts disturbances (such as weather changes) and optimizes heating based on this information. This predictive aspect allows MPC to adapt to varying conditions and make informed decisions.
- Trade-offs and Constraints: as mentioned, energy management involves trade-offs. It considers these constraints while regulating the heating system, ensuring cost reduction without compromising comfort.
- Thermal Mass Utilization: MPC can fully exploit the potential of building thermal mass. By explicitly considering the building's thermal inertia, it predicts trends in indoor temperature and adjusts heating accordingly. This utilization of thermal capacity minimizes energy consumption and maintains indoor comfort levels, even when external weather conditions vary.

The long-standing barrier for MPC is scalable deployment. In this project, we elaborate a scalable predictive energy management strategy for MFHs with economically efficient management of HPs, PVs and building, taking full advantage of the building thermal inertia to store energy. For this objective, we built on previous joint experience from SOLECO and CSEM with multiple commercial deployment of MPC-based EMS and improve specific aspects of the MPC strategy that are particularly relevant to MFHs. This includes management of multiple cascaded heat pumps, optimization of the supply temperature to favour lower supply temperatures, and proper consideration of the building distribution loop inertia (see Section 2.4 for details)

1.2.2 **Objective 2**: Standard interfaces

The integrated energy management strategy developed in Objective 1 is only possible if appropriate monitoring and control interfaces are available. In addition, these interfaces need to be standardized to reduce the barrier for replication to new sites. We specifically focus on two aspects:

- Successful demonstration of standard interfaces to heat pumps. Standardized interfaces, such as the ones developed by SmartGridready contribute to this enable precise power control of heat pumps and enable a more aligned operation of heat pumps with the PV power production and a facilitated integration of HPs in any EMS.
- Simple integration of the heat distribution system. Smart thermostatic valves within the Loxone ecosystem enable to unlock the potential for thermal energy storage in the building.

1.2.3 **Objective 3:** Validation of concept

The validation of the proposed development is a crucial component to boost replicability and interest in the future. Our validation approach is composed of two pillars:

- Primarily, an extensive field campaign that will aim to evaluate the benefit of the integrated management approach in a real building. This relies on an extensive measurement concept devised by OST.
- A simulation experiment to complement the results for the field tests, in particular the alternative of a self-consumption focused management strategy

2 Approach, method, results and discussion

2.1 Description of the pilot site

The project pilot site is a residential multi-family apartment located in Neuchatel downtown area. The North facing façade is illustrated in Figure 1. It is composed of 20 apartments spread over 6 floors with a reference surface area of 1700m^2. Prior to renovation, space heating (SH) and domestic hot water (DHW) were generated via an oil burner. The average yearly consumption was 171 MWh for SH and 50 MWh for DHW. There were no PV, the average yearly electricity consumption was of 54 MWh.

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

The scope of renovation includes the insulation of the envelope of the building, the modification and extension of balconies on the southern façade, the addition of a rooftop solar PV installation and solar balustrade on the top floor, the modification of the heating system with a replacement by heat pumps and of the addition of floor heating for the distribution system. The building sketches are provided in Figure 2 and Figure 3.

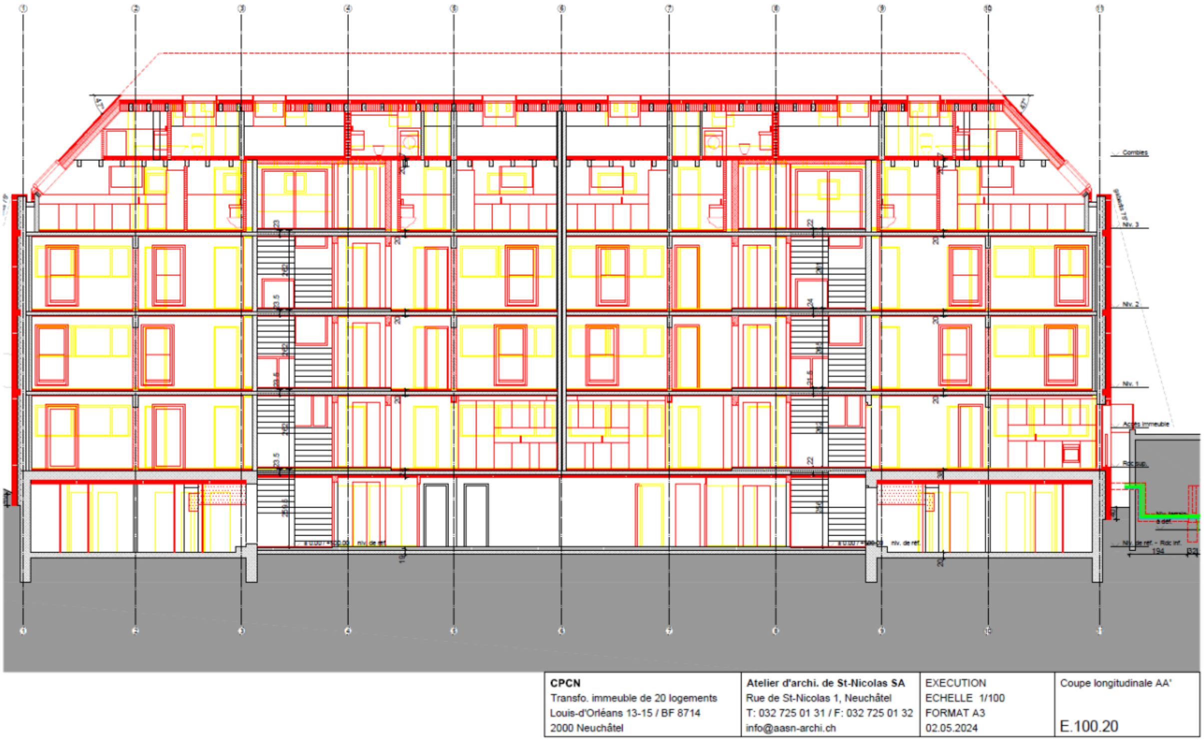


Figure 2: longitudinal view of building after renovation

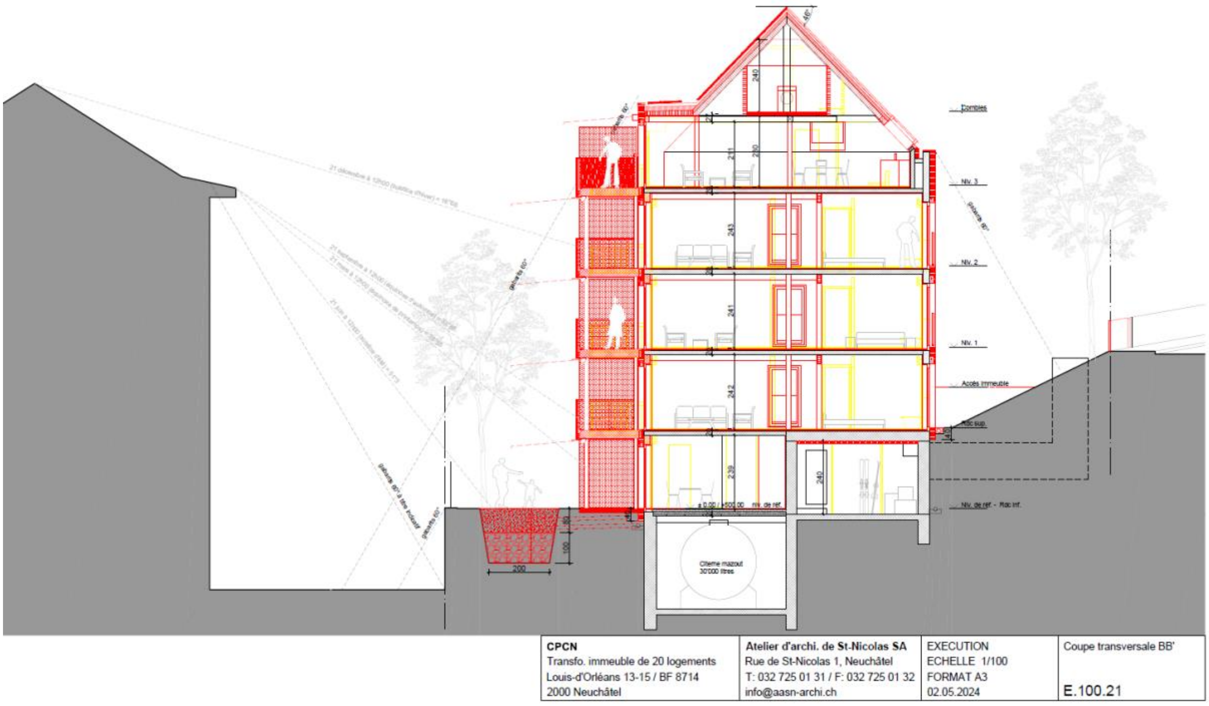


Figure 3: lateral view of building after renovation

The new energy production and monitoring concept is depicted in Figure 4. The following equipment are included:

- Two air-water reversible heat pumps (left-side on Figure 4) that can generate heat for the heating systems or domestic hot water production and be also used for cooling. The nominal heating power of each heat pump is 20 kW_{th} for heating. The selected model is model TCA Optimaheat HM-HP20L-M-BC[1] which is equipped with a variable speed compressor.
- A heat recovery heat pump (right side on Figure 4) extracts heat from the exhaust air through a connection to the ventilation block. This presence of this heat pump is mandated by the local regulations. It is used for DHW production only and should run most of the time.
- A buffer tank for heating of 800 litres (middle left of Figure 4)
- Two domestic hot water tanks connected in parallel (middle right of Figure 4). The presence of two tanks is due to space limitations.
- Two supplementary 3-phase electric heaters for domestic hot water production
- A 21 kW_p rooftop PV-installation mostly on the southern roof slope (orientation of 27 deg. East from South) with a few panels on the East and West slopes
- A 9kW_p balcony -integrated PV-panels on the last floor, also facing 27 °C east from South

[1] Datasheet: TCA_20170420_BC_Luft-Split.indd (optimaheat.ch)

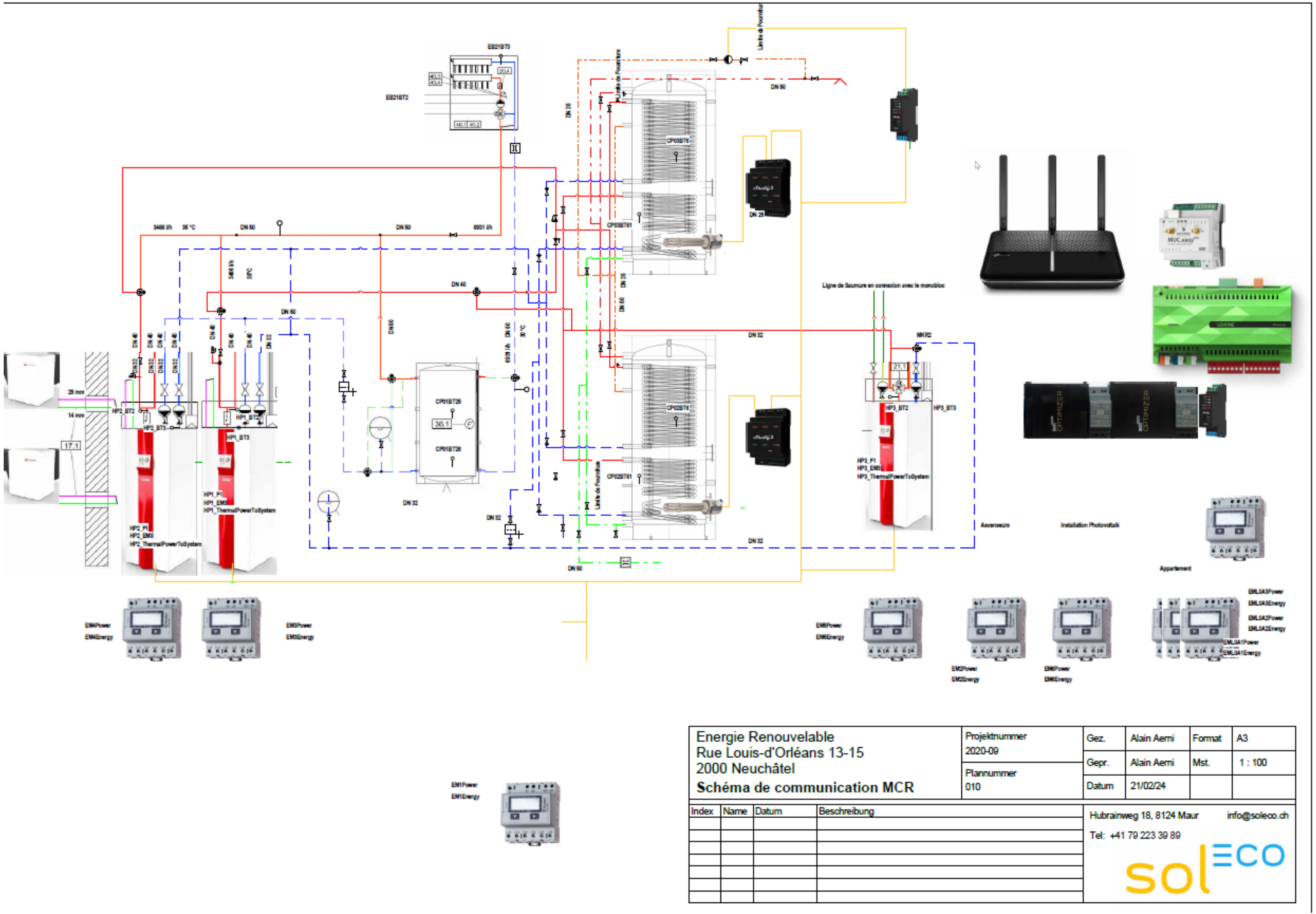


Figure 4: Energy system and monitoring concept

The measurement concept for control (there is a more extensive measurement concept for the project result monitoring, see next sections) includes a main meter for the building, electric meters for each heat pump, one electric meter monitoring the outputs of the PV plants (on the AC side), metering and controllable relays for the supplementary heaters. The building is also equipped with meters in each apartment for billing purposes.

Finally, to enable advanced heat distribution control, the building is equipped with Loxone domotic systems: in each apartment, Loxone tree valves (Figure 5) are installed for the floor heating. These are wired valves that are actuated with continuous opening control and also allow the measurement of the return temperature. The Loxone system also enables the management of shades and blinds, centralized lighting management and room thermostats. Each apartment is equipped with a tablet for central management (Figure 6) of the apartment as well as Loxone Touch flex elements (Figure 7) for light and thermostat management in each room.

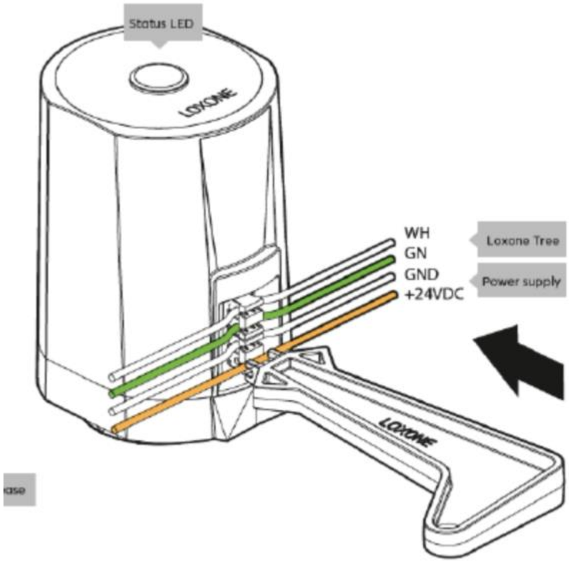


Figure 5: Loxone tree valves. Source: Loxone

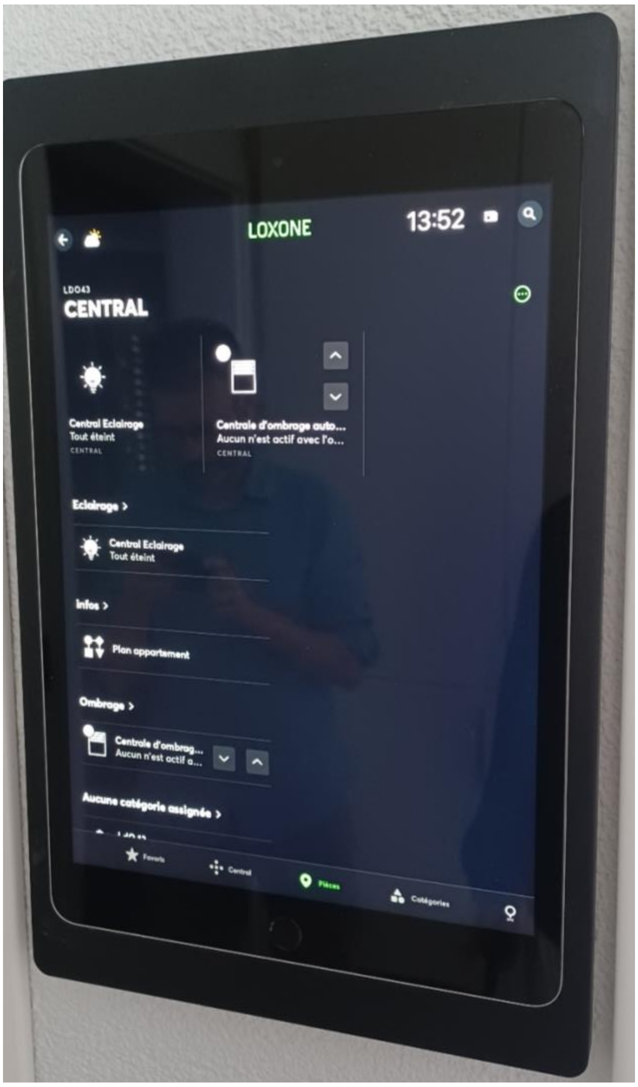


Figure 6: Tablet in each apartment. Photo from site

Figure 7: Loxone Touch pure flex in the pilot site

2.2 Objective 3: Validation of concept

One of the key objectives of the project (objective 3) is the validation of the proposed concepts. This is a crucial component to boost replicability and interest. Our validation approach is composed of two pillars:

- Primarily, an extensive field campaign that will aim to evaluate the benefit of the integrated management approach in a real building.
- A simulation experiment to confirm the benefits in a controlled environment that allows one-to-one comparison and therefore complements the findings of the field tests.

