2025

PnP controls TABS
Final Report

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PnP controls TABS

Development of plug-and-play control strategies for energy-flexible buildings with focus on heat pumps

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1 Introduction

1.1 Task

New buildings and buildings undergoing major refurbishment are increasingly equipped with heat pumps and thermally activated building systems (TABS), such as concrete core activation in load-bearing slabs, underfloor heating, wall heating, and similar systems. These technologies represent cost-efficient solutions for space heating, provide high indoor comfort through radiant heat, and offer significant potential for load shifting to support the increased use of renewable energy sources.

During periods of excess availability of renewable electricity or heat (see Figure 1), thermally activated building components can be charged and used as thermal storage. The stored thermal energy can subsequently be released during periods of low renewable energy availability, thereby reducing energy demand at those times (see Figure 2). In addition, these concepts enable the feed-in of locally generated energy into public electricity or district heating networks (see Figure 3).

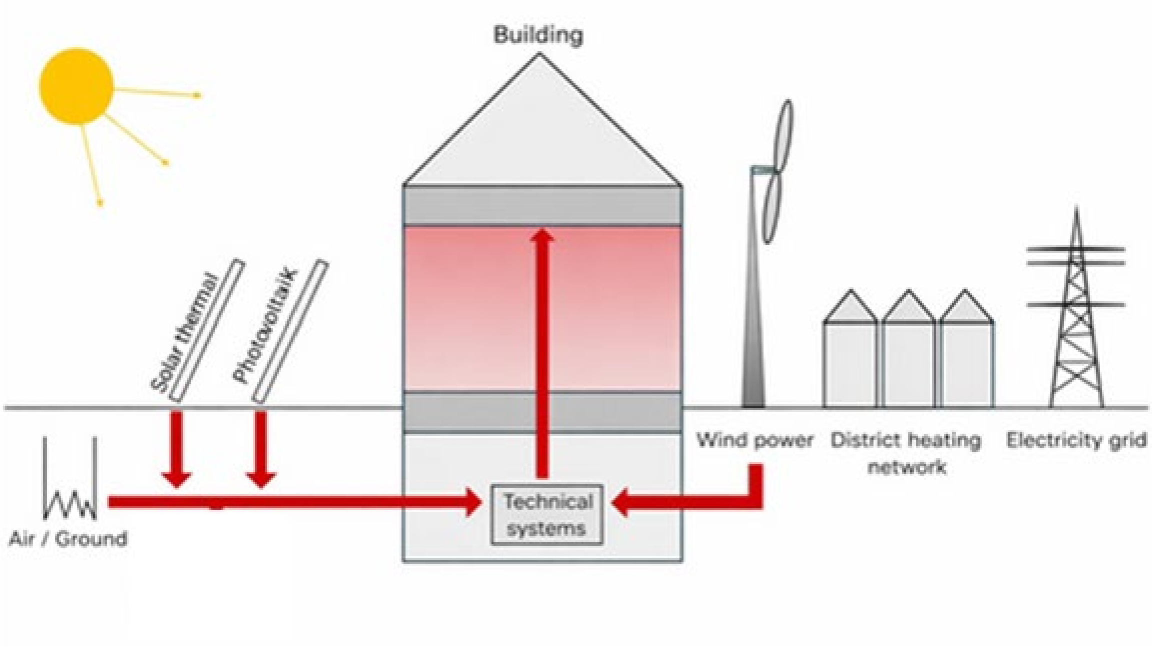

Figure 1: Charging of thermal storage using renewable environmental energy (Source: e7 GmbH, 2024)

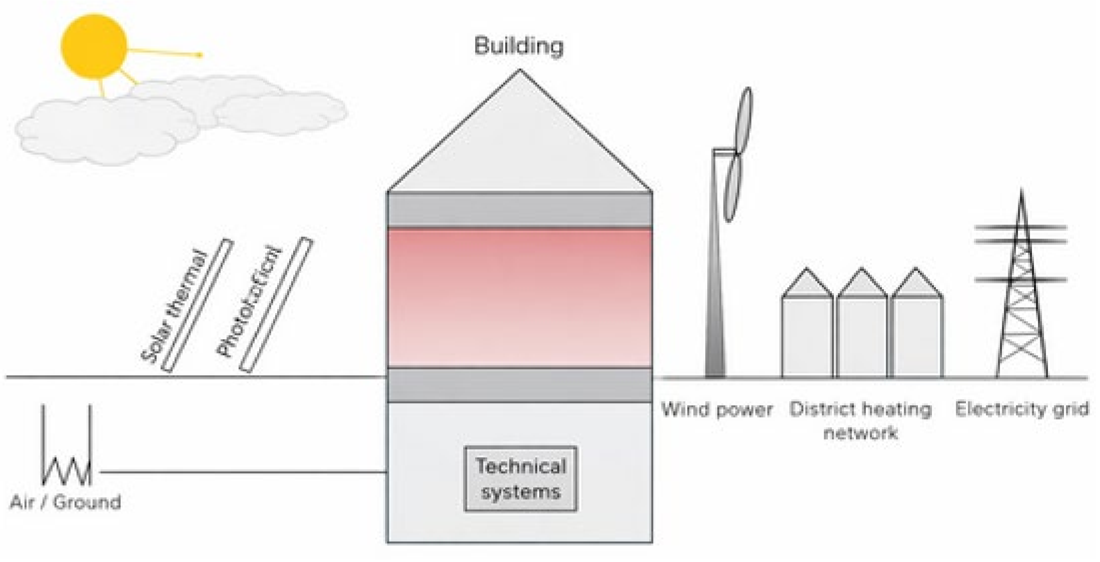

Figure 2: Coverage of building heat losses using stored thermal energy (Source: e7 GmbH, 2024)

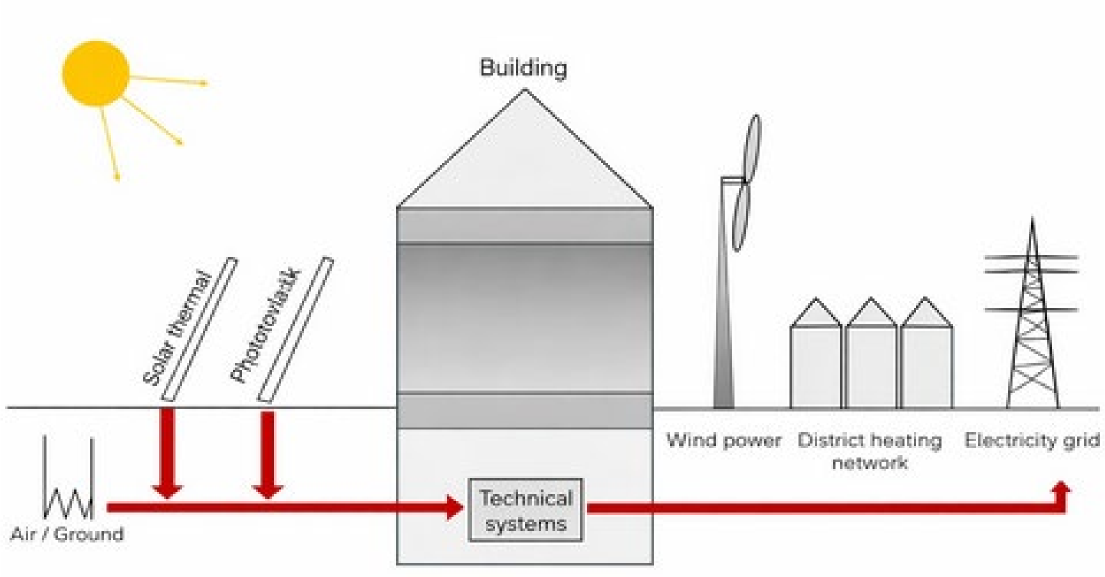

Figure 3: Feed-in of locally generated energy into public energy networks (Source: e7 GmbH, 2024)

Utilizing the thermal storage capacity of existing building structures represents a key contribution to the development of a renewable energy system. These structures can significantly help to compensate for the temporal mismatch between energy generation and energy demand, which is characteristic of renewable energy sources. As a result, buildings become active elements of the energy system, enabling the utilization of energy flexibility in buildings.

Energy Flexibility in Buildings

- Energy flexibility describes the ability of a building to adapt its energy demand and on-site energy generation in response to local weather conditions, the availability of renewable energy, occupant requirements, and grid needs.
- Achieving energy flexibility requires appropriate system design and control strategies that explicitly enable flexible operation and controllability of energy flows.

1.2 Focal points of the project

The objective of the research project is to develop plug-and-play control strategies for heat pump systems combined with thermally activated building components used as thermal storage, while taking additional influencing factors into account, such as local weather conditions and price signals from renewable energy providers.

The control strategy is designed to communicate with internal and external renewable energy resources and to trigger a parallel optimization algorithm. Throughout operation, indoor climate requirements must be maintained, ensuring that occupants do not perceive differences between conventional and advanced control strategies. At the same time, the inclusion of weather forecasts enables predictive control operation, allowing renewable energy to be utilized more effectively, particularly during periods of temporary energy surplus.