The following scenarios of Table 1 have been shortlisted.

Table 1: List of scenarios for comparison

#	Name	Building	PV	HP control	Zone control	Measured
1	**Historic**	Old	No	-	Fixed setpoints	yes[2]
4	**Baseline mode**	Renovated	Yes	Heating curve	Fixed setpoints	yes[3]
5	**OptiClassic-PV**	Renovated	Yes	Self-consumption optim[4]	Fixed setpoints	-
6	**control**	Renovated	Yes	MPC (SOLECO)	Range of setpoints used by SOLECO	yes

- Scenario 1 is the building prior to renovation. Only yearly consumption figures are available and it is only relevant insofar as to evaluate if the renovation targets are met.
- Scenario 4 is the main baseline scenario where the building is operated following a “standard” operating strategy. This “standard” strategy is typical of buildings operating without smart EMS and consists in the regular heating curve to set the heat pump supply temperature. DHW is production based on a standard hysteresis controller independently of other factors such as PV production.
- Scenario 5 is the same as scenario 4 but assumes a slightly more sophisticated control strategy that aims at increasing self-consumption. This consists in increasing tank temperature setpoints when there is solar excess available. This is typical of multiple commercially available EMS’s and is the most widely used strategy for self-consumption optimization with heat pumps.
- Scenario 6 is the target scenario with Optimized control of the heat pump based on predictive control, and the opportunity to buffer energy in the building by operating room setpoints in a range rather than at a fixed value (and therefore indirectly influencing the heat distribution in the room by causing valves to open/close).
- Scenarios 4 and 6 will be demonstrated on the site while scenario 5 was simulated.

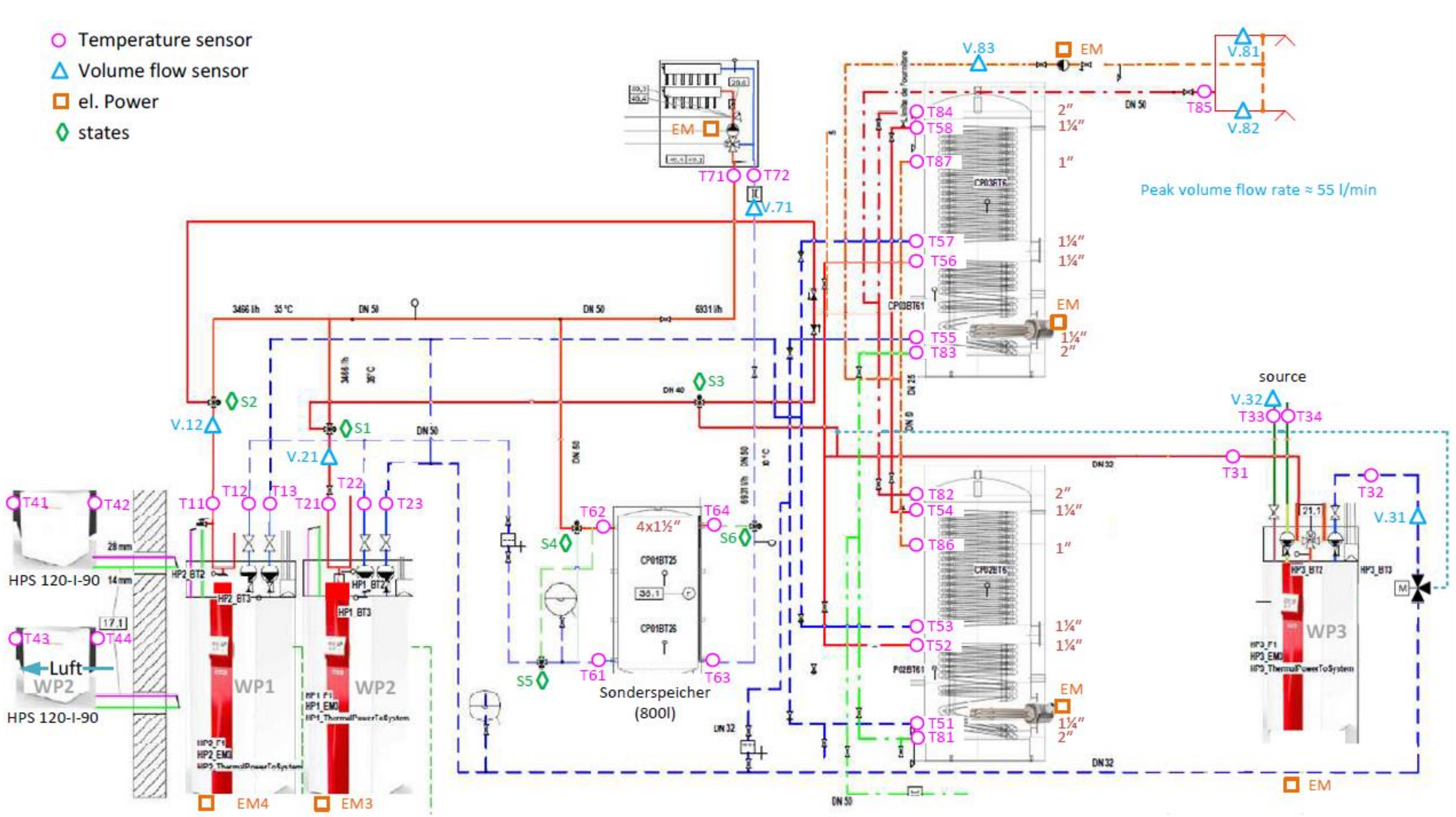
[2] Yearly data available (not detailed timeseries)
[3] To measure this case, we must agree to be less energy efficient for a given time (typically a few months)
[4] Rule based (SmartFlox like, https://smartfox.de/)

2.2.1 Measurement concept for field tests

Considering that the ultimate objective of the energy management strategy is the reduction of costs, it is important to acknowledge that it needs to arbitrate between multiple trade-offs, namely:

- Potential gains in self-consumption versus potential increases in losses and/or reduction in efficiency: it has already been shown [2-3] that basic self-consumption increase strategies based on increasing supply and storage setpoints decrease the seasonal COP of heat pumps.
- Potential gains in selling PV power vs savings in storing it which is dependent on tariff levels.
- Optimization against varying tariffs, for example day night.

To evaluate properly these aspects, a more extensive measurement concept was designed by OST and implemented on the test site through mandates to the electrician, DHW and heating installers. A schematic of all sensors installed is shown in Figure 8.


Temperature sensor
Volume flow sensor
el. Power
states
Peak volume flow rate ≈ 55 l/min
source
Sonderspeicher
(800l)
4x1½″
WP1
WP2
WP3
Luft
HPS 120-I-90
HPS 120-I-90
EM4
EM3
EM
V.81
V.82
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V.71
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V.21
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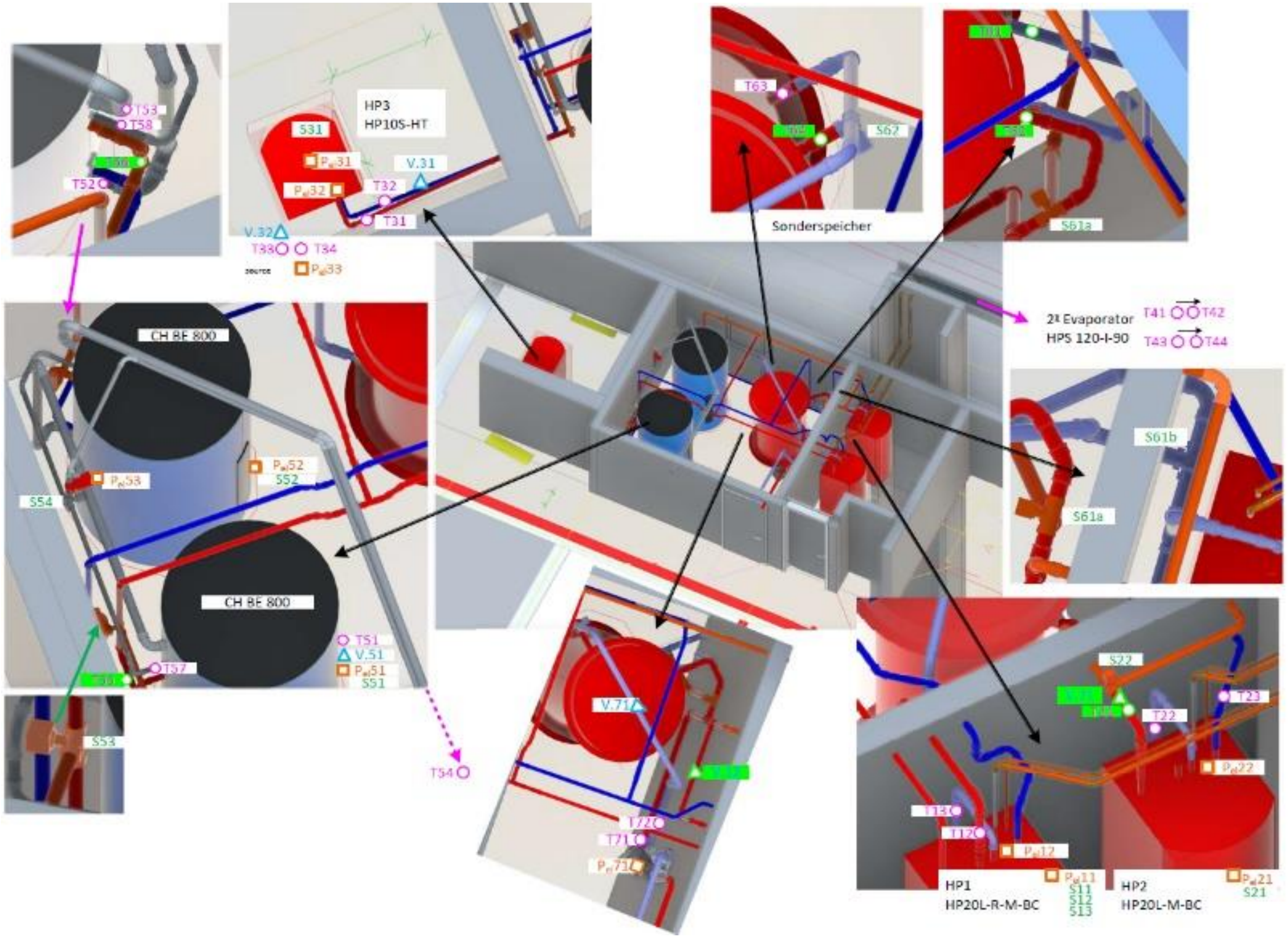

Figure 8: Sensor layout concept. (previous page): overall schematic. (this page): zoom on key mechanical locations. Source: OST

2.2.2 KPIs for field tests

The Coefficient of Performance (COP) and the resulting Seasonal Performance Factor (JAZ - Jahresarbeitszahl) have been calculated independently for both the space heating system and domestic hot water production. This separation allows for a more nuanced understanding of the system's performance across different operational demands. The calculations utilize specific sensor configurations to ensure accurate measurement of energy inputs and outputs in each subsystem.

The following sensors were strategically deployed to capture the relevant performance data:

$COP_{spaceheating}$, $JAZ_{spaceheating}$: T_{11},T_{12},V_{12},EM_3,T_{21},T_{22},V_{21},EM_4

$COP_{hotwater}$, $JAZ_{hotwater}$: T_{31}, T_{32},V_{31},EM_5

Following guidelines from [], in addition to the standard COP and JAZ metrics, the enhanced System Performance Factor (SNG+) was calculated. After careful analysis, the Heat Utilization Factor (WNG) was deliberately excluded from our evaluation framework as it was determined that this metric would not provide supplementary insights beyond what JAZ and SNG+ already reveal about system performance.

The SNG+ incorporates additional peripheral energy consumers such as circulation pumps and heating rods.

$SNG+_{spaceheating}$: T_{72},T_{71},V_{71},EM_3,EM_4,SP_4 where SP_4 is the pump delivering the heating to the flats.

$SNG+_{hotwater}$: T_{85},T_{81}, T_{83},V_{81},V_{82},EM_5, (eventually EM_3 ,EM_4 too when use to create hot water), EM_{32},EM_{31},SP_5 where EM_{32} & EM_{31} are the heating rod and the SP_5 circulating pump.

The table below presents the comprehensive JAZ and SNG+ values calculated across the entire heating season, spanning from September 25, 2024, to April 30, 2025. This extended monitoring period captures the system's performance across varying external temperatures and demand profiles, providing a robust dataset for analysis. It should be noted that due to technical issues with the data acquisition system, nine days within the monitoring period had to be excluded from the calculations. This exclusion was necessary to maintain the integrity and reliability of the performance metrics. The missing data represents approximately 4% of the total monitoring period, which is within acceptable limits for seasonal performance assessment. The calculated performance indicators provide crucial insights into the overall energy efficiency of the heating system under real-world operating conditions.

System	**JAZ**	**SNG+**
Only space heating	3.36	3.47
Only domestic hot water	3.04	1.59
Overall	3.25	2.78

The enhanced System Performance Factor for heating (SNG+ space heating) should theoretically never exceed the Seasonal Performance Factor (JAZ) as the thermal energy is similar or lower (due to heat loss) and the electrical energy is higher (due to adding the pump consumption). The observed anomaly—where SNG+ values exceeded JAZ values—can be attributed to systematic measurement errors in the volume flow sensors. These sensors are critical for accurately determining the thermal energy transfer rates within the system. To address this discrepancy in the comparison between the JAZ and SNG+, a corrected calculation could be made with two key adjustments:

- Assumed zero heat loss in the distribution system (a conservative simplification).
- Used the heat produced directly at the heat pump rather than the heat consumed at the building level.

With these methodological adjustments, the recalculated SNG+ value was determined to be 3.13, which aligns with theoretical expectations by falling below the JAZ value. This correction provides a more realistic assessment of the system's actual performance while highlighting the importance of sensor accuracy in performance metric calculations. It is possible that a similar situation occurs with the domestic hot water calculation however, unlike the space heating system, corrected SNG+ calculations cannot be reliably applied to the domestic hot water system due to its more complex thermal dynamics. The DHW system involves substantial and variable heat losses through:

- Storage tanks with continuous standby losses.
- Hot water circulation systems throughout the building.

These inherent thermal losses cannot be accurately estimated with the available measurement setup. The irregular flow patterns in DHW usage further complicate precise measurement, making it impossible to implement the same correction methodology used for the heating system calculations. Therefore, the calculated SNG+ values for domestic hot water must be interpreted with these measurement limitations in mind.

The COP, JAZ and SNG+ values across different control modes are compared in this report. However, this comparative analysis presents significant methodological challenges due to the inherently variable nature of operating conditions. Each day presents a unique combination of:

- External temperature profiles,
- Solar radiation levels,
- Occupancy patterns and internal heat gains,
- Building thermal inertia effects,
- Thermal storage usage.

To establish statistically robust comparisons between different control strategies, one would ideally require multiple days with nearly identical operating conditions under each control mode. The natural variability of weather conditions and usage patterns makes such direct comparisons difficult without extensive data normalization procedures.

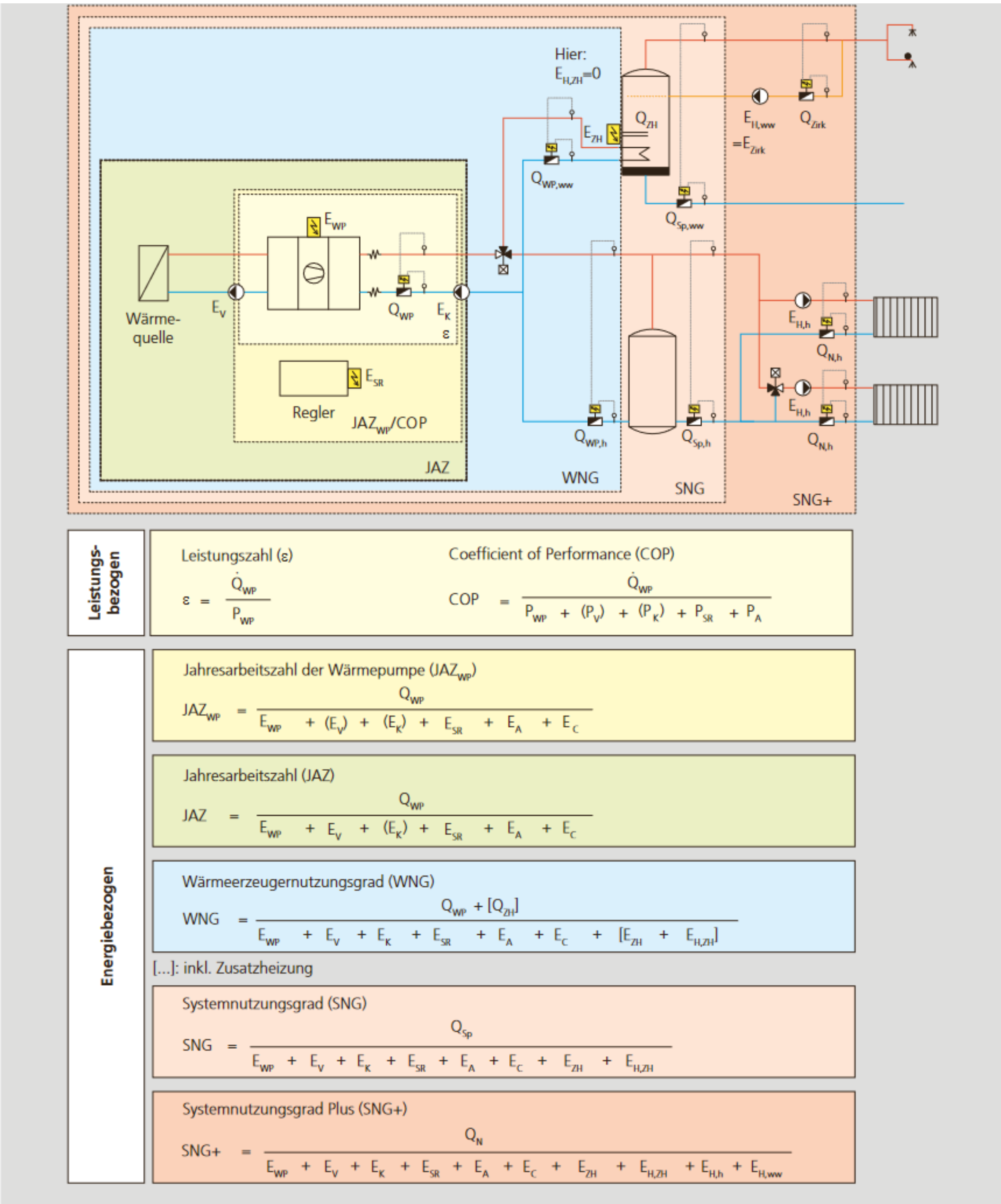

Figure 9: Efficiency computation chart. Source: [12]

In addition to the energy and efficiency KPI mentioned above, we will also compute:

- Energy costs: we recall that the default behaviour of the SOLECO Optimizer is to minimize the cost of operation while maintaining comfort, most importantly the net cost of purchasing/selling electricity. With standard day/night tariffs, the optimization needs to balance the relative gains of consuming at night during low tariffs and the potential gains from self-consumption from consuming during the day, in addition to the overall efficiency of the system. Naturally these objectives which can be sometimes in competition).
- Comfort: absolute deviation w.r.t the temperature set-point. Also broken down into over/under-heating.
- Self-consumption and autarky.