Within the scope of this research project, three core activities were carried out:

1. Development of control algorithms for plug-and-play controllers
2. Design and implementation of a “Grid Data Manager” for grid data communication
3. Implementation and validation in demonstration buildings

1.3 Placement in the Programme

Contribution to programme goals

- **Technology development:** “Development and model use of local energy and energy-related transport technologies for the large-scale field testing of intelligent system solutions in live operation”
    - Heat pumps in combination with thermally activated building systems (TABS) offer significant potential for the implementation of demand-side flexibility measures. This potential can be further enhanced by incorporating building energy load behaviour and forecast-based models into the control strategy. The project contributes to the development and validation of intelligent, predictive control solutions under real operating conditions.
- **Market development:** “Strengthening and developing Austria as a lead market for innovative energy and energy-related transport technologies and services”
    - Electrically driven heat pumps represent a rapidly growing market, while flexibility options are becoming a key requirement for future energy systems. The project strengthens the market by developing a plug-and-play control strategy that is provided as a freely available open-source solution.
    - Future market implementation is additionally supported through the preparation of specific tender texts for system integrators, facilitating practical adoption and scaling.
- **Acceptance:** “Involvement and active participation of users”
    - The project primarily focuses on technology development. Consequently, direct end-user involvement is limited to field tests in demonstration buildings and targeted dissemination activities. User feedback from these demonstrations supports the assessment of usability and acceptance under real-world conditions.

Contribution to goals of model region

- **Systemic Interaction of End Users, System Intelligence, and Energy Services**
  - The core objective of the project is the development of a plug-and-play control solution for heat pumps combined with thermally activated building systems (TABS). The solution aims to increase self-consumption in buildings equipped with local renewable energy sources, such as photovoltaics, and to provide additional flexibility options for demand-side management.
  - By applying intelligent control based on building energy models and forecast data, the solution connects end users on one side with energy suppliers on the other side.
- **Bridging Research and Market**
  - The project delivers a freely available open-source control strategy, enabling reuse and further development by a wide range of stakeholders.
  - Project results are directly applicable beyond the consortium and are supported by the preparation of implementation-oriented tender texts to facilitate market uptake by system integrators.
- **Thematic Spotlights for the Energy Future**
  - The development of a plug-and-play heat pump control solution combined with an open communication interface for data exchange between heat pumps and electricity suppliers represents an important step towards the decarbonization of heat supply. The solution enables sector coupling, load shifting, and the utilization of excess renewable energy for heat generation, thereby contributing to a flexible and climate-neutral energy system.

1.4 Methods used

Development of Control Algorithms for Plug-and-Play Controllers

Within the scope of the research project, a plug-and-play control strategy for heat pump systems is developed. In combination with thermally activated building components used as thermal storage, the control strategy increases building flexibility by enabling efficient grid interaction and prioritizing the use of locally available renewable energy. An overview of the general control approach is shown in Figure 4.

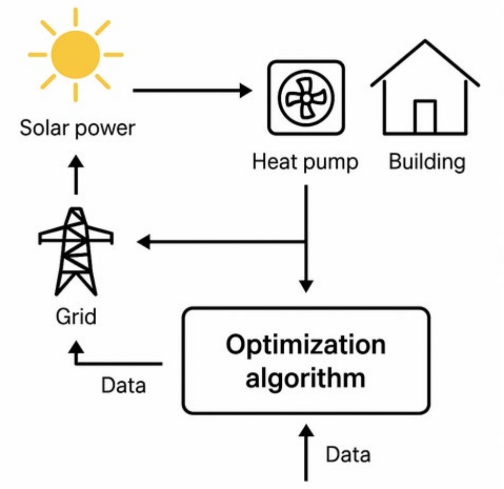

Figure 4: Simplified procedure of plug & play control strategy (source: e7 GmbH, 2024)

The control procedure is designed for heat pump operation in residential buildings and aims to demonstrate demand-side flexibility through power-to-heat applications. Several load-shifting scenarios are considered, with highest priority given to the increased use of locally generated renewable energy, provided by an existing photovoltaic system installed at the building.

In addition, the control strategy targets a low-carbon and grid-friendly operation of the controlled heat pump. For this purpose, day-ahead electricity market prices of the Austrian bidding zone are assumed with an hourly resolution to model electricity imports from the grid. The control concept is implemented as a data-driven, predictive control algorithm.

The core developments and technical key specifications of the control procedure include:

- **Forecasting of internal and external operational boundary conditions**, such as outdoor temperature, expected solar irradiation, availability of local renewable energy, domestic electricity consumption, and future electricity prices. The scope of the forecasts (number of data points and prediction horizon) depends on the respective scenario and is provided either by publicly available external sources (e.g. day-ahead market prices) or by internal prediction models integrated into the control framework.
- **A data-driven thermal building model**, representing the dynamic behaviour of the building, including the controlled heat pump and the hydraulics of the heating system. The model structure is optimized for residential applications, for example by assuming a reduced influence of solar gains due to the absence of large glazed façades. A grey-box modelling approach is applied, with model parameters identified from historical monitoring data or estimated based on expert knowledge.
- **A receding-horizon optimization algorithm** to determine the optimal future operation of the heat pump while respecting the defined objective function and the thermal constraints of the building. As a linear model formulation can be derived, the optimization problem is solved using Mixed-Integer Linear Programming (MILP).

Development of a “Grid Data Manager” for Grid Data Communication

The **Grid Data Manager** is a centralized and fully automated software agent that communicates with verified and authenticated grid participants via secure, encrypted connections (VPN). It enables structured data exchange within the framework of **Grid Data Communication**.

The currently implemented data exchange includes:

- Site-specific weather forecast data
- Price signals from renewable energy providers
- Forecast data for electricity consumption
- Potentials for (electrical) load shifting

All data exchange is encrypted according to the current state of the art and follows a standardized data format (JSON). The software components required to implement Grid Data Communication at the level of grid participants are available as a proof of concept. In a subsequent step, these components are intended to be technically verified and validated in cooperation with grid operators and energy suppliers.

Implementation in Demonstration Buildings

The developed control strategies have been implemented for functional validation in **six demonstration buildings**, comprising **four residential buildings and two office/educational facility**.

2 Content Presentation

2.1 Control Strategy Development

2.1.1 Comfort Assessment Scenarios

All control strategies developed in this project must maintain thermal comfort while allowing demand-side flexibility. Therefore, indoor comfort must be measured or estimated.

A **thermal zone** describes the part of the building that the control system regulates. It includes the heating system (e.g. TABS), heat losses to the outside, and the building's storage capacity. Depending on the system, one thermal zone can be a single room, several connected rooms, a floor, or even the entire building.

Thermal comfort is usually defined by the **air temperature**, measured with a wall-mounted sensor about 1.5 m above the floor.

Four main approaches can be used to assess comfort:

1. **Multiple room sensors** – The most accurate method, as it captures local temperature differences. However, it requires many sensors and complex data handling.
2. **Central ventilation measurement** – Uses the exhaust air temperature from a central ventilation system to estimate average comfort. Reliable, but only possible if such a system exists.
3. **Single reference room** – A simple and common approach. One well-chosen room represents the overall building temperature. Easy to install, but less precise.
4. **Estimation without indoor sensors** – Setpoint for supply temperature of heating system to achieve appropriate indoor comfort is estimated from outdoor temperature or weather forecasts. This traditional approach is widely used and can be improved with dynamic models and online weather data.

2.1.2 Control Input Scenarios

In control theory, a system can be described as an input–output model. Inputs that can be influenced by the controller are called manipulatable, such as the thermal power delivered to a thermally activated building system. All other inputs, like internal heat gains or transmission losses, are treated as disturbances.

To ensure a general and transferable control concept, these manipulatable inputs—directly linked to controller outputs—must be clearly defined.

Heat Pump Control Interfaces

Modern heat pumps offer three main options for external control:

1. **EVU Contact** – Allows the energy provider to temporarily disable the heat pump (e.g. for up to two hours per day) in exchange for a lower electricity tariff.
2. **Smart Grid Ready (SG Ready)** – Adds *recommended* and *active* switch-on signals to the basic EVU contact. Typically, this results in small increases of room or water setpoint temperatures. The interface has been widely adopted since 2020 (BWP, 2013).

3. **Variable Power or Temperature Setpoint** – Enables direct control of power or supply temperature via communication protocols (e.g. ModBus, KNX). Common in large systems but not yet standardized.

Implementation in the Project

Within the project, both the EVU contact and a variable power input via ModBus were tested. The developed mixed-integer optimization algorithm supports both interfaces.

Since hydraulic systems vary between buildings, the plug-and-play (PnP) controller output is defined as a thermal load command (e.g. 6 kW for 15 minutes). Each implementation converts this command into suitable signals for the local heat pump and hydraulic components.

If a buffer storage tank is present, the controller primarily influences the circuits downstream of the buffer. The project focuses on exploiting the building's inherent thermal mass for flexibility, while additional rule-based functions (e.g. for buffer or domestic hot water control) can complement the core algorithm.

2.1.3 Model Setup

Using the Building's Ability to Store Heat

The building can store heat in its structure – in the walls, floors, and ceilings. To make use of this ability, the control system uses simple models that predict how different parts of the building will behave in the future. This helps the system decide when it's best to heat or cool, so that energy is used efficiently.

At the start of the project, a model was developed that describes several temperature points (or "states") in the building. Figure 5 shows an example with four of these states:

- **Return temperature of the TABS** – The temperature of the water that flows back from the thermal activation system (TABS) pipes.
- **Temperature of the TABS or underfloor heating (UFH)** – The heat stored in the building's structure, such as floors or walls.
- **Air temperature in the room** – The temperature of the air inside the zone or room.
- **Temperature of passive building materials** – The heat stored in building parts that are not actively heated or cooled, like walls or ceilings.

These temperature points are connected by heat transfer between them. The exchange of heat depends on several factors, including:

- **Outdoor temperature** – How warm or cold it is outside.
- **Solar radiation** – The amount of sunlight hitting the building.
- **Supply temperature to the heating system** – How warm the heating water is when entering the system.
- **Operation of the heating system –** Whether the heating pump is running or not.

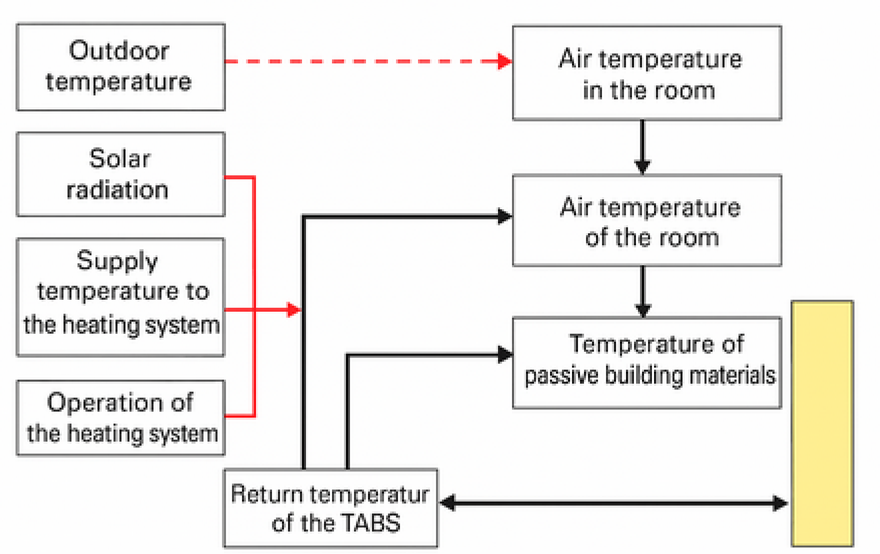

Figure 5: Basic structure of temperature-based model (Source: e7 GmbH, 2024)

The model uses these inputs to predict the key temperatures in the building, such as:

- the room air temperature,
- the temperature of the walls or inner surfaces, and
- the temperatures of the heating water in different parts of the system.

These calculations are based on fixed parameters that were estimated from the building's real performance data.

The model has been tested with real measurements from one of the demonstration buildings. It performs well, especially in predicting the return temperature of the heating water. This temperature is important because it determines how much heat the building's system (TABS) can absorb.

The amount of heat transferred into the system depends on the difference between the supply and return water temperatures. Since the goal is to keep the supply temperature from the heat pump as low as possible, the energy input is limited by the current and predicted return temperatures.

Issues Found with the Temperature-Based Model

Although the temperature-based model worked well overall, two main challenges were found:

1. **Sudden changes when heating switches on or off:** When the heating system starts or stops, the temperature in the model changes abruptly. These jumps make it difficult to use the model smoothly in optimization.
2. **Changing energy limits:** The control system not only needs to deal with variable energy prices, but also with limits on how much energy can be used at different times.

Solution: Switching to an Energy-Based Model

To solve these issues, the model was simplified from a temperature-based model into an energy-based model. Key differences between the models are shown in Table 1.

Table 1: Key difference between temperature-based and energy-based-models

Feature	Temperature-Based Model	Energy-Based Model
Focus	Tracks room and surface temperatures	Tracks stored energy (State of Charge)
Problem	Sudden changes when heating switches	Handles energy use more smoothly
Use in optimization	Harder to use directly	Easier and more stable
Comfort control	Based on temperature	Based on stored energy and estimated comfort

2.1.4 Optimization algorithms scenarios

Within the PnP control concept, the decision on *if* and *how much* thermal energy is supplied to the thermal zones is determined through an optimization of the predicted operation schedule of the heat pump and the hydraulic system.

In the current implementation, the optimization is executed every 15 minutes and covers a three-day prediction horizon. The objective is to minimize the operational costs of the heat pump while maintaining user-defined thermal comfort limits.

Evaluated Optimization Approaches

Several algorithm types were evaluated for use within the PnP control framework:

1. **Linear and Mixed-Integer Linear Programming (MILP)**
   - Well suited for linear model structures such as the energy-based formulation.
   - Provides fast and robust performance.
   - Mixed-integer extensions allow flexible representation of different system behaviours:
     - ON/OFF operation,
     - continuous control (0–100 %),
     - semi-continuous control (e.g. minimum to 100 %).
   - Multiple solvers are available, including options free for academic use.
2. **Non-linear Optimization**
   - Offers higher model flexibility but generally slower and less stable performance.
   - Genetic algorithms performed well for temperature-based models, but their computational demand makes them unsuitable for long prediction horizons or high-resolution (15 min) operation plans.
3. **Brute-Force Search**
   - Limited applicability due to high computation time.
   - Potentially useful for specific extensions such as buffer storage or domestic hot water scheduling.

Selected Approach

Considering the trade-off between computational effort, flexibility, and robustness, the PnP control algorithm in its latest version applies the Gurobi Mixed-Integer Linear Programming (MILP) platform (Gurobi, 2023).

2.1.5 Experimental database

The demonstration building No. 3 (STBG) is equipped with a comprehensive monitoring and automation system providing long-term operational data for control development and validation.

The residential building, constructed in 2019, is a two-storey single-family house with approximately 170 m² of heated living area. It is equipped with a reversible air-to-water heat pump, a zoned underfloor heating and cooling system, a domestic hot water system with a 1,000 L thermal buffer storage, a central ventilation system with heat and humidity recovery, and automated shading. A roof-integrated photovoltaic system combined with electrical battery storage enables local renewable energy use and demand-side flexibility.

Figure 6 illustrates the hydraulic configuration of the building. The heat pump supplies either the underfloor heating systems or the buffer storage with an integrated fresh-water module for domestic hot water preparation.

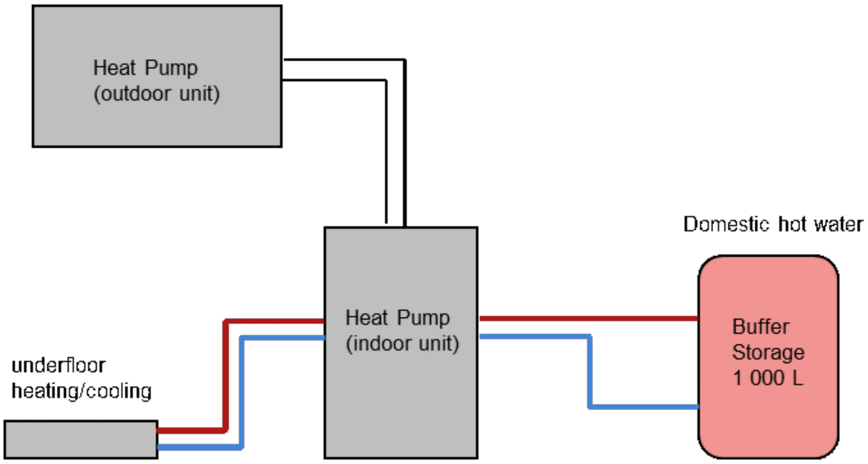

Figure 6: Heating system of Demo building No 3 (STBG) (Source: e7 GmbH, 2024)

All components are connected to a central building automation system (BAS) and an extensive data acquisition setup, including thermal and electrical energy meters as well as indoor and outdoor environmental sensors. A continuously maintained time-series database with a sampling rate of 1 Hz has been available since February 2021, complemented by historical weather forecasts, photovoltaic yield data, and dynamic electricity price signals.

Within the PnP project, the monitoring infrastructure was extended to enable active control of the heat pump and hydraulic system. An optimization server with a MATLAB-based development environment was integrated, providing live data access and bidirectional communication with controllable system inputs. Operation and maintenance are carried out by the University of Applied Sciences Burgenland in cooperation with the building owner. All data are processed in anonymized form in compliance with data protection regulations.

The automation and data acquisition system comprises four functional subsystems:

1. operational data acquisition via a Beckhoff PLC,
2. real-time control algorithm testing via a MATLAB server,
3. integration of forecast and market data via web interfaces, and
4. actuator control for the heat pump and hydraulic components.

2.2 Theoretical Evaluation of Control Strategies

2.2.1 General Procedure

In this project, a plug-and-play control strategy is developed for heat pumps working with thermally activated building systems (TABS).

The goal is to make buildings more flexible and energy-efficient by using local renewable power (for example, from solar panels) and reducing the need for electricity from the public grid. A simplified overview of the concept is shown in Figure 7.

The control system shows how a residential building can support the energy system by converting extra renewable electricity into useful heat. This helps make the most of locally produced energy and supports a low-carbon, grid-friendly operation.

When electricity from the grid is used, the system also considers hourly day-ahead electricity prices, so that heating happens when power is cheaper or renewable resources are available.

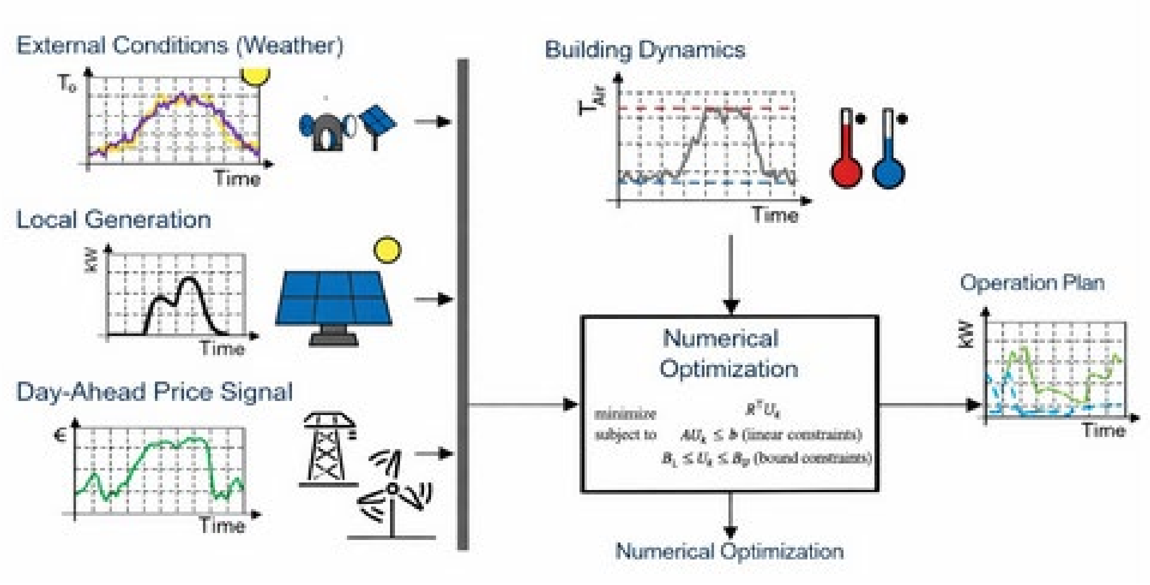

Figure 7: Overview of the Plug-and-Play control strategies (source: FH Burgenland, 2024)

Main Elements of the Control Concept

1. **Forecasts:** The system predicts future conditions such as weather, sunlight, available solar energy, indoor demand, and electricity prices. These forecasts come from public data (like market prices) or from built-in prediction models.
2. **Building Model:** A simplified data-based model represents how the building and heating system store and use heat. It’s designed for typical houses with limited solar gains. The model uses both measured data and expert knowledge.
3. **Optimization Algorithm:** A smart algorithm continuously decides how the heat pump should run in the next hours. It aims to minimize energy costs while keeping comfort high. A special method (MILP – Mixed Integer Linear Programming) finds the best balance between comfort, cost, and available energy.