2.2.3 Baseline strategy and comparison

These KPIs are computed for OPERA mode as well as the “standard” mode (Table 1). The “standard” control uses a regular heating curve for the heat pump and lets the distribution system valves operate independently of the heat pump. To allow a fair comparison, an standard controller was purchased and commissioned according to the standards in the field. PV production is not considered for the HP operation. The remaining modes of Table 1 are considered in simulation only.

To make a meaningful comparison, the system should be operated in similar conditions (most importantly, weather) for a sufficiently long period of time.

Regarding energy consumption, it is notable that energy consumption and efficiencies are dependent on various external factors including heat demand for DHW, space heating, and outside conditions.. For this comparison the following factors are considered:

- **Outside temperature** which will impact heat demand for space heating and heat pump COPs. A possible way of conveying the relation between consumption and outside temperature is by charting the considered metric (e.g. primary energy consumption for heating) against outside temperature. To summarize the data into a single KPIs, normalization by heating degree days is usually used. They, however, assume a linear relationship between consumption and outside temperature which is only approximately true, especially for air to water heat pumps where the COP depends also on the outside temperature.
- **Solar irradiance** impacts heat demand significantly, although in our experience to a lesser extent than outside temperature during the heating season. The impact of solar irradiance is also dependent on blind use. The current plan includes blind position monitoring and simple, active blind control.
- **Indoor temperatures**: higher setpoint leads to higher heat demand, everything else being equal.
- **Hot water consumption**: this obviously influences heat needs for DHW.

2.2.4 Simulation model

The simulation environment selected for the project is DIMOSIM (District Modeller and SIMulator) developed by CSTB (Centre Scientifique et Technique du Bâtiment, France). The DIMOSIM platform can simulate multiple combinations of systems, models, and buildings at various scales (building, city or district). Other considered tools were: EnergyPlus, Polysun. The reasons to select DIMOSIM are the following:

- Parametrization based on files which is suited for programmatic approaches: the DIMOSIM model is parametrized through two types of scripts: 1) A GeoJSON file to configure the thermal zones and the building envelope, and 2) a JSON file to configure the active systems such as power generators (e.g., heat pumps for thermal heat and domestic hot water (DHW)). Additional json files can be used to define various scenarios such as custom weather data, DHW consumptions, internal gains profiles, etc.
- Cosimulation :capabilities: the DIMOSIM is accessed through a websocket API interface which allows co-simulation between the DIMOSIM building model (server) and the client programs. In our case, we use a Python client to reproduce the Optimizer behaviour, as well as the baseline and self-consumption controllers. The co-simulation can be parameterized to select the desired input variables.
- Speed: DIMOSIM is particularly fast as it was designed for district simulation which is useful for yearly simulations.
- Support from the development team: specific modifications to fit our simulation need could be implemented. A simplified model with four floors and two zones per floor (North & South) is built with DIMOSIM.

In collaboration with CSTB, the following modification were brought to the simulation engine.

- Increasing the thermal inertia of the distribution system to better represent floor heating behaviour and exposing a parameter to control this inertia.
- Allowing explicit sizing of the generator and water storage tank (and therefore disabling the automated sizing). DIMOSIM normally relies on automated sizing of the distribution system and generator, which is convenient to reduce the number of input parameters but is not fully appropriate for our case as we intend to size the system based on the real hardware installed on site.
- Allowing modulation rate control of the Generator. This proved more complex than initially anticipated by CSTB and required multiple iterations to properly work. This was finally validated in March April 2024. Indeed, in regular simulation mode, DIMOSIM uses a backwards computation strategy starting from thermal zones heat demand based on temperature setpoints, to heat going through the distribution system and finally to heat generated at the generator. This is a common strategy in building simulation (e.g. EnergyPlus) that avoids the explicit modelling of control loops and therefore allows fast and efficient simulation. To be able to meet modulation setpoints for the heat pump, the calculation must then introduce some forward computations.
- Allowing modelling of multiple heat pumps for heating and DHW. It was deemed too complex to model explicitly heat pumps that serve multiple heating circuits (Heating circuit and DHW circuit); therefore it is rather assumed in simulation that they are served by separate HPs, and the controller ensures that the operation of DHW and heating do not overlap. Note that in the background, the two heat pumps for heating are still modelled as one. After this modification, the model includes two HPs for heating (corresponding to HP1 and HP2) and two HPs for cooling (corresponding to HP1 and HP3) with HP3 using the room exhaust air as heat source.

The simulation model can receive the following control input signals:

- Supply temperature of the HPs.
- Supply temperature for the distribution loop of each zone (since there is no recirculation, this is be set identical to the HP supply temperature).
- Modulation rate of the HPs (note that supply temperature retains priority over modulation rate.
- Zone setpoint temperatures.

2.3 Objective 2: Standard interfaces

To optimize the management of heat pumps and PV, one required feature is the capacity to modulate the operation of heat pumps as a function of solar production or variation in tariffs. Simple strategies that consist in increasing tank temperature hysteresis threshold are widely implemented in commercial EMS. The problems of those strategies are:

1. Increased temperature leads to higher supply temperature for the heat pumps (on average) and therefore lower seasonal COPs.
2. Low storage capacity in the storage tanks. In residential buildings, storage tanks (for heating or DHW) are typically small[5] with respect to the heat demand (only few hours of typical DHW demand can be covered by the storage tank in most cases).
3. They do not allow accurate control of the HP power which therefore cannot follow precisely the PV power fluctuation.

To address those issues, we need to focus first on interfaces with the building and the HPs.

2.3.1 Interface to building

The solution to problems 1. and 2. listed above is to exploit the inertia of the building itself. In a building with floor heating, the building offers significantly higher storage capacity than the tanks, estimated to up to 0.3kWh/°C/m^2 of storage capacity per unit of reference surface area. This means that even a modest increase in room temperatures of 1 °C can correspond to a large amount of energy due to the storage capacity. Additionally, an increase in room temperature only requires marginal increase in heat pump temperature which therefore mitigates problem 1. Nevertheless, storing energy in the building requires to have at least partial control over the distribution loop to allow the heat to enter in the building. This is currently not easily achieved with standard heat pump control strategies. Indeed, typical control in residential buildings relies on a simple heating curve and hysteresis on buffer tank temperatures and hence does not even have any information about the room setpoint temperature or the distribution loop. A pre-requisite to our goal of storing energy in the building is therefore the interface between the energy manager to both the heat pump and the distribution loop. The outline of our proposed approach is shown in Figure 10.

[5] It should be noted that the storage capacity of storage tank is approximately 1kWh/°C/m^3

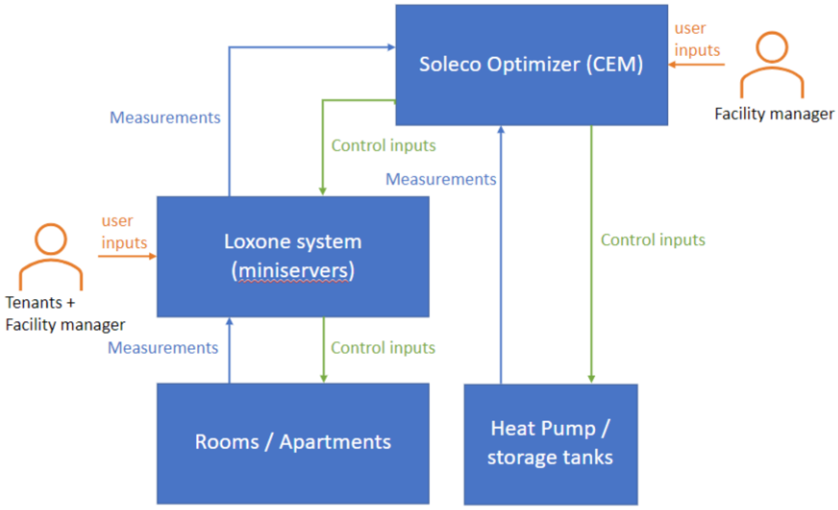

Figure 10: Overview of data interfaces between subsystems

The guiding principles are the following:

- The interface should be compatible with the system that manages the distribution loops, in this case based on Loxone. The EMS should not hinder all the rich features that Loxone brings for house automation, including the distribution valve control. Note that the approach proposed is compatible with other similar system.
- Room control is always based on thermostat so the most natural input to influence the distribution is to modify **room temperature setpoints**. Obviously, this potentially impacts users and should be considered carefully. This is discussed in the next section.
- In a large building, detailed information about all rooms is not necessary for the purpose of heat pump control, therefore we gather aggregated information from the building. The optimization approach (see Section 2.4) works with thermal zone and communication inputs and outputs for the EMS should be aggregated per thermal zone. Based on data available in the Loxone system, we use aggregated measured and setpoint temperature as well as shading. The Loxone is configured to compute the desired aggregated measurements and makes them available to the EMS. This is illustrated in Figure 11.

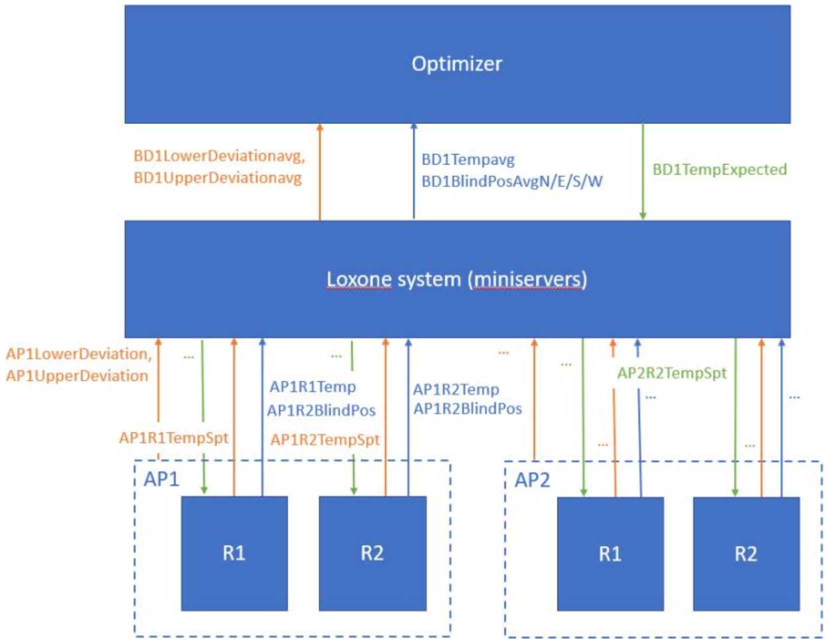

Figure 11: Details of the data flow between Optimizer and heat distribution control system

2.3.2 Interface to HPs

Problem 3. is addressed to allow standardization in interfaces to HPs. In particular, direct power modulation is the ideal input from the point of view of the optimizer that manages electricity costs. This is however not available in most cases. Lack of standard data and control interfaces to HPs is a long-standing problem and originates from difficulties on multiple levels: technical (need to support legacy equipment, complexity of heating systems), organizational (installer training and troubleshooting processes), and political (conservatism of manufacturers, lack of incentives for modernization of interfaces). SmartGridready is a Swiss association that tries to address this problem. In this project, we rely on their approach to guide our HP interfacing efforts. SmartGridready has proposed a scale to describe the control and communication levels that various grid-connected devices such as Heat Pumps can offer. (Figure 12) shows the levels defined by the association. It ranges from 1 for on-off switching to 6 for forecasts of setpoint range. Continuous setpoints resides at level 4 so this is the minimum level required for continuous power control of HPs. Level m is independent from control and considers readings required to monitor the device.

Figure 12: SmartgridReady control levels. Source: SmartGridready

Using this scale, SmartGridready defines interoperable data formats and format converters. It defines so-called functional profiles (FPs) that define for each device class (e.g. heat pumps) groups of read-write datapoints that allow management of the device in a particular way (see list of HP functional profiles in Figure 13). In addition, specific device interface (specific model / brand) is described with so-called external interface description (EID) that describe how to manage device at different functional profiles. For example, it lists what communication transport protocols shall be used (e.g. Modbus TCP, API) and where to find datapoints (registers for Modbus, endpoints for APIs).

In parallel to the OPERA project, FPs have been defined for the external control of heat pumps and EIDs have been prepared and officially validated for three heat pump manufacturers (Hoval, CTA and Stiebel-Eltron) and published in March 2024. The functional profiles for the heat pump are organized in a modular way. The manufacturer decides which profiles are implemented. The HeatPumpBase profile as well as the energy monitoring profile must be implemented, the others are optional.

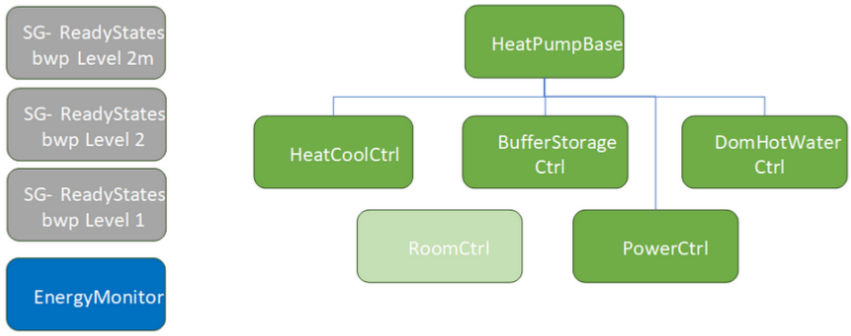

Figure 13: HP functional profile. Source: SmartGridready [5]

The low-level profiles are listed on the left side, consisting of the level 1 and level 2 profiles as well as the energy monitoring profile. The level 1 profile represents a simple on/off switching according to the lock time of the grid operator ("EVU Sperre"). The level 2 profile represents a switching of 4 states according to the SG-Ready standard according to BWP ("Bundesverband Wärmepumpen Deutschland") which is closer described in the following link: https://www.waermepumpe.de/normen-technik/sg-ready/ . The high-level profiles are listed on the right side. Currently they are on level 4, which means that a dynamic change of setpoints is possible. As mentioned, the manufacturer must provide the HeatPumpBase profile, which contains some basic data points for setting and reading the operation mode of the heat pump as well as reading basic data. Note that the operation mode is typically controlled by the heat pump itself (e.g. “heating”, “hot water production”, “cooling”, etc.). However, it may also be set externally.

The energy monitoring profile is on level “m” and provides “read-only” data for monitoring purpose, such as energy data at run times.

In the frame of the OPERA project, a critical analysis of the current status was performed and the EID for the Heliotherm HP was prepared. This was done partly based on previous experimentation of SOLECO on a heat pump of the same model. The device functional profile has been uploaded on the repository of SmartGridready interface and will be published in the future after some final tests are run and publication is discussed with company Heliotherm. Currently, it is only accessible as draft (accessible to SmartGridReady member organizations).

In addition, a comparison of the scope of control required and used by SOLECO in their past deployment and the control enabled by the specifications provided by SmartGridready. The main differences identified are the following:

- The notion of mode control included in the SmartGridready compromise falls short compared to what typical EMS may expect for heat pump control: most heat pumps include a notion of mode control which pilots the operation mode of the heat pump, e.g. cooling, party mode, vacation mode, etc for the Heliotherm heat pump. The explicit control of the switching between heating circuits, e.g. between heating and domestic hot water, or even to start start/stop in some cases, is not included in this mode control. The key point is that the HP controller is designed to assume responsibility for effectively delivering heat to the respective heating circuits according to their setpoints and therefore does not open this control which would basically delegate that responsibility to the external EMS. SOLECO and other predictive controllers on the other hand would explicitly require controlling e.g. the production of hot water as it effectively forecasts and optimizes that to operate at lowest costs.

- Experience from SOLECO has shown that the information included in the SmartGridready profiles is necessary but not sufficient as it is also needed to know a number of “tricks” (some documented, some undocumented). E.g. under which conditions the values to some registers will be applied or not, etc. Some known “tricks” have been included in the device profile as comments for developers, but as such they still reduce the potential for full automatizing of the control of the heat pumps if they are not known machine-readable fashion. To some extent, this can only be solved through internal heat pump controller update to explicitly expose this information. We refer to section 0 for a discussion about those specificities of the Heliotherm heat pump.

2.3.3 Results of HP control

Tests have been conducted on a Heliotherm heat pump emulator which was shipped by Heliotherm to perform lab tests and put in service at CSEM with the intervention of M. Steinke from TCA (Figure 14). It was connected to the SOLECO optimizer and data (temperature measurements, mode and control registries information) from the emulator were tested. Note that this emulator does not allow full scope test as it i) does not emulate the heat pump even in a basic fashion and only returns fixed temperature readings, ii) contains only the heat pump controller and not the compressor controller which is a separate unit and therefore no readings related to power and compressor speed are available.

Figure 14: Heliotherm HP emulator

The communication tests, conducted in collaboration with SmartGridReady CH, have allowed to establish and validate an external interface description (EID) for the Heliotherm HP controller. This EID contains 9 functional profiles, namely *HeatPumpBase* (basic monitoring), *PowerCtrl* (control with power setpoints), *HeatCoolCtrl* (setpoint control for a heating circuit) for two distinct heating circuits, *DomHotWaterCtrl* for the control of hot water production, *BufferStorageControl* (control of the heat buffer storage), *RoomTempCtrl* (control of zone temperatures) for two distinct zones and *EnergyMonitor* for monitoring of energy use. We refer to the Smart Grid Ready website for the detailed description of all datapoints in every functional profile (link). With the validation of the external interface description, the profile is now available as a draft to Smart Grid Ready members pending a possible inclusion of the profile in officially published profiles by Smart Grid Ready (this would require Heliotherm membership in Smart Grid Ready). The availability of this external interface description opens the possibility to communicate with Heliotherm HPs in a standard and automated fashion.