The control follows a feedforward approach, meaning that all calculations can be done in the cloud — no on-site computing is needed. Only a short setup with past data is required. If unexpected changes occur, a simple local controller can adjust operation in real time.

2.2.2 Pre-Processing

Weather Forecast Data

Weather data for the project are provided by the Open-Meteo API (Open-Meteo API, 2024). This free online service delivers weather forecasts worldwide using the geographical coordinates of a given location — here, the demonstration building. Open-Meteo collects data from official national weather services and automatically combines or selects the most accurate forecasts. It provides variables such as temperature, solar radiation, wind speed, and humidity for the next seven days, which is sufficient for building control purposes.

1. **Weather Models Used:** For sites in Austria, Open-Meteo mainly uses data from the German Weather Service (DWD) and its ICON model family:
    - ICON-D2: Detailed forecasts for Central Europe (2 km, 15 min, up to 2 days).
    - ICON-EU: Europe-wide forecasts (up to 5 days).
    - ICON-Global: Global forecasts (up to 7.5 days).

    The ICON-D2 model is updated every 3 hours at 00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, and 21:00 UTC.
2. **Use in the Control System:** The control algorithm uses several weather parameters:
    - Outdoor air temperature for the building and PV models.
    - Solar radiation, sunrise/sunset times, and wind speed for the PV model.
3. **Data Resolution and Processing:** Weather data are usually available in hourly steps, but the control system uses 15-minute intervals to better match smart meter data and fluctuating solar production. For this purpose, all input data are resampled before each control run.

    Including sunrise and sunset times in the resampling process improves accuracy. Solar radiation values are set to zero before sunrise and after sunset to achieve more realistic results.
4. **Adjustment for Tilted PV Surfaces:** Solar radiation data are used to predict the PV power output. Because PV panels are usually tilted, the data must be adjusted to represent the actual sunlight on the panel surface.

    Since late 2023, Open-Meteo also allows direct requests for tilted radiation data by specifying the panel tilt and orientation (azimuth) in the API call. This new feature can simplify future implementations by reducing the need for manual data processing.

Photovoltaic Power Forecast

To estimate how much electricity the photovoltaic (PV) system will produce, data can either be taken from specialized forecast services (for example Solcast™ – Free Rooftop Solar Power Forecasts, free for non-commercial use) or calculated using in-house models. These models use weather data such as solar radiation, air temperature, and wind speed to predict the expected PV output.

In this project, a simple steady-state model has proven sufficiently accurate. It estimates the PV power output using a linear relationship based on the standard test conditions (STC) of the installed modules.

This simplified model is appropriate because the uncertainty in solar radiation forecasts has a greater effect on accuracy than the complexity of the model itself. The current control system applies this approach successfully.

The main input for predicting PV power is the solar radiation on the tilted surface of the panels. As most weather services provide radiation data for horizontal surfaces, these values must be converted to account for the panel tilt and orientation. This conversion uses a radiation calculator based on the formulas of Duffie and Beckman (Duffie & Beckman, 2013).

Next, the temperature of the PV cells is estimated using the weather conditions, radiation on the tilted surface, outdoor air temperature, and wind speed. Several empirical methods have been published for this purpose. The current implementation uses the approach proposed by Kurtz et al. (Kurtz, et al., 2009).

Finally, the expected PV power output is calculated by adjusting the rated power at standard test conditions according to the estimated cell temperature and the actual solar radiation on the tilted surface. This is done using a simple linear interpolation. To perform this calculation, additional data from the PV module and inverter datasheets are required.

For plug-and-play applications, it is worth noting that most PV modules have similar temperature coefficients, so this parameter does not need to be customized for each individual installation.

Day-Ahead Electricity Prices

Day-ahead electricity prices for the Austrian bidding zone are available from several data providers, each offering their own API or web access. The list below provides an overview of possible data sources (please always check the respective terms of use):

- https://www.awattar.at/services/api or https://energy.tado.com/services/api (API)
- https://www.epexspot.com/en/market-data (web scraping)
- https://transparency.entsoe.eu/ (API)
- https://www.smartenergy.at/api-schnittstellen (API)
- https://www.energy-charts.info/charts/price_spot_market/chart.htm?l=de&c=AT (web scraping)

Prices for the next day are defined at midday and published around 14:00 local time. As a result, the available forecast horizon varies between 10 hours (worst case, just before new data release) and 34 hours (best case, shortly after publication). Depending on the dynamics of the building and heating system, the optimization horizon should cover at least 24 hours. For the demonstration building STBG, the control horizon is set to 72 hours.

Because of this, a short-term forecast of future day-ahead prices is required for most control applications. In the current plug-and-play strategy, the price forecast is based on the average hourly prices of the previous two weeks, separated into weekdays (Mon–Fri) and weekends (Sat–Sun). High accuracy is not critical since prices for the next 10–34 hours are already known from the published day-ahead market.

Day-ahead electricity prices are expressed in €/MWh as traded on the national energy market and represent only the energy cost. To calculate the final electricity price in €/kWh, additional components such as retailer fees, grid charges, taxes, and other costs must be added.

Excurse on negative energy prices: If the energy retailer calculates the total monthly cost by summing all hourly prices, positive and negative prices are combined. Value-added tax (VAT, 20%) is applied to the total monthly amount. If the total monthly balance is positive, the VAT for hours with negative prices must be subtracted on an hourly basis. If the total monthly balance is negative, the VAT handling for negative prices has not yet been clearly defined.

Heat pump efficiency (air-to-water heat-pumps)

The coefficient of performance (COP) of the heat pump directly influences the thermal cost within the control procedure. As most COP dependencies are highly dynamic and would result in non-linear optimization, only pre-estimable and operation-independent influences are considered.

For air-to-water heat pumps, the COP is modeled as a function of the outdoor air temperature using a lookup-table-based approach. Reference COP values are linearly interpolated and may originate from datasheets or historical operational data. For scalability, a generic COP dataset can be applied. For ground-source heat pumps or simplified use cases, the COP may be assumed constant.

Domestic electricity consumption

Domestic electricity consumption is estimated to determine photovoltaic surplus available for heat pump operation. To preserve the plug-and-play concept, standard load profiles are used.

The profile is applied with 15-minute resolution and scaled by annual electricity demand. Simplified constant-load assumptions were also found to yield acceptable results.

Thermal cost estimation

Dynamic boundary conditions (electricity prices, photovoltaic availability, COP) are aggregated into a future thermal cost signal.

For binary heat pump control, thermal costs are calculated prior to optimization. Energy source prioritization follows physical and regulatory rules, with photovoltaic surplus consumed first and grid electricity used subsequently. Electrical costs are converted to thermal costs using the estimated COP.

Model structure

The building is represented by a single-zone first-order thermal model (see Figure 8). Model inputs are the supplied thermal power and the outdoor temperature. The model primarily uses its steady-state component to estimate future heat losses and the building's thermal state for receding-horizon control.

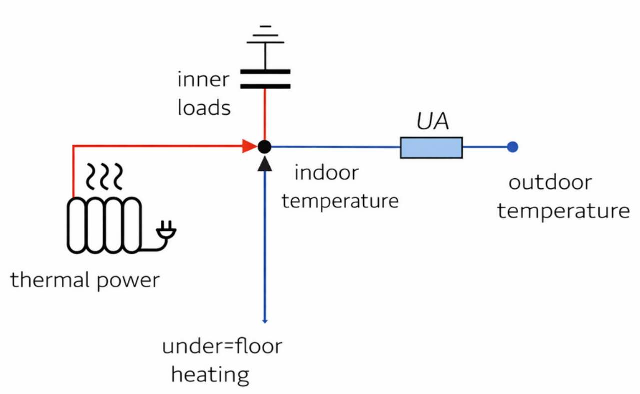

Figure 8: Thermal building model as electrical equivalent circuit diagram (Source: e7 GmbH, 2024)

Dynamic model identification

Model parameters are identified using a non-linear optimization solver (fmincon) by fitting the simulated indoor temperature to historical operational data. Following the low-complexity approach of the PnP concept, the model is not continuously re-identified during operation, and no linear identification procedure is required.

Steady state model estimation

The steady-state model is derived from the dynamic model by assuming zero temperature gradients over time. Under steady-state conditions, the thermal power supplied by the underfloor heating system equals the building's thermal losses. For a defined indoor temperature setpoint, thermal losses can be estimated as a function of the outdoor temperature (see Figure 9).