Thanks to the availability in the SOLECO portfolio of another site with the same HPs, tests have been conducted to test the HP control on a real machine. The Heliotherm HP offers the opportunity to directly send power setpoint which is the desired interface. It is however required to use this input in coordination with a signal to flag PV demand and with specific settings of the heat pump. The following comment was added to the Heliotherm functional profile as a programmer hint:

To allow setpoint control, register 117 for PV demand should be set to 1. In RCG web interface, Menu item "Photovoltaics" > PV selection on > MODBUS (TCP or RTU). Also, in web controller, Main menu > "WNA" > FU External on > ON and Hot water > DHW preparation > Parameters > DHW Max to "53" Heating circuit > Parameter> Offset to "3"; Mixer1 and 2 > Parameter> Offset to "3".

On-site tests however showed that it was difficult to maintain the required PV register to the required value of 1 to accept power setpoints, even with continuous writing. After consultation with the installation technician, internal settings manipulation was done to fix this issue, with satisfactory results in setpoint tracking as illustrated in Figure 15. The same configuration was conducted in the OPERA site and proved successful. The setpoints are well followed. In our experience, this exceeds what can be done by most heat pumps including newly installed ones in residential settings.

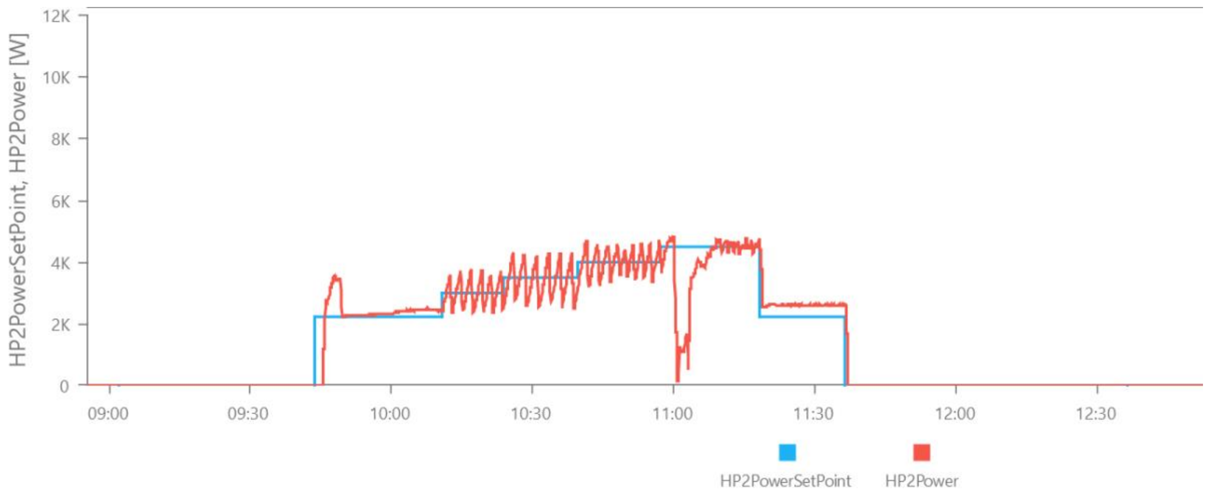

Figure 15: Power setpoint control with on-site HP. Source: SOLECO

2.4 Objective 1: Predictive energy management

In addition to a data concept that allows the integration of the HPs and building control, the EMS needs to implement an integrated energy management strategy. For this, we have drawn on the extensive prior experience collected through past collaborations between CSEM and SOL with commercial EMS deployment in various residential building. We first recap the working principles of the SOLECO Optimizer and then focus specifically on new developments conducted in the frame of OPERA to better address MFH.

2.4.1 Predictive energy management with the SOLECO Optimizer

The SOLECO Optimizer uses a predictive control approach for the energy management. Predictive control is a modern control strategy that relies on numerical optimization to calculate the operating setpoints of a system. The basic principles are illustrated in Figure 16.

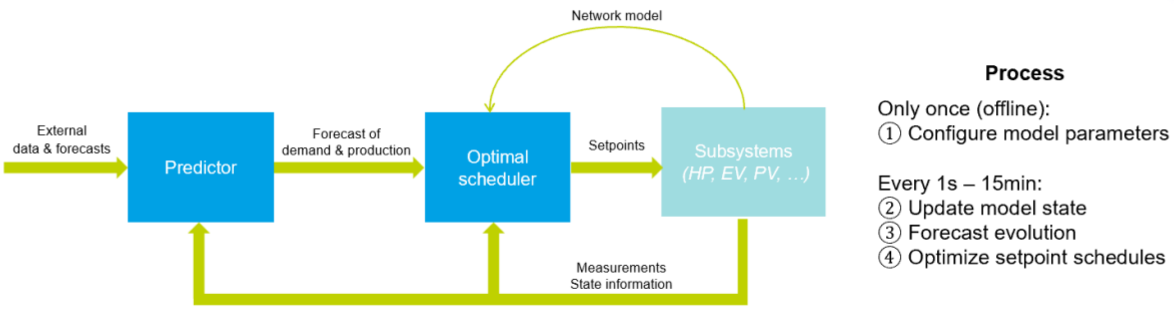

Figure 16: Logical blocks of predictive controller

The central "optimal scheduler" is a program that uses a model of the system to forecast the evolution of the system under various possible operation scenarios for a fixed duration horizon (in our case, 3 days). Its goal is to select the best operating strategy with respect to a cost function. To feed the optimal scheduler, we use:

- Data measured from the system, for example the building current measured temperature.
- Forecasts for non-controllable elements that are computed by another program (Predictor), such as for PV power production.

In the SOLECO Optimizer, we describe the system with few physical parameters for each element. In our model, this includes: the PV system, the 3 heat pumps, the storage tanks, the building, the uncontrollable electric power consumption and how water consumption. These parameters feed simple models that are used in the optimal scheduler. We refer to the original [6] for further details and recap here few key points about the approach.

- The cost is designed to reflect primarily operating costs, which :include:
    - Electricity purchase and resell costs (which are using day-night tariffs in this case).
    - Peak power :tariffs: they are estimated to be between 10% and 20% of the bill for the pilot site and are charged based on monthly peak power.
    - In addition, few additional minor costs are considered e.g. to limit heat pump cycling.

This is why self-consumption is not a goal in itself but only a possible way to lower costs when resell tariff are lower than purchase costs.

- The optimal scheduler relies on mixed-integer linear optimization. This means that all models must use mixed-integer linear models. This can be somewhat limiting to capture nonlinear behaviour. Indeed, it is always possible to approximate nonlinear relationships with piecewise affine functions that can be modelled with mixed-integer linear models, but that gets computationally heavy quite quickly. As the optimal scheduler runs on-premises on a light computing unit, it is generally necessary to sacrifice some accuracy to guarantee sufficient speed.
- All used models used in optimization are physical models and their parameters are hence physical values that need to be tuned.
- The optimization uses a scheduling horizon of 3 days and a time step of 15 minutes

2.4.2 Building model development for OPERA project

Naturally, as we intend to exploit the inertia of the building to store energy, we need a model that reflect that capacity, therefore we use a physical model that captures that capacity. We illustrate in Figure 17 the main phenomena affecting the building. First, it is important to notice that the building is divided in thermal zone. Generally, we consider a single zone per heating circuit. Each thermal zone is described with its own equations. The model predicts the evolution of the average thermal zone temperature in response to:

- Estimated convective/conductive losses through the envelope. These losses are assumed proportional to the temperature between outside and inside
- Estimated losses to the ground which are assumed approximately constant
- 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

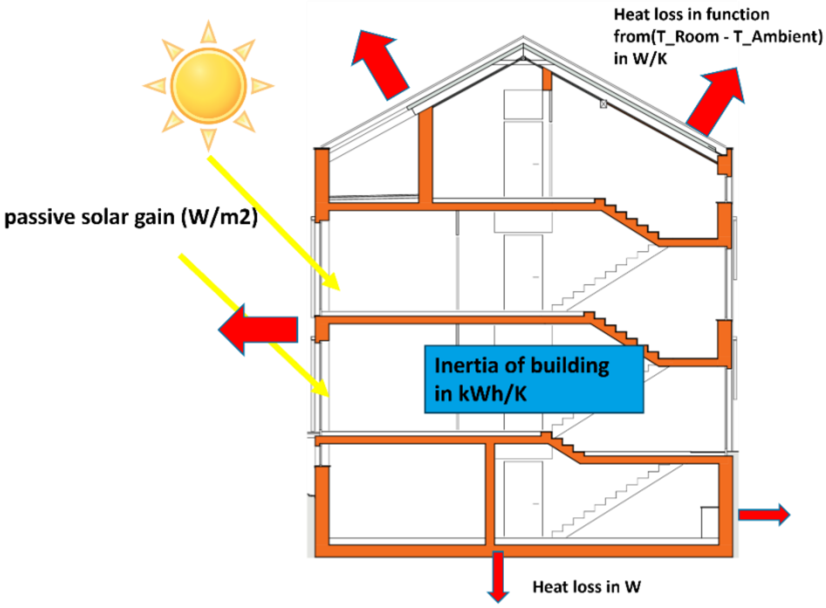

Figure 17: Building model physics

This gives the following equation in the most basic form of the model:

$$C\dot{T}^z = P^z_{sun}(t) + \beta(T_{out}(t) - T^z(t)) + Q^z(t) + P^z_{ground}$$

Where T^z is the zone temperature, P^z_{sun} the estimated solar gains, Q^z the heating input, P^z_{ground} the ground losses, T_{out} the outdoor temperature and the model parameters are β the envelope loss coefficient in kW/C and C the thermal zone inertia in kWh/C. This model allows to plan the amount of energy that can be stored in the zone while respecting some temperature constraints.

This form of the model had already been developed and tested prior to the OPERA project but several adaptations were made to better represent buildings such as the OPERA building:

- First, because the building has a significant size, it was observed that the distribution loop has its own inertia. In the model above, it is assumed that the heating system thermal input immediately enters the thermal zone, which is not true in practice and causes the model to be too optimistic to affect the room. We have therefore extended the model to include a first order response between the thermal outputs of the heating system and the thermal input to the thermal zone Q^z as follows:

$$\dot{Q}^z = \frac{1}{\tau^{\text{dist}}}(P^{hp}_{heat} - Q^z)$$

Where P^{hp}_{heat} is now the heat power from the heat pump and we introduce a new parameter τ^{dist} which captures the delay. This augments the model with a second state that now needs to be estimated.

- Second, we wish to relate supply temperatures in the distribution system and power to the rooms. We depict in Figure 18 the thermal zone heat exchange with the main notations. The thermal power can be calculated as $Q^z = \dot{m} * (T_{in} - T_{out})$. However, the flow rate $\dot{m}$ is not generally measured and depends on valve openings and circulation pump speed. Instead, we get inspiration the notion of heat exchanger efficiency which states that the heat exchange is a fraction of the maximum possible heat exchange, in this case $\dot{m} * (T_{in} - T^z)$ so that $Q^z = \eta * \dot{m} * (T_{in} - T^z)$ where η is the heat exchange efficiency. In general, it is reasonable to assume that η depends mostly on the flow rate. This removes the dependency on T_{out}. We show in **Error! Reference source not found.** the approximately linear correlation between supply temperature and thermal power in measurements. The approximation above is in principle valid only at steady state but it is assumed valid in the optimization because it adds complexity to try to model the temperature dynamics in the distribution loop more precisely without clear benefits. Now, let us consider this equation at maximum flow (valves fully open), then this gives us the minimum supply temperature required to achieve a certain heat transfer rate as

$$Q^z = \alpha(T_{in} - T^z)$$

With α the heat transfer rate to the zone in kW/C, assuming a maximum flow rate (valves fully open). This allows us to calculate the minimum supply temperature required to transfer some heat to the building.

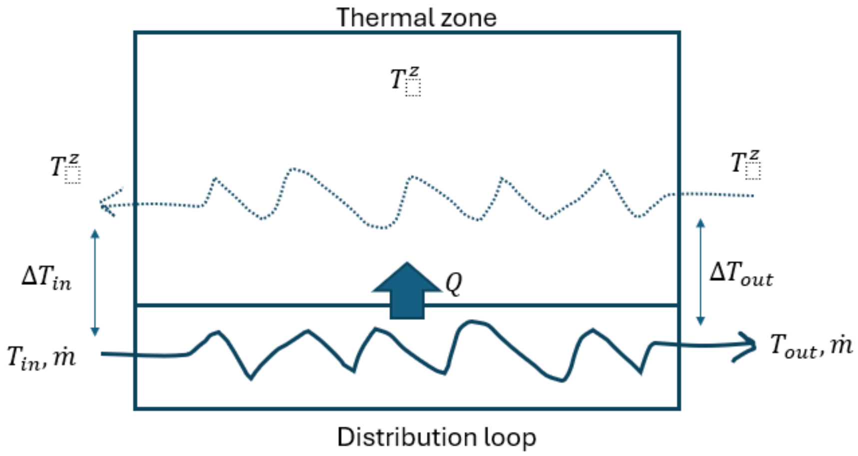

Figure 18: Thermal zone seen as a heat exchanger

2.4.3 Heat pump model development

We present in Table 2 the base heat pump model in the optimization. This was the model already used prior to project OPERA in other deployment.

Table 2: Optimization model parameters of a heat pump

Optimization name	Type	Symbol	Description
minPowerInputXXAlpha	configuration	$\alpha_{XX}^{P_{min}}$	Constant coef. of linear equation of minimum electrical input power [kW] as a function of the source temperature.
minPowerInputXXBeta	configuration	$\beta_{XX}^{P_{min}}$	Linear coef. Of linear equation of minimum electrical input power [kW] as a function of the source temperature.
maxPowerInputXXAlpha	configuration	$\alpha_{XX}^{P_{max}}$	Constant coef. Of linear equation of maximum electrical input power [kW] as a function of the source temperature.
maxPowerInputXXBeta	configuration	$\beta_{XX}^{P_{max}}$	Linear coef. Of linear equation of maximum electrical input power [kW] as a function of the source temperature.
mode	configuration	–	Name of the mode, e.g. 'heating' 'dhw', 'cooling'
minimumRunTime	configuration	–	Minimum run time of the heat pump. When switching on, the pump should stay on for that amount of time minimum.

COPXXAlpha	configuration	α_{XX}	Constant coefficient of quadratic equation of COP at flow (supply) temperature XX. XX takes values 35, 45, 55
COPXXBeta	configuration	β_{XX}	Linear coefficient of quadratic equation of COP at flow (supply) temperature XX. XX takes values 35, 45, 55
COPXXGamma	configuration	γ_{XX}	Quadratic coefficient of quadratic equation of COP at flow (supply) temperature XX. XX takes values 35, 45, 55
inputPowerProfile	Actuator	$P_{in}(\tau)$	Optimized input power of the heat pump
outputPowerProfile	Actuator	$P_{out}(\tau)$	Optimized output power of the heat pump
On-Off	Actuator	$\delta_{on\|off}(\tau)$	On or Off status of the heat pump
rateCost	Configuration	$f^{rate}(\tau)$	Cost of changing power input in CHF/kW.
CostSwitchingOn	Configuration	$f^{on}(\tau)$	Cost of switching ON the pump in CHF/switch
currentPower	Sensor	$P_{out}(0)$	Current output power of the pump
currentMode	Sensor	–	Current mode. Can take values 'off' or the value of the mode parameter ('dhw', 'cooling' or 'heating'
sourceTemp	Sensor	T_{source}	Source temperature. Can be fixed or a profile (e.g. outside temperature)
flowTempMethod	Configuration	–	Method to calculate the flow temperature. Can be 'heating_curve' or 'fixed'
flowTempAlpha	Configuration	α_{flow}	Constant coefficient in linear model of flow temperature
flowTempBeta	Configuration	β_{flow}	Linear coefficient in linear model of flow temperature
OutsideTemp	configuration	$T_{outside}$	If flowTempMethod is 'heating_curve', the flow temperature is approximated as the one from the heating curve. It is then a linear function of the outside temperature. Note that this may be different from the source temperature if the heat pump is for example ground coupled.

We show equations for a heat pump with a single heating circuit. To represent a heat pump with multiple modes (heating, hot water and/or cooling), we have introduced a multi-mode heat pump device that derives from the model for a single mode.

According to the switching logic of the heat pump, we have,

$$If\ \delta_{on|off}(\tau)\ is\ True$$

$$P_{in}^{max}(T_{source}) \geq P_{in}(\tau) \geq P_{in}^{min}(T_{source}), \qquad \forall\tau = 1, \dots, H$$

$$else\ P_{in}(\tau) = 0 \quad \forall\tau = 1, \dots, H$$

Where the minimum and maximum input electric power are linear function of the source temperature, so that

$$P_{in}^{min}(T_{source}) = \alpha_{XX}^{P_{min}} + \beta_{XX}^{P_{min}} T_{source}$$

$$P_{in}^{max}(T_{source}) = \alpha_{XX}^{P_{max}} + \beta_{XX}^{P_{max}} T_{source}$$

The coefficient of performance relates input electric power to output heat power:

$$P_{out}(\tau) = \eta(T_{flow}, T_{source}) \quad P_{in}(\tau)$$

A positive heat input refers to heating and negative one to cooling. Therefore, while $P_{in}(\tau)$ is always positive, a negative value of η results in a negative thermal power, ie cooling. The COP depends on the flow temperature (supplied to the system) and the source temperature. The source can be outside air, or a brine. The model specifies a quadratic model of the COP at different values of the flow temperature, namely 35, 45 and 55 (not adapted to cooling yet), such that

$$\eta\left(T_{flow} = XX, T_{source}\right) = \alpha_{XX} + \beta_{XX} T_{source}(\tau) + \gamma_{XX} T_{source}^{2}(\tau)$$

From these equations, the COP at other flow temperatures is linearly interpolated.

The supply temperature can either be fixed, in which case it is taken as equal to α_{flow}. Or it can follow the heating curve, according to the equation:

$$T_{flow}(\tau) = \alpha_{flow} + \beta_{flow} T_{out}(\tau)$$

Note that this is an approximation as the flow temperature will change as the heat pump heats or cools the flow.

To summarize, the heat pump uses a COP, minimum and maximum input curves that are pre-computed based on source temperature.

The cost function contribution of the heat pump includes one term to promote limited power changes of heat pump and one term for penalizing switches

$$cost = \sum_{\tau=1}^{H} f^{rate}(\tau) |P_{in}(\tau) - P_{in}(\tau-1)| + \sum_{\tau=1}^{H} f^{on}(\tau) \max(\delta_{on|off}(\tau) - \delta_{on|off}(\tau-1), 0)$$

Based on the experience made by SOLECO on a similar site, equipped with two heat pumps running in parallel, it was evaluated that a potential for improvement is to exploit the fact that part-load operation of the heat pump offers higher COPs than operation at nominal power. We depict below a typical part-load efficiency curve for a heat pump at given operating temperatures, compared to the linear COP model currently used in the optimization

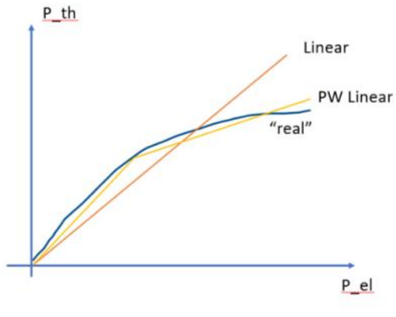

Figure 19: Illustration of part-load efficiency, and different models used

With the current fixed COP model, heat production is proportional to electric power and the optimization is not aware that running with reduced part-load is beneficial compared to higher loads. However, modifying the optimization to capture this is complex because:

1. Part-load efficiencies are generally not documented in datasheets of heat pumps which typically provide curves at nominal rated power.
2. A nonlinear model may be required which breaks the current modelling approach which uses mixed-integer linear models.

In practice, the main implication with two heat pumps is that it is almost always beneficial to spread the load equally between the two heat pumps rather than use just one. The main reason for this is that often the optimum efficiency is not at the maximal power (the details depend on the heat exchanger and compressor designs as well as the flows in particular). In order to push the optimization in this direction, a first modification has been implemented whereby the power deviation between the heat pumps is penalized: this consists in adding a new cost contribution of $c * | P_{hp}^1 - P_{hp}^2 |$. This creates a simple incentive to run HPs in parallel at the same power but only approximately captures reality. Therefore, a more advanced model using a piece-wise affine COP model has been implemented and tested to better capture the HP behavior (see Figure 19). While it does promote use of part-load and spreading the load between multiple heat pumps, when possible, it adds to the computational burden of the optimization which has led to lack of optimality of the solution in some cases.

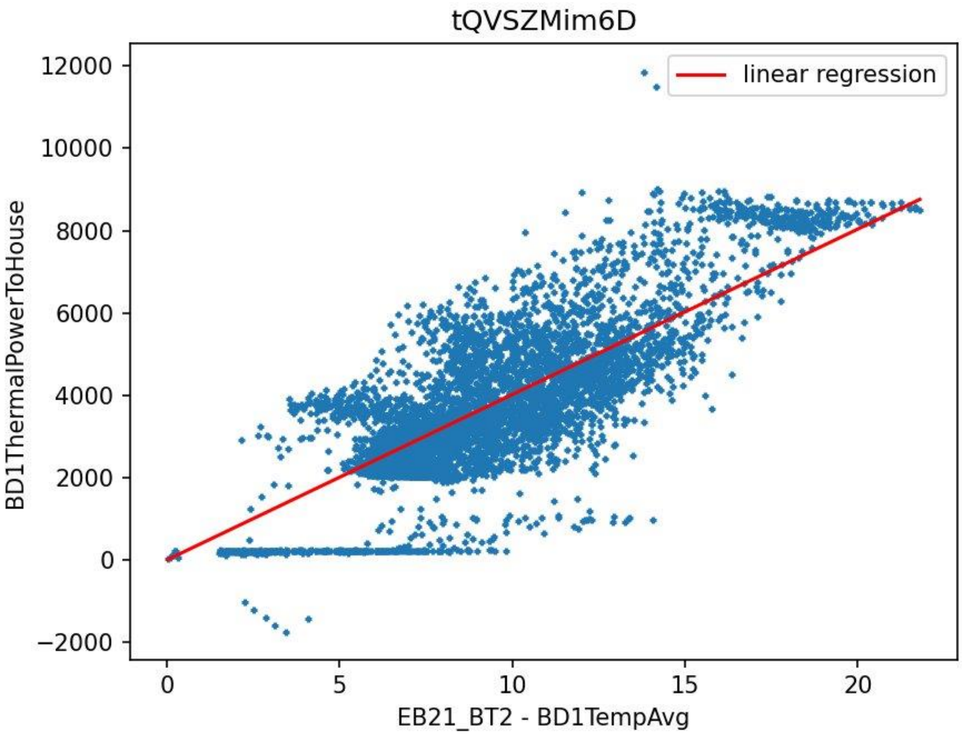

Figure 20: correlation between supply temperature and thermal power to building

2.5 Results

2.5.1 Measurement campaign methodology

Referring to Table 1, the measurement was designed to collect data corresponding to scenarios BL and Optimized. To have consistent and comparable results, we have chosen to alternate operation between these two modes every two to three weeks. This allows us to ensure similar operating conditions in the building, especially considering that the building got progressively filled with occupants over the first phase of the measurement campaign. The switch-over was generally done on Wednesday mornings. For the analysis, days of switch-over have been excluded, as well as a number of days due to various issues: loss of data or malfunction of data collection, failure in the system operation, etc.

In the results presented below, we report data with

- 66 days in baseline operation,
- 56 days in optimized operation.

The number of days left out of the analysis is 26.

The measurement campaign started on July 29th, 2024 and lasted until June 2025. The initial months were used for tuning the heat pump and controller by the craftsmen, as well as adjustments to occupant feedback to settle the parameters of the baseline and optimized control.

In the quantitative analysis, the focus was put on the heating season, the start date for this quantitative analysis is October 1st, 2024, and it was terminated on February 26th. After that date, it was decided to implement energy saving measures based on some of the observations. This brought results that are discussed in section 2.5.6 Energy saving measures implemented in the site

All KPIs were collected and aggregated into daily values for comparison.

2.5.2 High-level comparison

Comparing the two operating strategies over the full length of available data gives the following high-level KPIs. All KPIs are reported as daily sums (cost, energy) or averages (temperatures)

Table 3: High-level comparison table for experiments

KPIs	Outdoor temperature	Building [indoor] temperature	PV production	Self-Consumption	Autarky	HP Electricity	Rest electricity	Normalized HP electricity	Cost (real)	Cost adjusted (PV)
Unit	**°C**	**°C**	**kWh**	**%**	**-**	**kWh**	**kWh**	**kWh/°C**	**CHF**	**CHF**
BL	5.97	20.98	38.31	72.4%	13.6%	125.22	78.52	8.34	64.13	64.13
OPT	6.06	21.08	35.15	78.5%	13.6%	124.16	78.69	8.26	61.21	59.99
delta	*0.1°C*	*0.1°C*	*-9.0%*	*7.9%*	*0.1%*	*-0.9%*	*0.2%*	*-0.9%*	*-4.8%*	*-6.9%*

We report here the following KPIs directly based on measurements:

- Outdoor temperature: the average outdoor temperature.
- Building Temperature: A weighted average (w.r.t. room size) of all temperatures measured in rooms inside the building
- PV production: measures the total PV production and serves as a proxy for the level of solar radiation
- Self – consumption: the share of local power produced used locally
- Autarky: The share of consumption produced locally
- HP electricity: the electric consumption of the heat pumps and heating system, therefore including heating and DHW
- Rest electricity: Electric consumption of other appliances over which we do not have control
- Cost (real): Real cost of electricity computed as the net cost of electricity for the energy community. This equals the cost of electricity bought, minus the payment received for the electricity sold to the network. This is based on the 2024 tariff applicable to the energy community

The two remaining KPIs are computed:

- Normalized HP electricity: Electricity consumption of the heat pumps normalized by the temperature gap between the building and outdoor. This allows us to offset possible differences in indoor and outdoor temperatures between the compared periods of operation.
- Adjusted cost: These are estimations of the cost in the optimized mode of operation with corrections to account for the difference in experimental conditions. This reflects more accurately a cost that can be compared between the two periods since it corrects for the main external factors affecting the experimental results. The adjustment compensates for the excess solar power available in baseline mode. The details of the calculations and discussion are reported in section *Cost adjustment calculation*

We notice that on average, **the estimated cost saving in optimized mode is 6.9% compared to the baseline mode**. We refer to section *Focus on cost and self-consumption* for a discussion of cost savings. Figure 20 shows the cost level as a function of the primary external factor which is the outdoor temperature. In this plot, each dot represents one day of experiment and its corresponding cost and temperature. It can be observed that outdoor temperature conditions are well covering both experiment conditions.

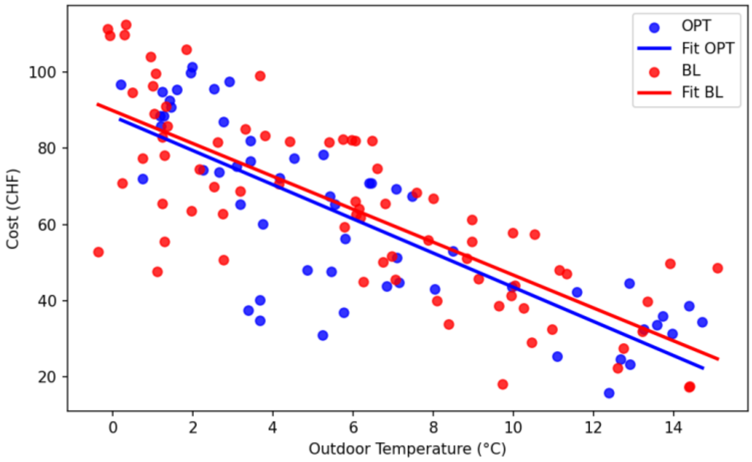

Figure 20: Daily cost (real) versus outdoor temperature.

This allows to observe the spread of results in terms of outside temperature and a consistent trend across the range of outdoor temperature. Naturally, this is not sufficient to conclude as other important factors come into play to compare the two groups, but it gives a general idea.

2.5.3 Focus on DHW

We report here 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 COP	Heating losses	SNG+ - DHW
Operating mode\Unit	kWh	kWh	kWh	kWh	-	%	-
baseline	48.1	126.1	65.8	60.0	2.9	47.7%	1.37
optimized	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%

Notes:

Thanks to the arrangement of sensors as illustrated in Figure 8, we are able to measure losses in the recirculation loop

Here are a few key observations:

- The heat losses computed as the ratio of consumed energy on produced heat energy are very high at 47% which leads to poor SNG+. After investigation, this is attributable to very high recirculation rates and heat losses in the hot water distribution system – details can be found in section Optimization for domestic hot water
- Despite having comparable DHW uses (7% gap), the electricity used for DHW is much lower in Optimized mode (-20%). This is due to a significantly higher COP and lower losses

A short investigation of the cause of the poor efficiency revealed that the circulation pump is always active and is operated at an unusually high power. This results in a recirculation measured at 2000lts/h whereas the average DHW consumption is around 80lts/h. We can observe on the recirculation line a consistent temperature drop of about 1 to 1.5 °C which at such a high flowrate is significant. It is moreover likely that such large recirculation causes significant remixing inside the tanks. We will discuss recirculation and overall efficiency measures in section Optimization for domestic hot water

Regarding the improvement in COP, it should be noted that the heat pump used for hot water uses the exhaust air from the apartments as the heat source and therefore should benefit from a relatively stable source temperature which makes it independent of the weather conditions. We report the average supply temperature for HP3 in Figure 21 for each HP3 heating cycle. Each dot corresponds to one HP activation. We see that on average the average supply temperatures are lower in Optimized mode. This reflects the fact that in many cases, the optimizer does not bring the temperature all the way to its maximum value around 62°C, contrary to the hysteresis controller which tends to start and end its activations at higher temperatures. This fully explains the higher COP achieved by the HP. It is important to notice that even so, the temperature in Optimized mode reaches 60°C every few cycles (about every 24 hours as advised by SIA 385, see Figure 22) which is the required temperature for antilegionella management. Also, the optimizer can enforce to reach the antilegionella temperature at a desired frequency, although this option has not been activated here.

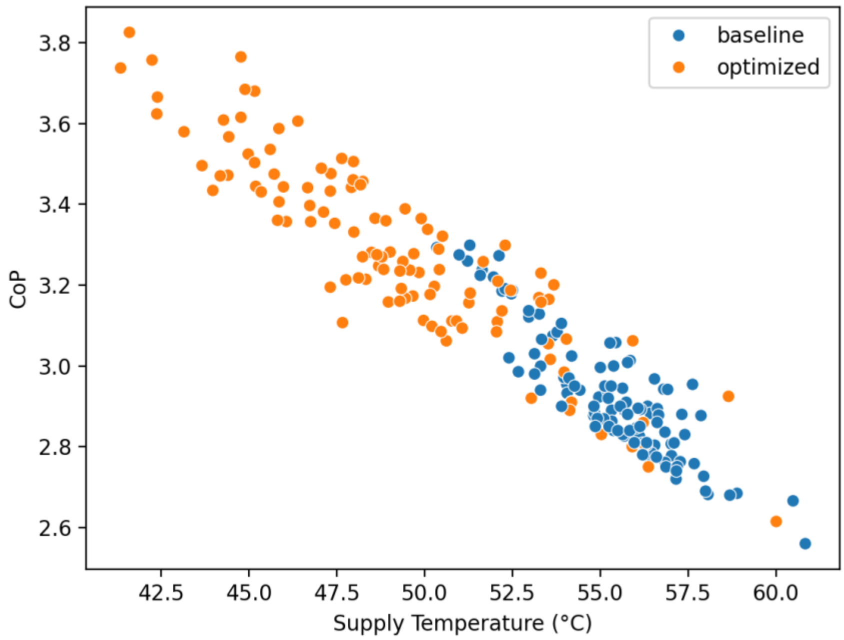

Figure 21: COP vs supply temperature for HP3 (DHW)

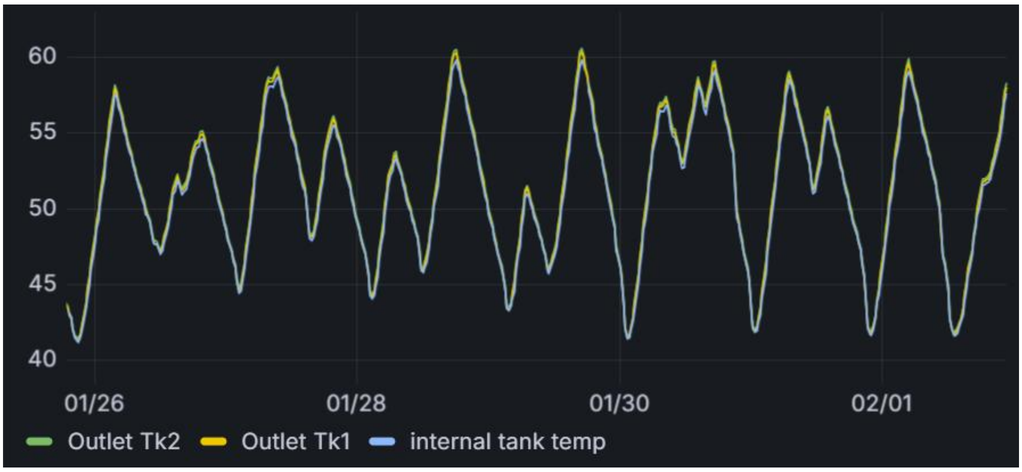

Figure 22: Representative example of tank internal temperature and temperature measured at outlet of tanks during optimized mode

2.5.4 Focus on space heating

We report here the main KPIs for space heating. Calculations are based on measurement of HP1 and HP2 which only produce heat for space heating.

KPIs	HPs Electricity	Heat to building	HP1 heat	HP2 heat	HP1 COP	HP2 COP	SNG+ - heating
Operating ode\Unit	kWh	kWh	kWh	kWh	-	-	-
baseline	81.9	285.3	93.3	167.4	3.2	3.5	3.5
optimized	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%

We make the following observations.

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 -3% on average). Notice that the higher heat partly reflects more favorable conditions during the baseline period, for example due to higher radiation, and is not fully attributable to the optimizer itself. We refer to section Cost adjustment calculation for a discussion of how this may impact the cost comparison.

We notice an experimental gap in performance of heat pumps between HP1 and HP2 although they are supposed to be identical HPs and are operated in the same way. According to further investigation, we could not identify the root cause of this difference in behavior, and it could be related to the hardware itself. We refer to the discussion below for details.

Regarding the gap in COP, we report here the supply temperatures used by the heat pumps as a function of the outside temperature.