The steady-state model is used within the control procedure to estimate future heat losses, the required thermal energy input, and the thermal state of charge of the building at the beginning of each receding-horizon optimization.

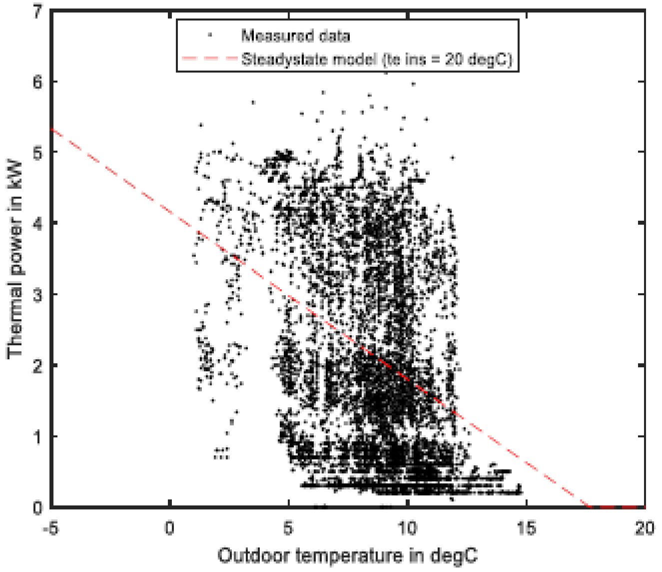

Figure 9: Steady-state thermal model of an exemplary building (Source: FH Burgenland, 2024)

For practical applications, model parameters (e.g. overall heat transfer coefficient and internal gains) can be estimated by installers or operators and adjusted during operation, analogous to conventional heating curve tuning.

2.2.3 Optimization Procedure

The control strategy follows a model predictive control (MPC) approach using a receding horizon principle. At each time step, an optimal operation plan is recalculated by numerical optimization.

The system is simplified to a binary control variable representing the On/Off state of the underfloor heating system. As a result, the optimization problem is formulated as a Mixed-Integer Linear Programming (MILP) problem. The optimization is implemented in solver-based form to ensure portability across programming environments. The formulation follows the Gurobi problem definition and uses only linear objective terms, linear constraints, and bound constraints.

Figure 10 shows a representative optimization result using both the Gurobi solver and the MATLAB solver "intlinprog".

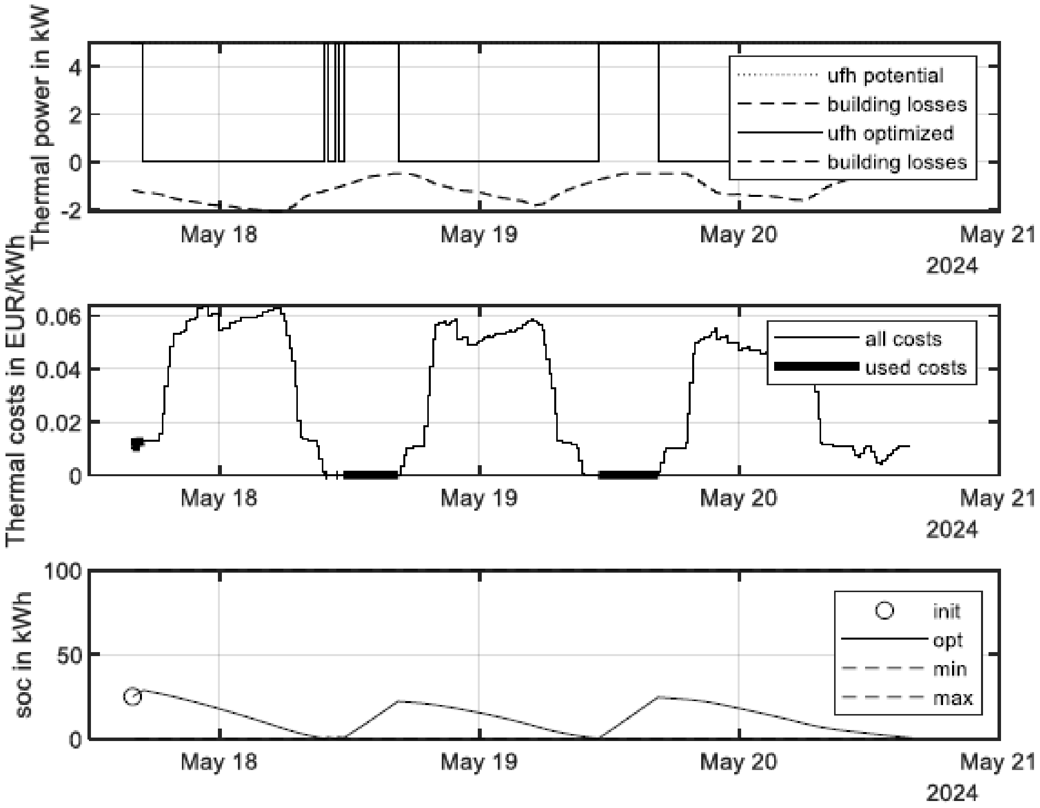

Figure 10: Optimization result of the minimal example (Source: FH Burgenland, 2024)

Objective Function

The objective is to minimize heat pump operating costs over the prediction horizon. The cost function is linear and depends on the binary control variable, the thermal power of the underfloor heating system, the time step length, and the thermal energy price.

The thermal cost signal combines electricity prices, photovoltaic availability, and heat pump efficiency into a single optimization variable, enabling a unified economic assessment.

Linear Constraints

The linear constraints describe the energy balance of the building using a simplified formulation based on conservation of energy. The building is represented by an abstract state of charge, which increases with supplied heating energy and decreases due to thermal losses.

Thermal losses are calculated a priori and higher losses caused by overheating are neglected for simplicity. The constraints ensure that the building state of charge remains within predefined comfort limits for all time steps of the control horizon.

Matrix-based formulations are used to avoid iterative loops and enable efficient computation for longer horizons.

Bound Constraints

Bound constraints restrict the control variable to binary values (On/Off). They are also used to incorporate:

- domestic hot water preparation periods,

- mandatory shut-off or activation commands from grid operators or higher-level control platforms.

Time steps can be blocked by fixing bounds in advance. Care must be taken to avoid infeasible solutions; the use of slack variables may be required in extended applications.

2.2.4 Post-Processing

Setpoint Translation

The optimization results in a binary operation schedule (On/Off) defining when heating should be activated. As heat pumps are often not directly hydraulically connected to the space heating system, the optimized signal must be translated into multiple plant-level setpoints.

Depending on the system configuration, this post-processing step may activate the heat pump compressor, storage charging pumps, heating circuit pumps, and underfloor heating valves (see Figure 11). The required translation logic is system-specific and must be adapted for each application.

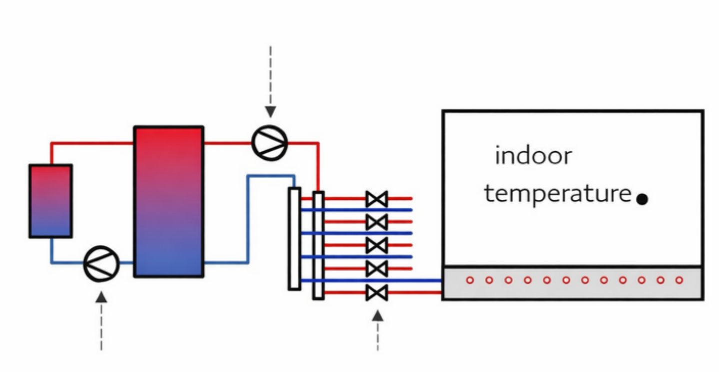

Figure 11: Translation of optimization results into plant-level control inputs (Source: e7 GmbH, 2024)

Possible control actions include:

- direct actuator control (e.g. compressor or pump),
- adjustment of temperature setpoints,
- EVU (grid operator) On/Off signals,
- or combinations of these options.

Combination with Room Temperature Control

If local room temperature controllers are present, the optimized operation plan can be translated into setpoint adjustments for these controllers. This applies to both simple On/Off controllers (e.g. underfloor heating) and PI controllers (e.g. concrete core activation).

This hierarchical approach ensures robust thermal comfort, even in the presence of disturbances, model inaccuracies, or forecast errors at the optimization level, and compensates for the simplifications required in the high-level control formulation.

2.3 Data exchange Platform Development

2.3.1 Requirements and Conceptual Background

Within the PnP Controls TABS research project, it became evident that existing data exchange mechanisms between grid operators, energy suppliers, and operators of electrically driven energy systems are highly fragmented and often based on proprietary or outdated solutions. In particular, the increasing use of flexible electrical loads such as heat pumps requires a standardized, secure, and interoperable communication framework that enables bidirectional data exchange across organizational boundaries.

To address this need, the project consortium developed an **open-source, open-interface communication concept**, referred to as the **Grid Data Manager**. The Grid Data Manager provides a common technical basis for structured data exchange between all relevant actors in the electricity system, while remaining independent of specific manufacturers or vendors.

At its core, the Grid Data Manager acts as a **central coordination instance**, enabling the exchange of forecasts, price signals, load information, and flexibility potentials between grid partners in a transparent and standardized manner.

To ensure a consistent understanding across different stakeholders, the terms in Table 2 are used throughout the project.

Table 2: Terms and definitions of data exchange platform

Grid Data Manager	A server-based software platform that enables standardized and secure data exchange between participating grid partners
User	An end customer or system operator, typically consuming electrical energy (e.g. heat pump systems, charging infrastructure, batteries, building automation systems)
Supplier	An entity supplying electrical energy to users
Grid Partner	Collective term for users and suppliers interacting with the Grid Data Manager
Communication Client	A system component that actively initiates a data exchange
Communication Server	A permanently available counterpart that accepts incoming communication requests

Network Architecture and Connectivity Requirements

A key requirement for participation in the Grid Data Manager ecosystem is reliable and continuous network reachability. To this end, each grid partner must be addressable via a fixed IP address. Since many partners operate behind firewalls or within protected local networks, the Grid Data Manager provides a WireGuard-based Virtual Private Network (VPN) infrastructure.

Using this VPN setup, grid partners can securely connect as WireGuard clients and are assigned predefined internal IP addresses. This approach ensures a stable, encrypted communication channel independent of the public internet configuration of the participants.

The following technical prerequisites apply:

- Both the Grid Data Manager and each grid partner must operate a TCP-based service listening on a predefined port.
- Prior to establishing a secure connection:
    - The **public key of each grid partner** must be registered at the Grid Data Manager.
    - The **public key of the Grid Data Manager** must be stored on the grid partner side.
- All application-level communication must be **fully encrypted**, with the sole exception of two protocol elements used during key negotiation:
    - session_key_request
    - session_key_response

To enable end-to-end encryption, both communication partners require an additional public/private key pair based on the libsodium cryptographic framework. The use of libsodium is mandatory for both key generation and data encryption.

It is important to clearly distinguish between:

- the WireGuard key pair, which is used exclusively for establishing the VPN tunnel, and
- the libsodium key pair, which is used for encrypting and decrypting application data exchanged over the secure connection.

Data Record Format and Error Handling

All data exchanged via the Grid Data Manager follows a unified record structure to ensure robust parsing and interoperability:

1. **Encryption indicator**
    - 'u' for unencrypted payloads
    - 'c' for encrypted payloads
2. **Payload length**, encoded as one or more digits
3. **Delimiter** (:)
4. **Payload**, represented as a JSON object
    - typically encrypted and encoded

In the event of any error during secure connection establishment or key exchange (for example, missing public keys or invalid signatures), the secure connection is immediately terminated without further feedback. This strict behavior is intended to minimize the attack surface and prevent unintended data leakage.

2.3.2 Grid Data Manager – Functional Description

The Grid Data Manager is implemented as a **central server-based software system** and fulfils three primary functional roles:

1. **Provision of external information to users**
   This includes:
    - electricity tariffs,
    - weather forecasts,
    - and grid-related load requirements relevant for thermal energy systems.
2. **Collection of operational data from users**
   Users provide information such as:
    - electrical load curves,
    - available power capacities,
    - and flexibility potentials.
3. **Aggregation and forwarding of data to energy suppliers**
   User data is aggregated in a standardized form and made available to suppliers to support grid operation, forecasting, and market processes.

Communication Setup and VPN Integration

Before any application-level data exchange can take place, each grid partner must establish a secure WireGuard (Donenfeld, 2024) VPN connection to the Grid Data Manager.

For this purpose, each participant receives:

- a predefined VPN IP address,
- the fully qualified domain name of the Grid Data Manager,
- the WireGuard server port,
- and the public key of the Grid Data Manager.

Identification and Cryptographic Security

Grid partners are uniquely identified by their libsodium public keys, not by their VPN credentials. Each participant must therefore generate a dedicated public/private key pair and securely transmit the public key to the Grid Data Manager administrator prior to any data exchange.

Encryption and decryption of application data is performed using:

- crypto_secretbox_easy for encryption, and
- crypto_secretbox_open_easy for decryption.

This ensures confidentiality and integrity of all transmitted data. See available data communications in Table 3).

Table 3: Overview of Grid Data Communication Messages and Security Levels

Message type	Protocol ID	Communication direction	Encryption level
Connection termination	0	Grid Data Manager ↔ Grid Partner	Completed
Echo / keep-alive	1000	Grid Data Manager ↔ Grid Partner	Completed
Session key request	1001	Grid Data Manager ↔ Grid Partner	Not yet available
Session key response	1002	Grid Partner ↔ Grid Data Manager	Partially completed
Weather forecast data	1010	Grid Data Manager → User	Completed
Tariff time slots	1020	Grid Data Manager → User	Completed
Load curve request	1030	Grid Data Manager → User	Completed
Load curve response	1031	User → Grid Data Manager	Completed
Aggregated load report	1032	Grid Data Manager → Energy Supplier	Completed
Power availability report	1040	Energy Supplier → Grid Data Manager	Completed
Power request	1041	Grid Data Manager → User	Completed
Power response	1042	User → Grid Data Manager	Completed

2.3.3 Data Transfer and Scope

The primary purpose of the Grid Data Manager is the structured exchange of data between grid partners. The platform supports the transmission of:

- weather forecasts,
- electricity price signals,
- load curves and consumption forecasts,
- power and capacity requests.

A detailed overview of all transferred data types, including direction, time horizon, temporal resolution, and update frequency, is provided in

Table 4

Table 4: Overview of Data Exchanges Managed by the Grid Data Manager

Data stream	**Weather forecast**	**Electricity tariff**	**Load curve (individual)**	**Load curve (aggregated)**	**Power request (aggregated)**	**Power request (individual)**
Initiated by	Grid Data Manager	Grid Data Manager	Grid Data Manager	Grid Data Manager	Energy supplier	Grid Data Manager
Data provider	Grid Data Manager	Grid Data Manager	User	Grid Data Manager	Energy supplier	Grid Data Manager
Data receiver	User	User	Grid Data Manager	Energy supplier	Grid Data Manager	User
Data content	Outdoor temperature, solar radiation, wind speed	Electricity price	Electric power, electric capacity (positive / negative)	Electric power, electric capacity (positive / negative)	Electric capacity request	Electric capacity request
Time horizon	24 hours	up to 36 hours	24 hours	24 hours	3 hours	3 hours
Temporal resolution	Hourly	15 minutes	1 minute	1 minute	1 minute	1 minute
Update frequency	Hourly	Every 2 hours	On request	Every 15 minutes	On demand	On demand
Primary purpose	Energy consumption forecasting	Cost optimization	Net load scheduling	Net load scheduling	Balancing forecast gaps	Additional cost savings
Remarks	Site-specific data required	Price range supplier-dependent	–	–	–	Transaction required

3 Results of demonstration sites

3.1 Overview of demonstration sites

For data protection and anonymization purposes, all buildings are referenced using four-letter building codes. An overview of the six demonstration sites and their key characteristics is provided in Table 5.

Table 5: Overview and key data of the six demonstration buildings participating in the project

Code	**Proposal**	**Use type**	**Year of construction / refurbishment**	**Heated floor area**	**Heat pump type**	**Heating system**	**PV system**
ENRG	No. 1	Office	2015	~800 m²	Ground-source	Concrete core	Yes
LWRG	No. 2	Office	2020	~800 m²	Ground-source	Concrete core	Yes
STBG	No. 3	Residential	2019	~250 m²	Air-source	Underfloor heating	Yes
URBZ	No. 4	Residential	2015	~200 m²	Ground-source	Underfloor heating	Yes
PLBG	No. 5	Residential	1988 / 2009	~550 m²	Ground-source	Underfloor heating	No
HERZ	No. 6	Residential	2022	~160 m²	Air-source	Underfloor heating	Yes

It should be noted that the demonstration buildings served different roles within the project. Depending on factors such as accessibility for the consortium, cooperation of owners and occupants, available monitoring infrastructure, and controllability of the heat pump and building automation system, each building was assigned the most suitable role. Some buildings were used as development environments, others for experimental validation, and others as reference cases operating without PnP control.

The PnP control strategy addresses four main use-case scenarios, all aiming to shift thermal loads while maintaining defined thermal comfort limits:

- **Improved heat pump efficiency**
  By considering the outdoor-temperature-dependent coefficient of performance and weather forecasts, the optimization prioritizes heat pump operation at higher outdoor temperatures to increase efficiency and reduce defrosting cycles.
- **Increased photovoltaic self-consumption**
  By combining photovoltaic generation forecasts with estimated non-flexible household loads, the control strategy shifts heat pump operation to periods with a high probability of photovoltaic surplus.
- **Reduced operating costs**
  Time-dependent electricity prices, including fixed tariffs, dynamic market prices, and prospective grid fees, are incorporated to minimize heat pump operating costs over the prediction horizon.

- **Grid-friendly operation**
  The control strategy considers hard and soft grid commands, such as shut-on or shut-off requests, while respecting thermal comfort constraints. Both immediate and future grid interactions are handled within the optimization framework.

The project follows a plug-and-play approach with respect to both hardware integration and software deployment. In its final version, a single, generic control logic addresses all use cases individually or in combination. The complete PnP control setup was demonstrated at four of the six building sites, depending on the available technical infrastructure (e.g. heat pump type, photovoltaic system, smart meter, or flexible tariffs).

Table 6 summarizes the specific role of each demonstration building and the corresponding use cases demonstrated with the PnP control strategy.

Table 6: Role of demonstration buildings within the project use cases

Demonstrated use case / role	**ENRG**	**LWRG**	**STBG**	**URBZ**	**PLBG**	**HERZ**
Development environment	✓		✓			
Reference case without PnP control				✓		
Heat pump operation efficiency			✓			✓
Photovoltaic self-consumption		✓	✓	✓		✓
Use of flexible tariffs (energy & grid)		✓	✓		✓	
Grid communication command	Prep.*	Prep.*	Prep.*		Prep.*	Prep.*

** Prep.: Control environment prepared and successfully tested for upcoming hard and/or soft grid commands.*

3.2 Results demonstration site No. 1 (ENRG)

The ENRG demonstration building (Figure 12), located on the campus of the University of Applied Sciences Burgenland, was used during the initial project phase as a living lab environment for the development of a forecast- and optimization-based control strategy following a receding horizon principle.