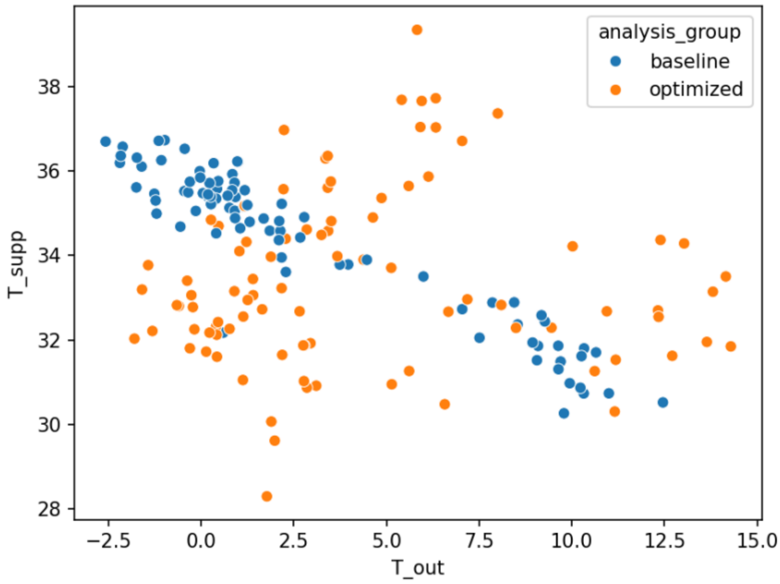

Figure 23: Supply temperature vs Outside temperature for HP1

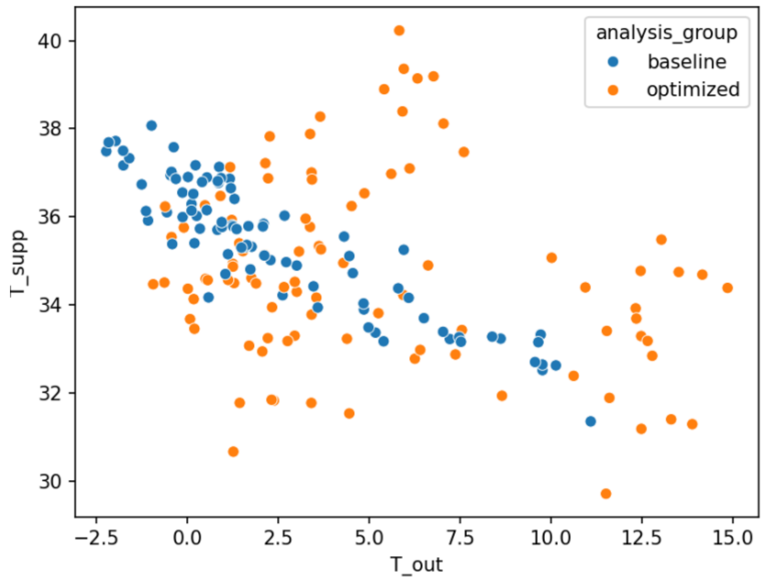

Figure 24: Supply temperature vs Outside temperature for HP2

We clearly see a different pattern of use. While in baseline mode, we can observe the heating curve, the heat pumps are used differently in optimized mode, with no clear pattern. Although some of the instances where the supply temperature is much higher than the heating curve may contribute to lower COPs, it should be noted that on average, the supply temperature in optimized mode is lower. This is visible in Table 5 which reports statistics across heat pump activations. Note that in this table, we report the average activation duration, electrical energy (Eel), heat produced (Eth). The part-load ratio, outside temperature and supply temperature are reported with a weighted average with respect to the heat produced so that short cycles do not skew the average.

Table 5: Statistics of heat pump activations

heat_pump_name	analysis_group	T_out	T_supp	Eel	Eth	duration	partload
HP \ Units		°C	°C	kWh	kWh	h	%
HP1	baseline	2.0	34.5	17.6	52.4	5.5	40%
	optimized	3.4	34.2	20.1	58.6	6.0	43%
HP2	baseline	2.8	35.1	33.3	116.2	10.6	39%
	optimized	3.4	35.4	22.3	73.6	6.3	45%
HP3	baseline	4.5	55.2	22.4	65.2	6.7	42%
	optimized	5.3	48.9	12.8	41.9	4.3	37%

It is interesting to notice that although the running conditions seemed better in optimized mode with respect to temperatures in theory (higher outdoor temperatures and almost identical supply temperatures), this did not result in improved COPCOPs. The exact cause of this is not known but it is possible that the dynamic operation with more frequent setpoint changes in optimized mode could contribute to lower performance.

Focus on cost and self-consumption

The goal of the optimizer is to find the right tradeoffs between various sources of costs. In this setup we will look more closely at the cost of electricity used for powering the heat pumps. By computing on each 15 minutes interval its individual self-consumption ratio and looking at the share of the consumption covered by the heat pumps, we can calculate the fraction of energy used by the heat pumps that is served by the local production. The remaining energy is then bought from the grid, and we can differentiate between energy bought in low and high tariff periods. Using the cost of energy in high and low tariff periods and assuming PV power is" free", we can compute an equivalent unit cost of energy for the power of the heat pump as a weighted average.

This gives the following summary:

Table 6: Origin of energy for HPs

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

This clearly shows two effects:

- The optimization shifts a large portion of the demand to low tariff periods.
- 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 (cf previous discussion). This effect remains small due to the low availability of PV power.

This is best illustrated looking at the hourly spread of HP use across the optimized and baseline modes. Figure 25 clearly shows how the optimizer shifts consumption for the heat pumps away from evening and early morning hours to avoid consuming in the beginning and end of the HT period.

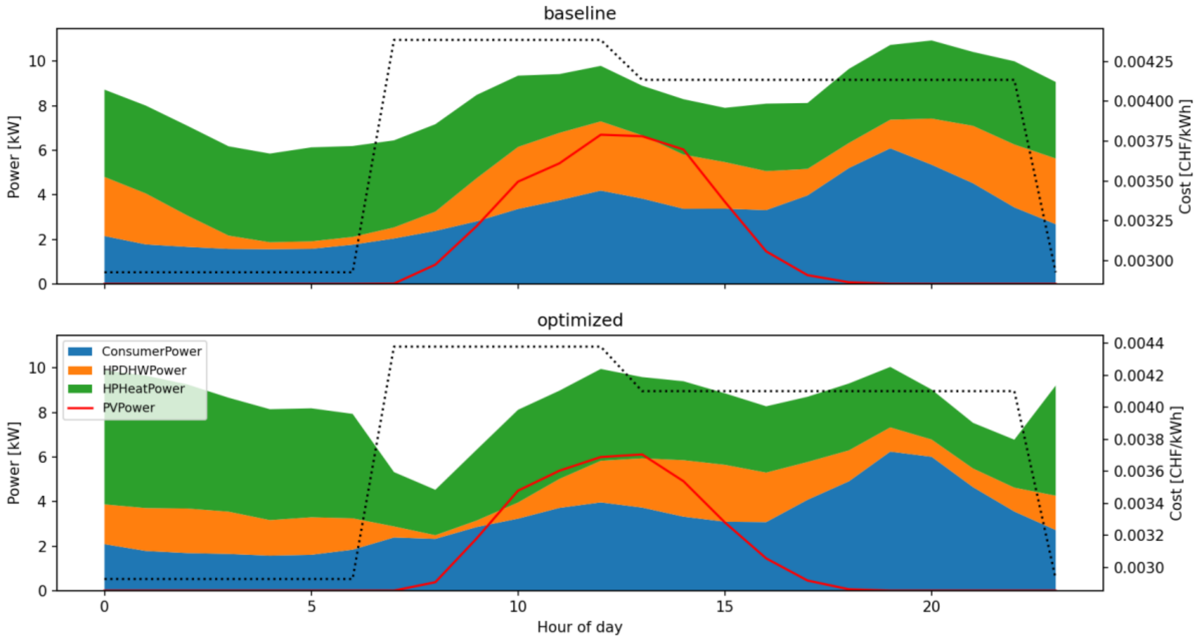

Figure 25: Average hourly consumption over test periods. dotted line shows the average price profile

Regarding self-consumption it is important to notice that due to the relatively small installed capacity of the building, the PV production is often lower than the consumption even in baseline mode, which leaves no room for improvement. Nevertheless, there are occasional sunny periods where the optimizer can exploit the available solar power. Figure 26 shows an ideal example of optimized behavior whereby the controller uses the HP during the day to follow the PV production (1.) and then can avoid any HP power (2.) until the LT period at night (3.). We can contrast this with Figure 27 which shows consumption patterns typical of the baseline mode: the consumption of the heat pump is continuous and relatively independent of solar conditions or tariffs.

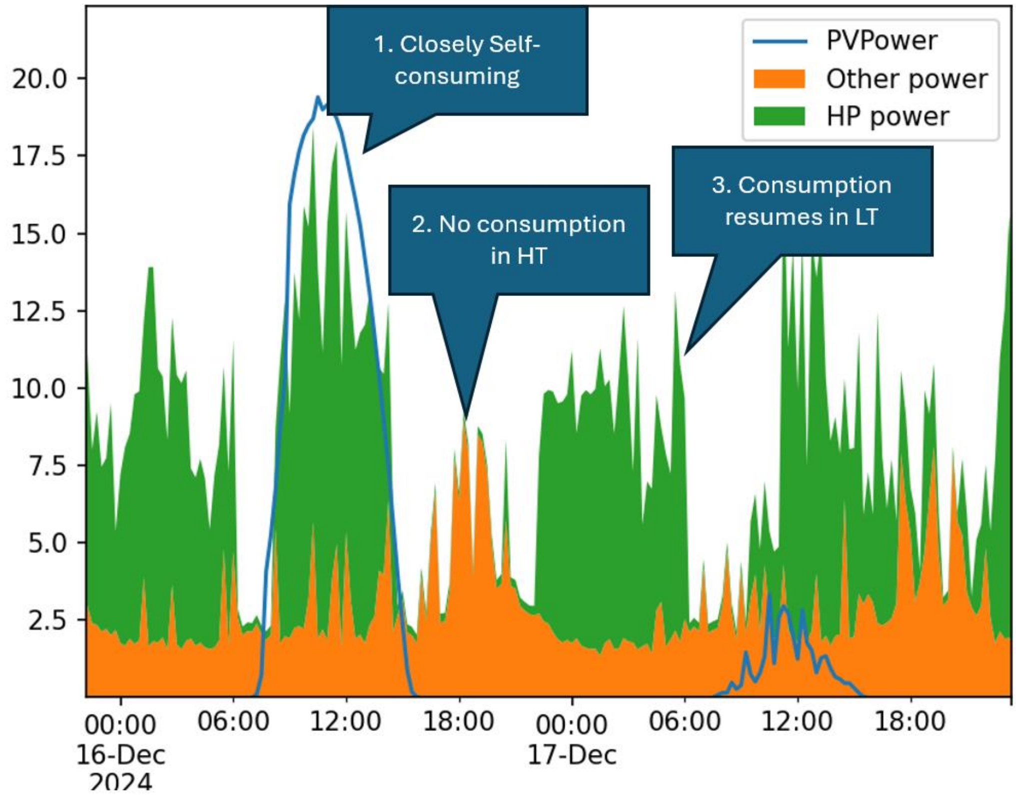

Figure 26: Ideal day of self-consumption in optimized mode

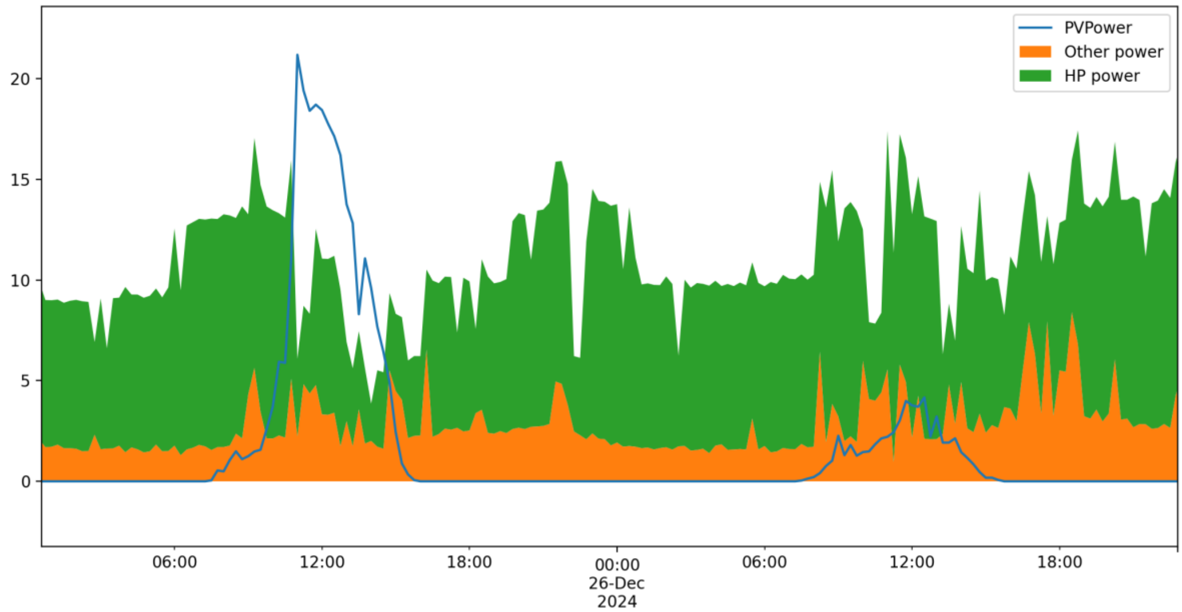

Figure 27: Typical consumption in baseline mode

2.5.5 Focus on Comfort

The Loxone system includes temperature measurement in all apartments (temperature measurement of each thermostat of each heating circuit). As discussed in section *2.3.1 Interface to* building, the optimizer uses only the weighted average temperature across the building. In this section, to analyze comfort, we look at individual room temperatures in the building.

Table 7: comfort KPIs

KPIs	Average temperature	Average setpoint	Underheating
Unit	°C	°C	°C*h/day
baseline	21.33	21.26	11.76
optimized	21.45	20.82	9.36

Table 7 reports the average measured and setpoint temperature in the building and the calculation of underheating which is the average cumulated negative constraint violation (when the temperature was lower than the setpoint) in °C*h/day, averaged over all rooms in the building. The higher this KPI is, the more and/or longer the temperature was lower than the desired setpoint in the room.

We see that the average temperature was indeed slightly higher in optimized mode than in baseline mode, as already reported, while the underheating was lower in optimized mode. That is additional evidence that the overall heating level and comfort were superior in optimized mode.

One may notice that the reported underheating values may seem large, but this can be explained by the fact that temperature cannot always reach the level of the setpoints. In particular the bottom floor apartments could not be very well isolated from the ground due to space limitation in the renovation, so their temperature tends to be lower than the rest of the building and the distribution loops somewhat undersized in these apartments.

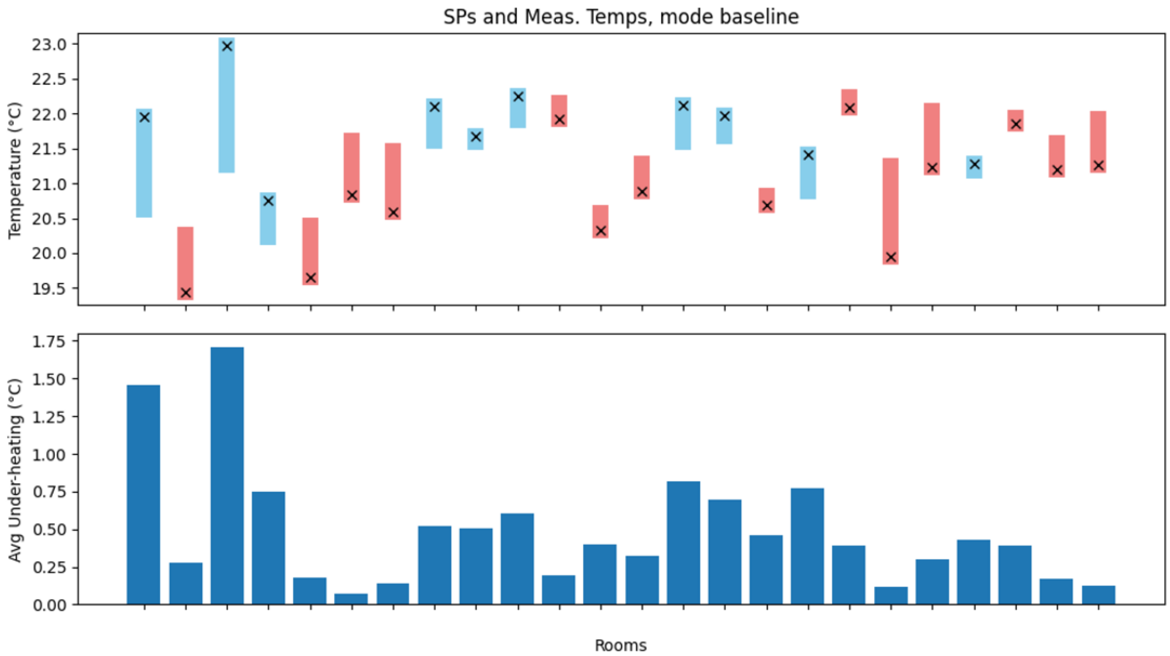

Figure 28: temperature and setpoints (x) (top) and underheating per apartment (bottom), baseline mode

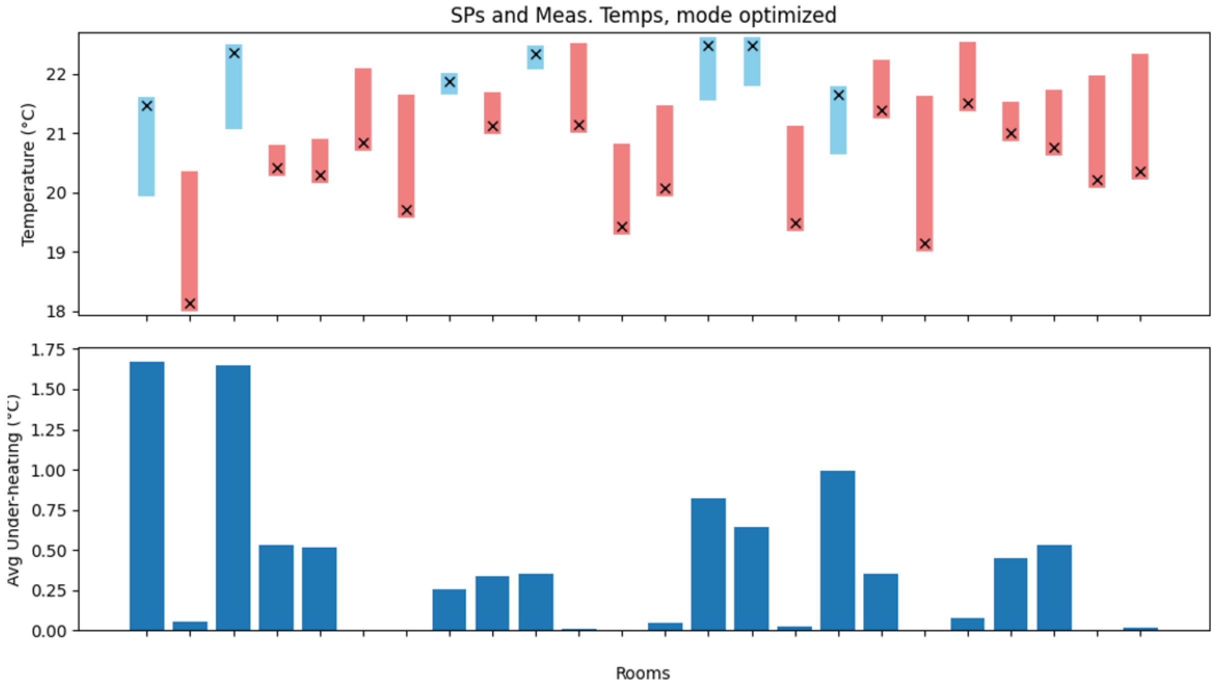

Figure 29: temperature and setpoints (x) (top) and underheating per apartment (bottom), optimized mode

This is illustrated in Figure 28 and Figure 29, which show the average setpoint and temperature in all apartments. Red and blue lines show the average deviations between both, red showing “overheated” apartments and blue bars “underheated” ones. We see that in most cases apartments cannot exactly reach the desired temperatures. The lower floor apartments tend to have lower temperatures. This is expected as the renovation did not allow a good insulation of the interface between the building and the ground, so it was expected that ground floor apartments could be colder. This was also evidenced and discussed in the section *2.5.7 Simulation* results. and also explains the relatively high underheating values since some apartments are constantly colder than their setpoint temperatures.
Finally, we report in Figure 30, the average daily temperature pattern in both modes. We see that the higher temperatures in optimized mode are broadly consistent throughout the day.