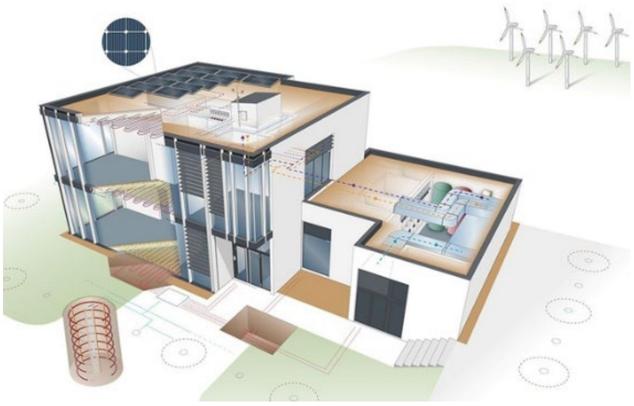

Figure 12: Visualisation of demonstration site No. 1 (ENRG) (Source: FH Burgenland, 2024)

In the early stages of the project, the ENRG site provided a well-instrumented test environment and enabled the development and preliminary validation of the PnP control concept. Over the course of the project, however, it became apparent that the installed HVAC systems and the building automation infrastructure were not representative of typical real-world building applications. In particular, the high degree of controllability—such as continuous room-level thermal load control and detailed monitoring of individual shading systems—exceeded the level of complexity commonly found in standard residential or office buildings.

In addition, the ENRG infrastructure was intensively used for parallel research activities throughout the project period. This resulted in limited availability for extended experimental control campaigns, restricting the execution of long-term or continuous PnP control tests under realistic operating conditions. Nevertheless, the ENRG demonstration building fulfilled an important role as a development environment. It provided extensive monitoring data, stable data access, and a flexible platform for early-stage algorithm development and testing. As the project advanced, experimental validation activities were progressively shifted to more representative demonstration sites, in particular the residential building STBG. Consequently, the final demonstration of the latest PnP control implementation was not carried out at the ENRG site.

3.3 Results demonstration site No. 2 (LWRG)

At the demonstration site LWRG (Figure 13), two PnP use cases were demonstrated:

- operation with flexible electricity import tariffs only, and
- a combined use case including flexible tariffs and photovoltaic self-consumption.

Figure 13: Visualisation of demonstration site No. 2 (LWRG) (Source: FH Burgenland, 2024)

Due to significant delays in the building commissioning, LWRG became available to the project only at the end of 2024. At the time of the final demonstration, parts of the hydraulic system and the building automation were still not fully operational. Nevertheless, the two PnP control scenarios illustrated in Figure 14 were successfully tested.

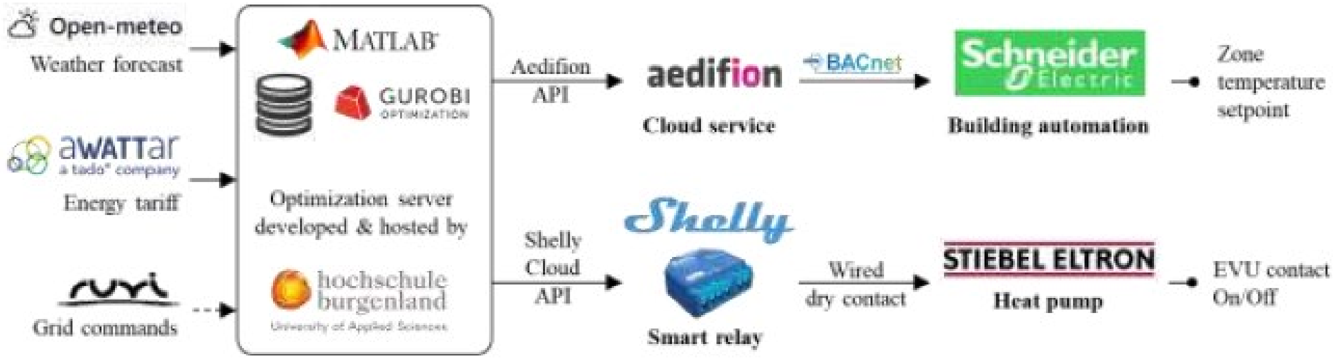

Figure 14: Automation and communication setup for the final PnP control demonstration in the LWRG building (Source: FH Burgenland, 2024)

In the first scenario, the optimization server was connected to the building automation system via a cloud-based service interfacing with the local BACnet network. In this configuration, the PnP control logic adjusted temperature setpoints for four thermal zones. In the second scenario, optimization results were implemented through a Shelly smart relay (Shelly smart relay, 2024), connected to the EVU contact of the heat pump, enabling direct On/Off control.

As no monitoring data from the local photovoltaic system were available, solar generation was estimated using historical radiation data for the site combined with a simple steady-state model scaled to the installed module capacity.

The heat pump at LWRG supplies not only the concrete core activation system but also provides heating and cooling for ventilation systems serving laboratories and computing clusters. As a result, the available flexibility is lower than in purely residential buildings. Despite favourable building characteristics, such as high insulation standards and concrete core activation, the operational use case limits the overall flexibility potential. This represents an important finding from the final demonstration activities.

Figure 15 compares the standard, non-optimized heat pump operation with the estimated solar generation and assumed variable electricity import tariffs. Despite the use of modern inverter technology, the heat pump exhibits frequent cycling behaviour.

In Figure 16, the PnP control logic is activated considering flexible electricity import tariffs only. The optimization effectively avoids operation during periods with high electricity prices. For example, on January 2nd, available solar generation is deliberately not used due to unfavourable price conditions.

In Figure 17, the PnP control logic is extended to consider both flexible tariffs and solar generation. The results again show a reasonable load-shifting behaviour. However, once the building's thermal storage capacity is fully charged during solar-rich periods, cycling operation reappears.

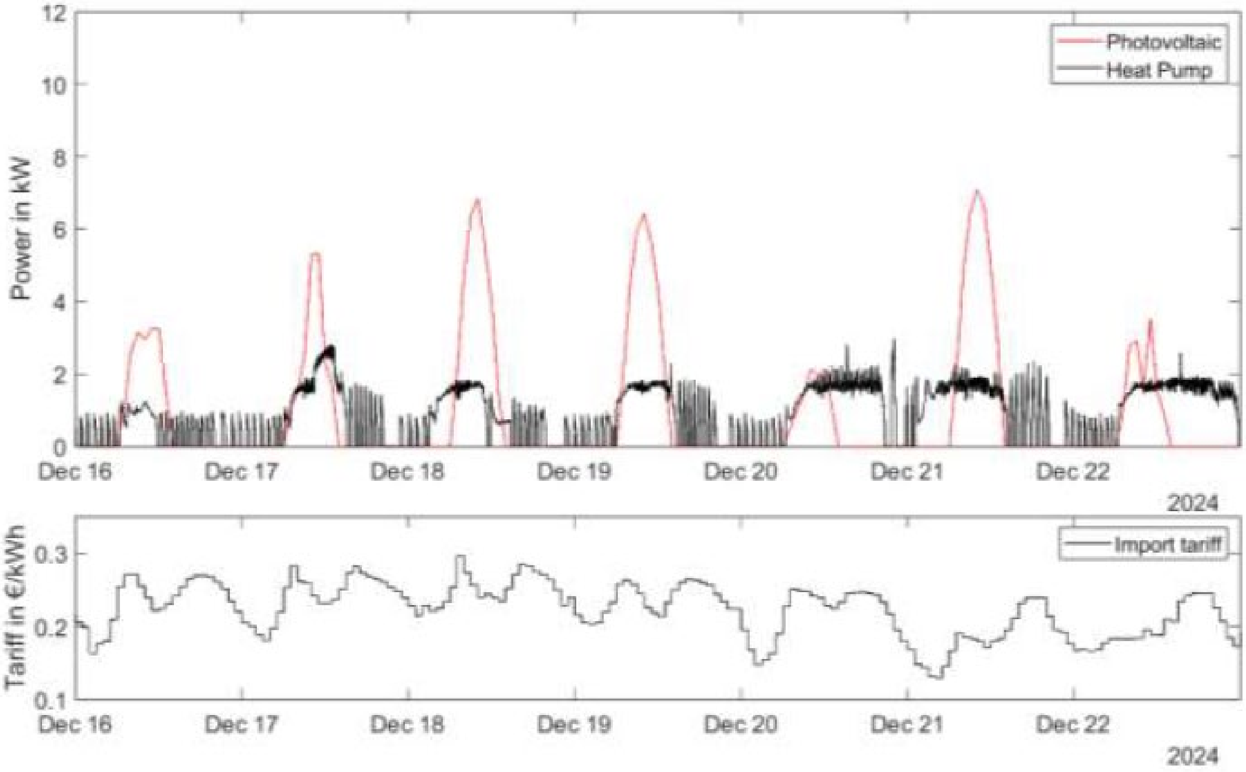

Figure 15: Heat pump operation without optimization compared to estimated solar generation and variable electricity tariffs (Source: FH Burgenland, 2024)