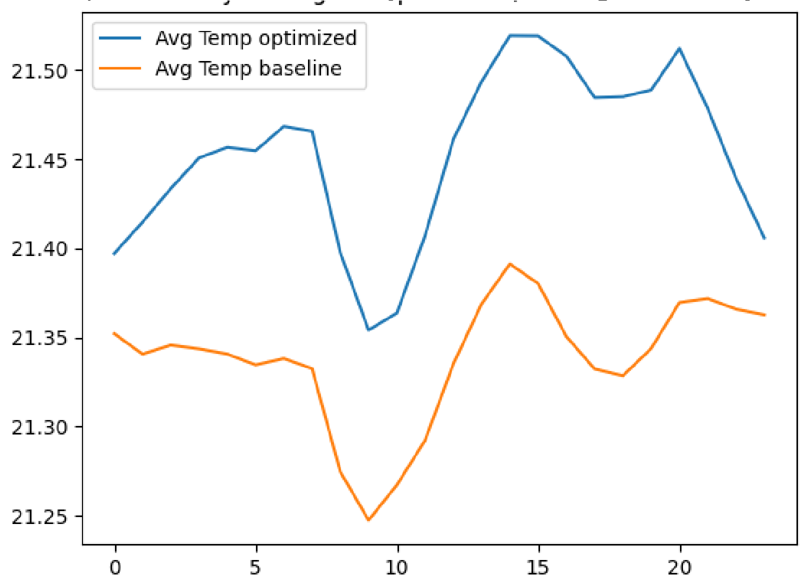

Figure 30: Average indoor temperatures in two modes

Cost adjustment calculation

The external factors affecting the net cost of electricity for which to adjust are outdoor temperature, indoor temperatures, amount of solar radiation and uncontrollable consumption.

Referring back to Table 3, we notice that the indoor and outdoor temperatures are very close in both periods and the difference of indoor and outdoor temperature is practically 0. Similarly, the uncontrollable consumption is almost identical. The main difference stems from the solar radiation which is visible since the PV production is 9% higher during the baseline period. Naturally, this generates an economic advantage that lowers the net cost of energy in the baseline period. To adjust, we consider the following: each supplementary kWh of PV production available can either be sold (at a tariff of 0.24CHF/kWh) or used locally and therefore substitute a kWh that should otherwise have been bought. The buying tariff will generally be the high tariff since PV is available during the day, except on Sunday, where it would be in low tariff. Hence, we estimate an average buying tariff of (6/7*0.4658 + 1/7*0.2927=0.44CHF/kWh). Because the self-consumption is at approximately 75%, it means each marginal kWh of solar power lost would have been 75% self-consumed (on average) and we can finally compute a unit adjustment price for surplus PV energy of (0.75*0.44+0.25*0.24 = 0.39CHF/kWh).

In Table 3, the first adjusted cost column corrects the real cost with a product of the estimated marginal cost of solar power above and the difference in solar production.

We emphasize that this is a somewhat conservative estimate as higher solar radiation should also contribute to lower heating needs in the building thanks to radiation inputs through windows. Regarding the final use of energy, we see that the final use of heat for heating is slightly higher and final use of DHW is slightly lower in optimized mode. Based on the measured SNG factors, it is estimated that these two effects approximately cancel each other (~+3kWh electricity per day for heating attributable to higher heating and ~-3kWh electricity attributable to lower DHW need). Note nevertheless that the heating comfort is higher in Optimized mode as shown in the previous section. Also, the optimizer has been using more heat from the HP that was found to have lower efficiency. This suggests further possible gains in optimized mode, that have already been factored in adjustments of optimizer configuration but is not captured in this measurement campaign since it was applied late in the season.

2.5.6 Energy saving measures implemented in the site

Optimization for space heating

Following observations reported in section *2.5.4 Focus on space* heating*,* we have evaluated different corrections to improve the heating efficiency. As a recap the following observations were made.

- It was identified that the typical flowrates measured were below 2000lts/h at the output of the pumps, significantly less than the design flow rate of 3600lts/h
- The flow rate through the distribution system is roughly at the design flow rates around 7000lts/h
- To compensate for the gap between these respective flows rates, there is a lot of recirculation through the heating tank
- This recirculation causes remixing between the return flow and the flow of hot water coming from the heat pumps, causing the supply temperature to be significantly below the hot water produced by the heat pump, more than 3 °C most of the time.

The goal of the corrective measures was to reduce the recirculation and remixing in order to allow a lower heating temperature for the heat pumps. The following corrective measures were implemented:

- Lowering of the delta T setpoint for the heat pump from 6 to 3 degrees.
- Lowering the circulation in the distribution loop which manifested by flowrates lower by about 20% in the distribution loop.

The resulting observation is that the supply temperature supplied by the heat pump were indeed significantly lower as shown in Figure 31. This should lead to direct improvement in COP but this is not readily visible: Figure 32 suggests that the COP may have improved but it is not that clear and the average SNG is not significantly higher. It is worth noting that comparison is difficult because outside temperatures were much higher on average after the energy saving measure was implemented (from March 2025) that during the rest of the winter. To find comparable outdoor conditions, we need to compare to the period of October 2024, but during that period the occupancy was much lower, so the heating was also likely lower. To conclude, more data would be required to make a definitive statement regarding the benefits of this measure.

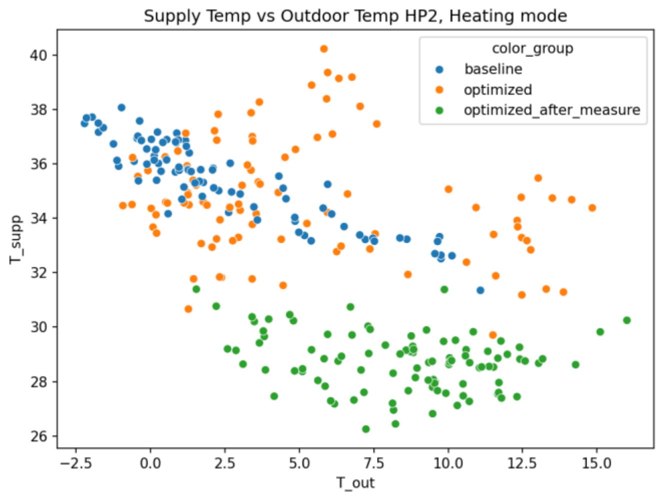

Figure 31: Supply temperature of HP2 against outside temperature (one point per HP on cycle)

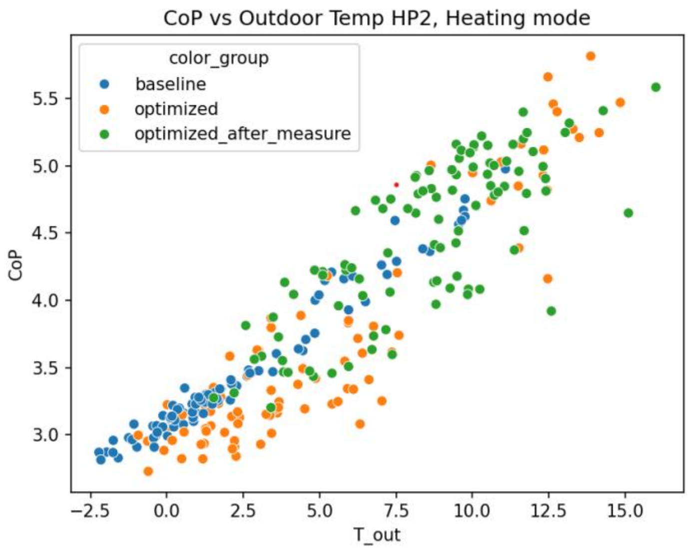

Figure 32: COP of HP2 against outside temperature

Optimization for domestic hot water

Following observations reported in section *2.5.3 Focus on* DHW , we have implemented corrections to improve the DHW production efficiency. It was hypothesised that the large overall losses were linked to very high levels of recirculation. Based on flow rates of consumption measured, we evaluate an average DHW use of about 80lts/h while the recirculation measured is around 2000lts/h. The corrective measure was to interrupt recirculation during periods of very low band or very high DHW consumption. This was implemented based on a schedule, so that recirculation was interrupted between 00:00 and 05:00 (low consumption), 07:30 and 09:00 (high consumption) and 18:00 and 21:00 (high consumption).

We report in Table 8 the losses and overall DHW efficiency. In both cases we compare the DHW circuit efficiency when operating in optimized mode before and after the modification of the recirculation schedule. The measure was implemented on March 24th. Since DHW is not completely consistent across time and has been steadily rising along 2024 and early 2025 due to more tenants arriving in the building, the period considered in the table below are the month immediately following and preceding March 24th. The efficiency is calculated as the ratio of thermal energy consumed in building for DHW by thermal energy produced for DHW. We see a progress from 34.6 to 40.1% thanks to lower losses. The electricity consumption for DHW has dropped 14% in line with the improved efficiency, despite a slight increase in DHW consumed of 6.8%. Note that it is unclear whether the increased consumption may be attributed to the measure itself or is independent of it.

Table 8: Aggregate KPIs showing effect of recirculation adjustments

	DHW electricity	DHW heat consumed	DHW heat circulation loss	heat losses	SNG+ DHW
Unit	kWh	kWh	kWh	%	-
optimized_before	46.2	80.0	55.5	33.1%	1.74
optimized_after	39.5	79.3	37.5	28.6%	2.02
Delta	-14.5%	-0.8%%	-32.3%	-28%	+16.1%

Finally, we can report no complaints related to how water availability or speed at the tap since the energy measure was implemented which suggests no significant impact on occupants' comfort.
Assuming a unit cost of electricity for heating of about 0.29CHF/kWh, this energy saving should result in cost savings of about approximately 700CHF/year for the heat pump electricity (6.7kWh / day). This is comparable to the savings brought by the optimized mode and comes on top of those previously identified savings.

We underline that is not per say a direct benefit of the optimized mode but setting up such scheduled operation of the recirculation pump is straightforward with the Soleco Optimizer. Finally, it is still noteworthy that the overall efficiency remains low and there could be further opportunities to save energy by e.g. lowering the recirculation rate, but we estimate that the problem is primarily a design problem in the recirculation lines.

2.5.7 Simulation results

We report observations based on the simulation model. In simulation, we perform yearly simulations based on a typical meteorological year with the following control strategy:

- Baseline (BL): We use the regular heating curve to set the heat pump supply temperature, and the power follows from the heat demand. DHW is produced based on a standard hysteresis controller from 45 to 60 °C and is produced with HP1. This is used to simulate scenario 4 (Standard mode) from Table 1. Room temperature setpoints are assumed to be fixed to 20.5 °C.
- Self-consumption controller (SC): It is very similar to BL but with a typical self-consumption increase tweak whereby the target temperatures for the DHW tank is increased by 5 °C when there is excess solar power available. This is used for simulation of scenario 5 (OptiClassic-PV). The room temperature also assumes fixed temperature setpoints set to 20.5 °C.

The following graphs show the monthly total electricity consumption and energy production from the photovoltaic fields.

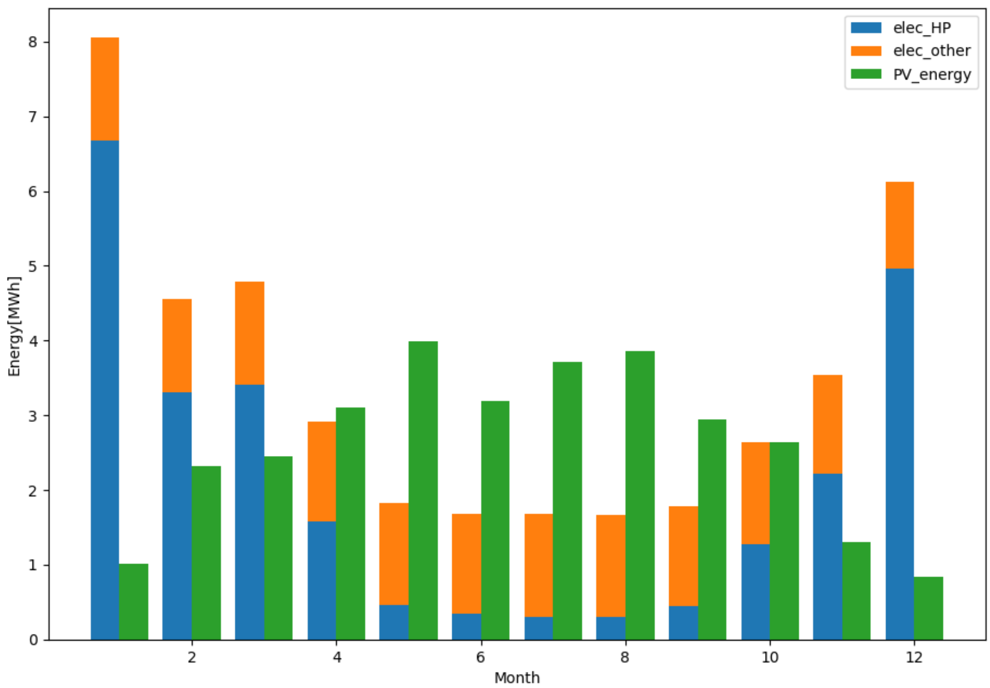

Figure 33: electricity consumption and production in BL scenario

The KPIs for the simulations are reported in Table 9.

In terms of thermal energy for space heating and domestic hot water (DHW), both strategies show similar results, with a slight increase in the OptiClassic-PV strategy. The electric energy for space heating and DHW also shows a marginal increase in the OptiClassic-PV strategy. The Seasonal COP for space heating remains constant at 3.5 for both strategies, while for DHW, it slightly decreases from 2.25 to 2.24 in the OptiClassic-PV strategy. Interestingly, the OptiClassic-PV strategy reduces the amount of bought electricity from 32.0 MWh to 31.6 MWh and also decreases the amount of sold electricity from 21.3 MWh to 20.7 MWh. This results in an increase in self-consumption from 32% to 34%.

However, despite the increase in self-consumption, the energy cost increases slightly from 4507 CHF to 4530 CHF, and the peak cost also rises from 746 CHF to 764 CHF in the OptiClassic-PV strategy. The energy produced remains constant at 31.3 MWh for both strategies.

In summary, the OptiClassic-PV strategy increases self-consumption but also slightly increases costs. The energy produced remains the same for both strategies. The main takeaway is that increasing self-consumption does not necessarily lead to cost savings. This is in line with findings from past projects as discussed in section 1.1.

Table 9: Simulation KPIs summary

KPIs	4: Baseline-PV	5: OptiClassic-PV
Thermal energy space heating [MWh]	75.5	75.6
Thermal energy DHW [MWh]	10.5	10.7
Electric energy space heating [MWh]	21.4	21.5
Electric energy DHW [MWh]	4.7	4.8
Seasonal COP SH	3.5	3.5
Seasonal COP DHW	2.25	2.24
Bought electricity [MWh]	32.0	31.6
Sold electricity [MWh]	21.3	20.7
Energy Cost [CHF]	4507	4530
Peak Cost [CHF]	746	764
Self-consumption [%]	32	34
Energy produced [MWh]	31.3	31.3
Underheating [Kh]	682	707

Note that this is based on a very rough building simulation calibration that will be updated based on observations from the real building.

In addition, a couple of qualitative observations are made:

As shown in Figure 34, we observe a significant spread of the simulated temperatures between the zones, with the trend that upper floors are warmer than lower floors and south-facing zones are warmer than north facing zones. This is in line with average measured temperatures in the real building, as shown in Figure 35. However, it seems that the spread is larger in reality compared to the simulation, which has more gap between North and South, compared to floors. This observation may have implication on the optimization as the current model was planning to use a single aggregate thermal model for the building. This approach works best with homogeneous temperatures in the building. Naturally in the heating period, the gap will close since heating will partly counteract that spread, but if spread remains, respecting temperature constraints on average may actually cause some heating comfort violations for the coldest zones. This will need to be confirmed quickly in the next season.

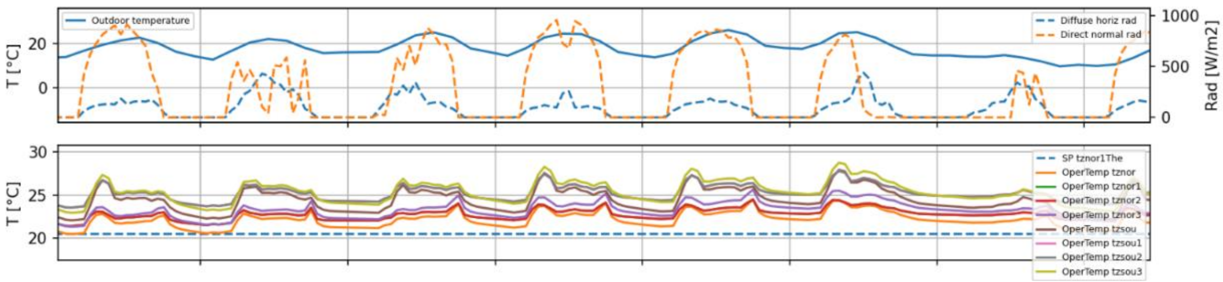

Figure 34: simulated zone temperatures

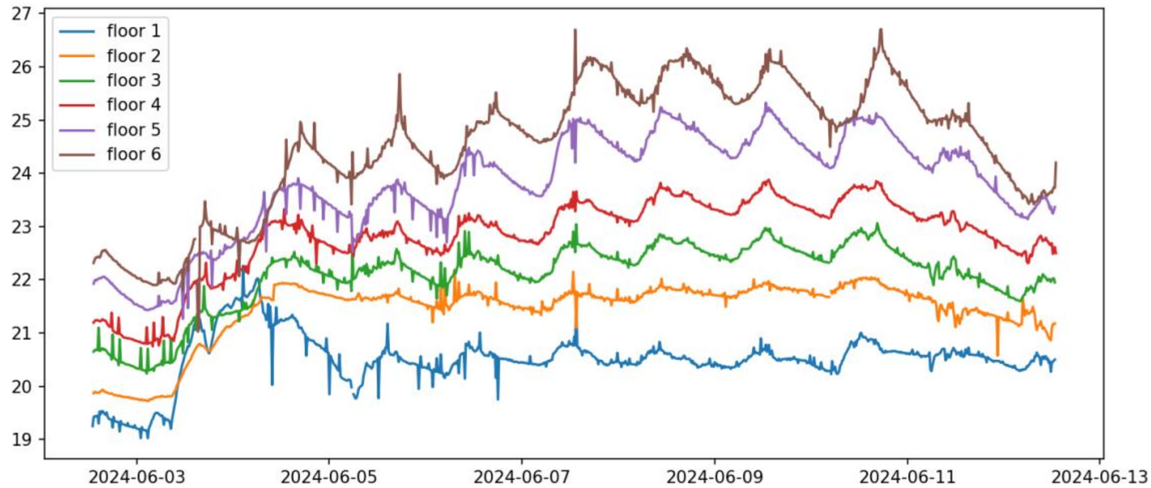

Figure 35: spread of measured temperature in real building

We observe a massive effect of the solar radiation on the Southern-facing zones in simulation, even in Winter, as illustrated in Figure 36. It is expected that this effect is not as present in the real building. Firstly, because there is direct communication between north oriented and south oriented rooms. Looking at Figure 37, we do observe higher temperatures in South facing rooms but only marginally. Note that in the real building, sensor placement and calibration can have a significant impact as well.

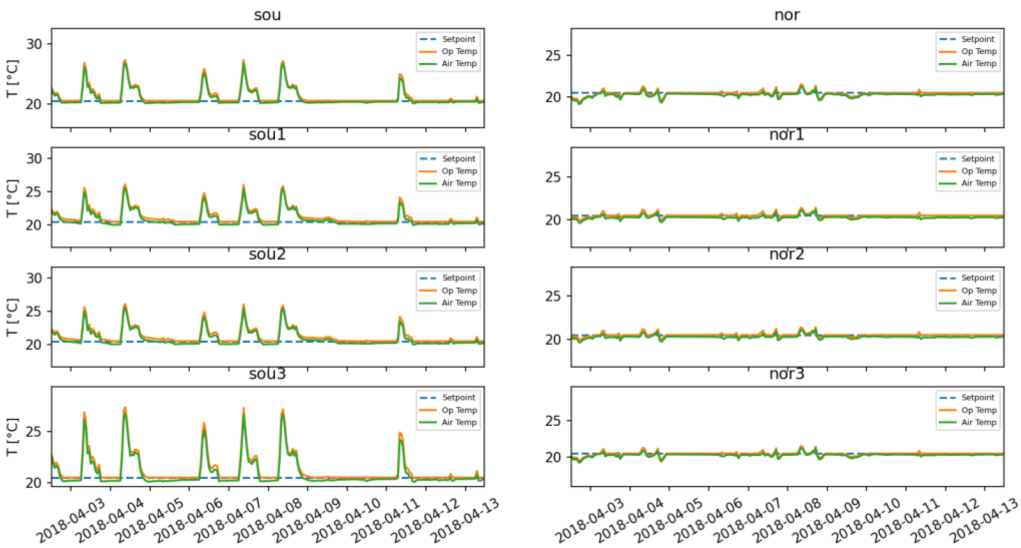

Figure 36: Simulated temperature in winter conditions

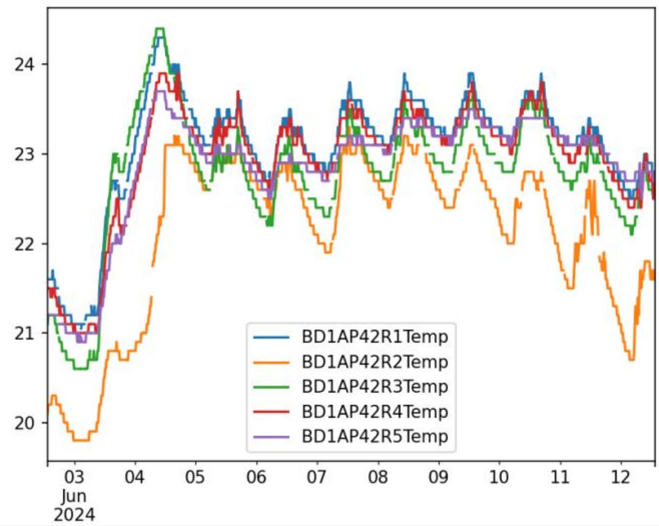

Figure 37: Room temperature in one apartment. South facing rooms (R1, R4) slightly warmer than rooms less exposed

3 Conclusions and outlook

From the experience of the project, we have compiled the following list of recommendations destined to stakeholders in the design, commissioning and operation of heat pumps and buildings of a similar type to the pilot site of the project:

1. Do not focus on self-consumption (SC:): Collective residential buildings have low production to consumption ratio and hence high self-consumption ➔ management of heat pumps focusing only on SC misses the point, because system efficiency and tariff variation are a bigger factor of savings
2. Store energy in the building, not the tank ➔ this requires acting on building room setpoints
3. COP is not the whole :story: global efficiency (SNGplus) is what ultimately matters
4. Recirculation and mixing are the enemy ➔ recirculation can cause massive losses (here 50% in DHW) and mixing lowers temperatures which hurts the COP
5. Lower DHW temperature can bring massive efficiency gains (20+%)
6. Predictive control manages trade-offs for you ➔we demonstrate it is scalable

We elaborate below on those findings one by one, their relation to the project and implication for future deployment.

1. Prioritize System Efficiency and Tariff Optimization Over Self-Consumption

In collective residential settings, the ratio of energy production to consumption is typically low, leading to inherently high self-consumption rates. For example, in this pilot, we have measured a self-consumption rate of 70% in standard operation during the October to February period, and autarky of only 13%. This means that even optimistic improvements of self-consumption would yield economic benefits of less than 3-4%. **This is inherent to this building-type.** In our case, we do still manage to increase self-consumption to 78%, but this only translates into savings of about 1-2% on the energy bill. Although our study focuses on the least favorable period in the year, as solar excess increases in the intermediate season, it is important to notice that heating needs in renovated buildings during the inter-season are rather low, which is another limitation on the potential for self-consumption increase. In summer, the picture is different with much more excess power available, but it is naturally relying on the presence of cooling, which is not widespread in Switzerland, even in new installations.

This means that focusing solely on maximizing self-consumption will overlook more significant opportunities for cost savings. Emphasizing overall system efficiency and strategically managing energy use in response to tariff variations typically yields greater financial benefits. **Here, leveraging thermal storage to shift energy consumption to periods with lower electricity rates is the main contributor to cost savings and allows to lower the unit cost of HP electricity by 11.5%** without increasing the overall consumption.

This is important because the main selling proposition of many EMS (see *e.g.* the webpage of the EMS market leader in Switzerland[6]) is that they increase self-consumption. While it makes sense for individual houses, it is not particularly attractive for the type of building we are now talking about. We refer to point 6. below for further discussion.

2. Utilize Building Thermal Mass for Energy Storage

Storing energy within the building's thermal mass, rather than solely relying on water tanks, can enhance the efficiency of heat pump systems. Adjusting room temperature setpoints allows the building structure to act as a thermal buffer, reducing the need for frequent heat pump cycling and improving overall performance. Research indicates that incorporating thermal storage systems in heat pump configurations contributes to increased energy efficiency and cost savings As we already discussed in

[6] Solar Manager - Eigenverbrauch optimieren

the introduction, this observation is not new or specific to this project but it is very important to reiterate it as the standard approach to energy management of heat pumps combined with PV remains overwhelmingly the use of increased tank temperature setpoints to increase self-consumption. There is now ample evidence that this type of strategy is at best marginally beneficial from a cost standpoint and is always detrimental from an energy efficiency standpoint.

In our opinion this is a side-effect of the massive emphasis on the need to increase self-consumption as the main message around energy management. It is important to remember that self-consumption is only a means to an end, namely improved financial returns for a PV installation. High self-consumption by itself is not a benefit.

Our concrete recommendation is that EMS that manage heat pumps should operate with temperature setpoints bands or similar concepts, and not with fixed setpoints. This is increasingly possible in modern EMS's but faces technical barriers in larger buildings such as the OPERA pilot. We have, however, demonstrated a reproducible integration approach of the room setpoint management in the building and the HP control.

3. Focus on Global Efficiency Beyond Coefficient of Performance (COP)

While COP is a critical measure of a heat pump's performance, it does not encompass the entire efficiency picture. Global efficiency considers factors such as system design, integration with other building systems, and operational strategies. A comprehensive approach that optimizes all components and their interactions is essential for achieving maximum energy savings and performance.

We report here examples of very large recirculation losses of 47% on the DHW side. According to previous findings from OST based on similar system monitoring [10], this is not an isolated case.

The root causes are discussed in point 4. One difficulty in troubleshooting this is that in most buildings that may be affected by this type of problem, the effect is invisible due to lack of sensors that would provide the data necessary to diagnose this issue, or due to the lack of automated monitoring of the data available to detect the problem. In many cases, heat metering is absent or insufficient to compare the thermal production of the heat pump and the heat consumption in the building.

Nevertheless, there are telltale signs of poor efficiency such as big temperature gaps between the heat pump output and the heating system inputs. We therefore recommend auditing the energy data available, especially after a few months of operation in the case of an energy renovation, comparing it with planned values and prior to renovation, and to include heat meters for the building and DHW aggregate consumption. This type of sensors tends to be a bit expensive but will be paid back immediately if they detect loss issues and provide very valuable information on the energy consumption of the building.

4. Minimize Recirculation and Mixing to improve efficiency

Recirculation and mixing within heating and domestic hot water (DHW) systems can lead to significant energy losses. Recirculation can cause substantial heat losses, and mixing can lower water temperatures, adversely affecting the heat pump's COP. Optimizing system design to reduce unnecessary recirculation and mixing is crucial for maintaining efficiency.

For DHW, recirculation is the most common solution to ensure the timely arrival of hot water at the tap, which is mandated in Swiss building norms [7]. The first implementation measure and common recommendation is careful thermal insulation of circulation lines, which is certainly important but cannot be expected to be perfect, as we have demonstrated here. As also underlined in cantonal law [8], recirculation pumps should be controllable thanks to a schedule or based on temperature feedback. In practice, although control-based on schedule is at least technically possible, it is often not actually used and the setpoints of the pumps are usually way too high. Again, as discussed in 3., the fact that actual losses are often unknown and assumed small prevents us from making informed decisions.

In this case, we have noticed that recirculation flow rates are much higher than actual DHW use flow rates (2000 against 80 liters/h on average). In this case, the pump was upgraded to improve the delay time to get hot water for some apartment. The typical temperature drop between the supply and return of the recirculation line is only 1.5K which suggest unnecessarily high recirculation rates. Past work, like [11, p12] explicitly advice maintaining a drop in the order of 5-10K. It is our view that this decision to increase flow rates of recirculation was misguided as it seems that if piping temperature cannot be maintained at lower flow rates, then there must be an insulation problem or a design problem in the sense that the recirculation lines are too short and increasing flow rates cannot solve that problem. Thanks to targeted interruption of the recirculation at times of low and high consumption, we demonstrate savings of 16% of the electricity use for DHW preparation, and some circulation pump consumption, which amounts to ~700CHF/year or 35CHF/year/apartment. This is already significant and is in the same order of magnitude as the savings enabled by the optimized control.

For an extensive discussion and recommendations regarding DHW setups, we refer to [11]

5. Lower DHW Temperature Setpoints for Enhanced Efficiency

Reducing the setpoint temperature for DHW can lead to significant efficiency gains. In the current system we demonstrated savings of approximately 20% of electricity with optimized management of the DHW production. 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 is significantly here since losses are quite large. However, it is essential to ensure that the set temperature complies with health and safety standards, namely SIA 385 norms, to prevent issues such as Legionella growth. It is recommended to increase temperature the temperature of water that has stood still every 24hours to 60 degrees. In MFH with small tanks like in this case, there are multiple heating cycles a day, so reaching 60 degrees is not necessary at every heat pump cycle, which has a big impact on energy consumption. Here also, the lack of quantitative evaluation of the energy losses in a standard setup is detrimental.

6. Implement Predictive Control Strategies for Optimal Management

Predictive control algorithms can effectively manage the trade-offs between energy consumption, cost, and comfort. These algorithms utilize forecasts of weather conditions, occupancy patterns, and energy prices to optimize heat pump operation and thermal storage utilization. Various studies have shown that predictive control can enhance the efficiency and cost-effectiveness of heating systems but still suffer from scalability. We refer for example to [9] for a recent survey of academic publications

We have demonstrated credibly reproductible deployment of a predictive control strategy adapted to MFH with heat pump systems. The scalability is guaranteed by the reliance on commercially available solution, and a standardized approach to system interfaces.

Our recommendation for EMS owners is to select EMS products that implement predictive control strategies. One common problem facing integrators or building operators is the lack of transparency regarding what EMS do and in turn what true benefits they can bring. Ideally, third-party certified performance assessments would be required to benchmark EMS products. As we have elaborated, their cost performance can vary greatly. As far as the authors know, most commercial products are based on a collection of rules. It is our position that a predictive control approach is ultimately preferable because of its flexibility in adapting to various objectives. The uptake of variable tariffs (enabled by the recent Swiss energy law package) particularly favours predictive control strategies because they ingest price profiles as an input rather than require a re-design of the rules. This observation is particularly true for MFH building with heat pumps because of the specific challenges discussed in point 1. and the relative inadequacy of self-consumption strategies for such buildings.

In this deployment, we have demonstrated savings of about 7% in electricity costs over a 4 month period. Extrapolating to a full heating season, we estimate total savings of about 750CHF or 37 CHF/apartment. Note that this excludes savings for the summer period, which could not be assessed in this study due to lack of summertime experimentation period.

4 National and international cooperation

N/A

5 Publications and other communications

List of past or upcoming communications and publications

- Poster, titled "**Multi-Family Building with Photovoltaic Systems and Heat Pumps**" with results at PV Tagung 2025 on April 1-2nd in Bern
- Presentation, titled "**Energy management for multi-family houses with PV and HPs**", at Swiss Heat pump days 2025 on June 12th in Bern
- Bulletin article, provisionally titled "**Optimisation de l'utilisation PV dans un immeuble locatif avec stockage dans la masse du bâtiment et contrôle des PAC: contexte, solutions, mise en œuvre**, planned for publication in number 7/2025
- Conference article for 15th IEA Heat Pump conference 2026, abstract submitted in May 2025
- Lunch talk at decarbCH (tbc)
- Highlight of results in CSEM scientific report 2025
- Participation in Fachvereinigung Wärmepumpen Schweiz FWS, November 2025, tbd
- Participation in evenement FWS Romandie, tbd

6 References

[1] Stratégie énergétique 2050, monitoring 2023: https://www.bfe.admin.ch/bfe/fr/home/versorgung/statistik-und-geodaten/monitoring-energiestrategie-2050.exturl.html/aHR0cHM6Ly9wdWJkYi5iZmUuYWRtaW4uY2gvZnIvcHVibGljYX/Rpb24vZG93bmxvYWQvMTE1ODE=.html

[2] https://www.bfs.admin.ch/bfs/de/home/statistiken/kataloge-datenbanken.assetdetail.27905545.html, accessed on 23.07.2024

[3] Innovative Eigenverbrauchsoptimierung für Mehrfamilien-Arealüberbauung mit lokaler Strombörse, https://www.aramis.admin.ch/Grunddaten/?ProjectID=38727

[4] Prosumer-Lab – Influence of novel strategies and components of the energy management of grid-integrated, smart buildings on the stability and quality of the house and distribution grids, https://www.aramis.admin.ch/Grunddaten/?ProjectID=38327

[5] SmartGridready, SGrSpecifications/doc/HeatPumpAppliances.md at master · SmartGridready/SGrSpecifications · GitHub, accessed in June 2024

[6] Tomasz T. Gorecki, William Martin, Maestro: A Python library for multi-carrier energy district optimal control design, IFAC-PapersOnLine, Volume 53, Issue 2, 2020, Pages 13293-13298, ISSN 2405-8963, https://doi.org/10.1016/j.ifacol.2020.12.160

[7] SIA norm 385-1: Installations d'eau chaude sanitaire dans les bâtiments - Bases générales et exigences, 2020, SIA

[8] Règlement d'exécution de la loi cantonale sur l'énergie, Conseil d'État de la République et Canton de Neuchâtel, 2021. Link: https://rsn.ne.ch/DATA/program/books/rsne/pdf/74010.pdf

[9] Lessons learned from field demonstrations of model predictive control and reinforcement learning for residential and commercial HVAC: A review, Arash J. Khabbazi, Elias N. Pergantis, Levi D. Reyes Premer, Panagiotis Papageorgiou, Alex H. Lee, James E. Braun, Gregor P. Henze, Kevin J. Kircher, 2024, arxiv preprint

[10] Burke, Stephen, et al. "Mapping of domestic hot water circulation losses in buildings–preliminary results from 134 measurements." *E3S Web of Conferences*. Vol. 172. EDP Sciences, 2020.

[11] Vetsch, Gschwend, Bertsch; Warmwasserbereitstellung mittels Wärmepumpen in Mehrfamilienhäusern, 2012, link: 03-ch-bernhard-vetsch-warmwasserbereitstellung-mittels-warmepumpen-in-mehrfamilienhaus.pdf

[12] Wärmepumpen Planung | optimierung | betrieb |Wartung, EnergieSchweiz, link: Buch_WP_Web_2018.pdf

N/A