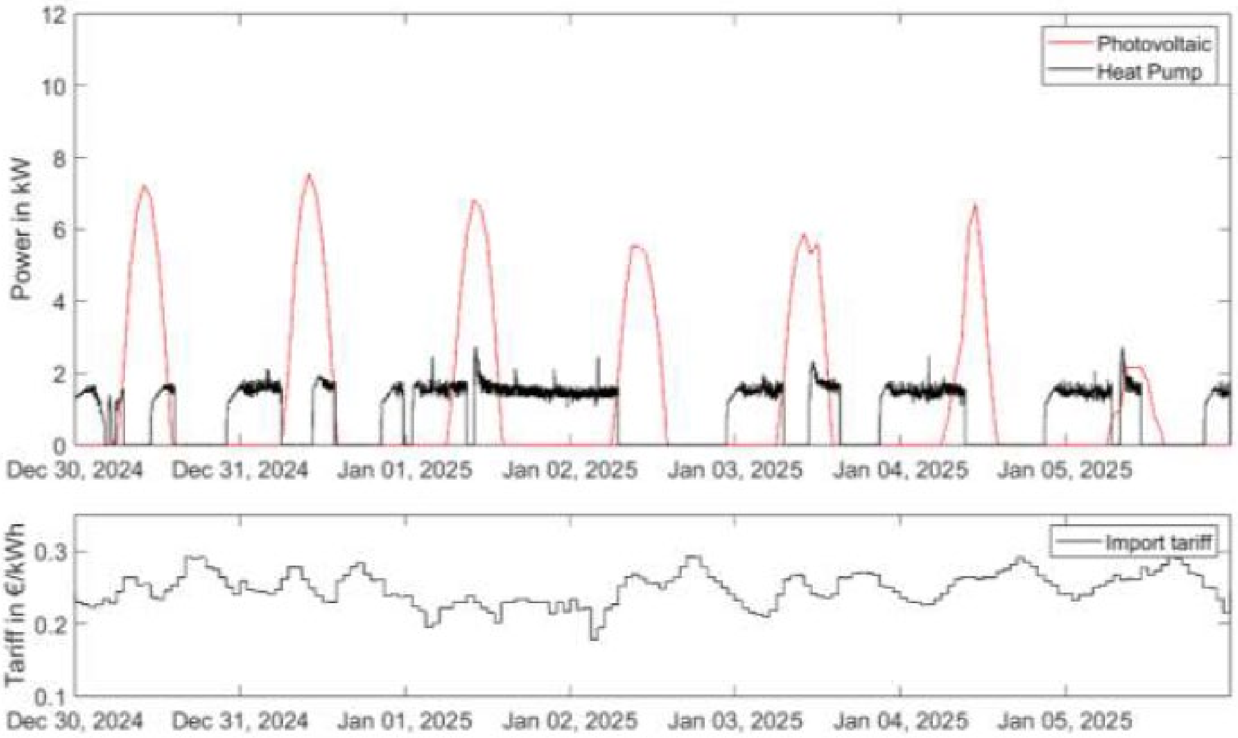

Figure 16: Optimized heat pump operation considering flexible import tariffs only (Source: FH Burgenland, 2024)

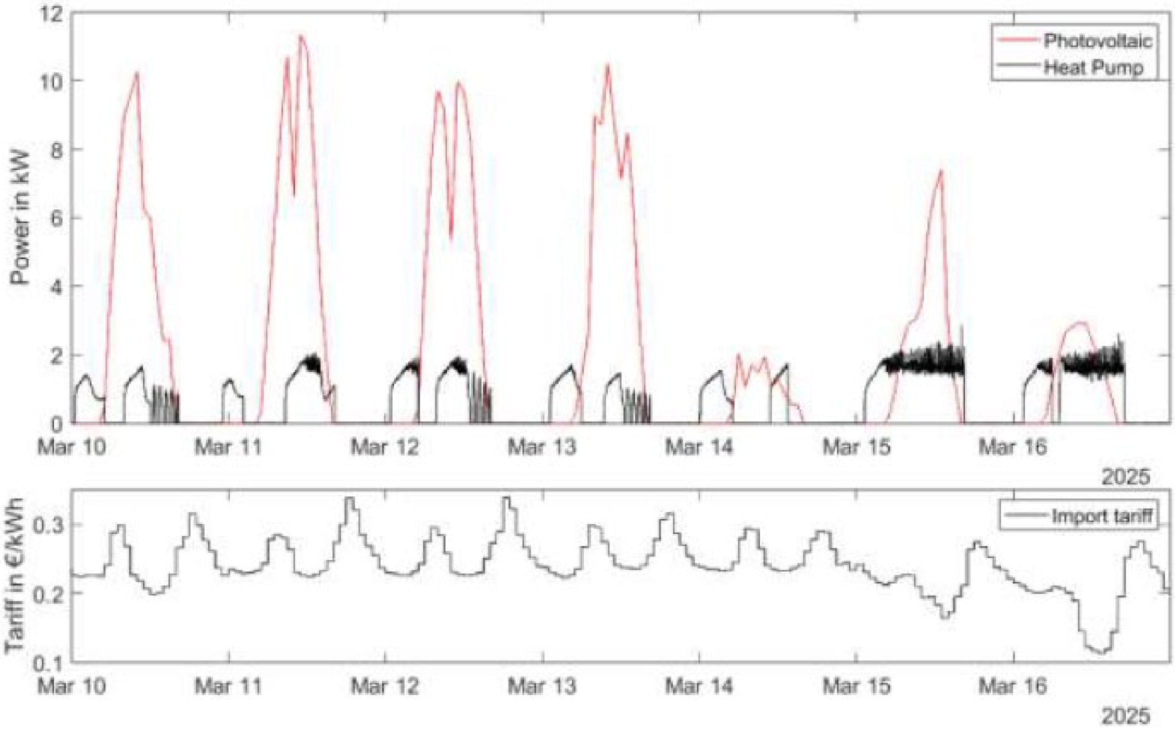

Figure 17: Optimized heat pump operation considering flexible import tariffs and solar generation (Source: FH Burgenland, 2024)

Overall, the application of load-shifting strategies reduces cycling behaviour, although it primarily mitigates symptoms rather than addressing the underlying causes related to system design and utilization.

Due to the limited duration and non-continuous nature of the available data from the final demonstration period, a quantitative performance analysis could not be carried out for the LWRG site.

3.4 Results demonstration site No. 3 (STBG)

The demonstration building STBG (Figure 18) served as the main experimental development and validation site for the PnP control algorithm.

Figure 18: Visualization of demonstration site No. 3 (STBG) (Source: FH Burgenland, 2024)

STBG was particularly well suited as a development and demonstration environment, as all four project use cases (Table 6) could be addressed within this setup. The building is equipped with an air-to-water heat pump that exhibited reduced performance due to refrigerant-related issues, resulting in frequent defrosting and low efficiency at outdoor temperatures below approximately 5 °C. This characteristic provided a high potential for efficiency improvements through optimized operation at higher outdoor temperatures.

A 15 kWp rooftop photovoltaic system is installed, and since 2023 the building has been operated under variable electricity tariffs based on the Austrian day-ahead spot market. In addition, comprehensive monitoring and control infrastructure was available, partly installed specifically for the project. The comparatively high ratio between photovoltaic generation and heat pump electricity demand makes STBG a representative case for future residential energy systems with high self-consumption potential.

Despite the extensive monitoring infrastructure used during development, the final demonstration interface was intentionally kept simple, in line with the Plug-and-Play concept. As shown in Figure 19, the PnP optimization server connects to external services for weather forecasts (Open-Meteo API, 2024), electricity prices (AWWATTAR, 2024), and grid communication (platform developed by consortium member ruvi), and continuously runs optimization routines using Gurobi (Gurobi Optiization, 2024) within a MATLAB environment (Matlab, 2024).

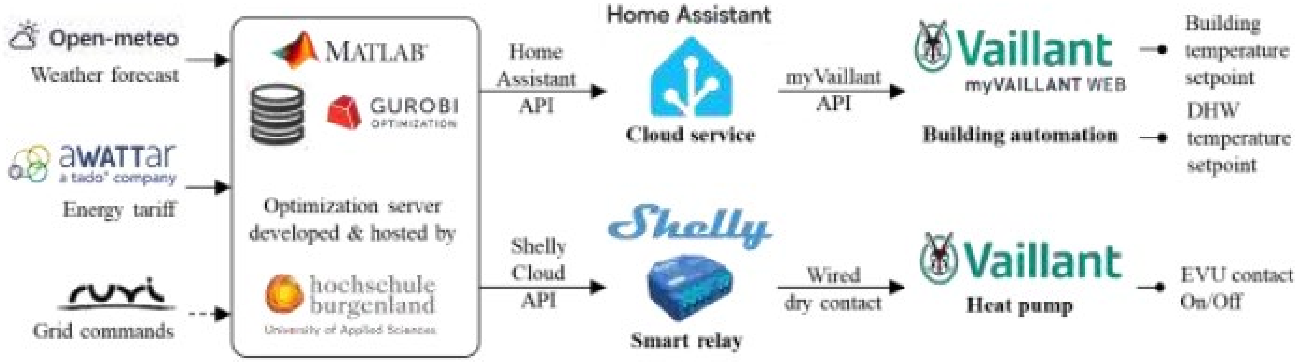

Figure 19: Automation and communication setup for the final PnP control demonstration in the STBG building (Source: FH Burgenland, 2024)

During the 2023/2024 heating season, optimization results were implemented via a binary EVU On/Off signal using a smart relay (Shelly smart relay, 2024). In the 2024/2025 season, the integration was extended through Home Assistant (Home Assistant, 2024), allowing the translation of optimization results into temperature setpoint adjustments for space heating and domestic hot water.

An important practical insight was that direct heat pump blocking via EVU contact requires conservative control settings, as thermal comfort violations cannot be corrected once the heat pump is disabled. In contrast, setpoint-based control allows local building automation systems to compensate for disturbances, enabling more aggressive and effective high-level optimization strategies with improved overall performance.

To illustrate the results, exemplary data from the 2023/2024 heating season are presented, as data from 2024/2025 have not yet been fully analyzed. Figure 20 compares the heat pump electricity consumption under PnP control with available photovoltaic generation and variable electricity prices. For generalization purposes, non-flexible household loads are neglected, and all photovoltaic energy is prioritized for heat pump operation. For reference, the heat pump consumption profile from the 2021/2022 heating season using standard control is shown.

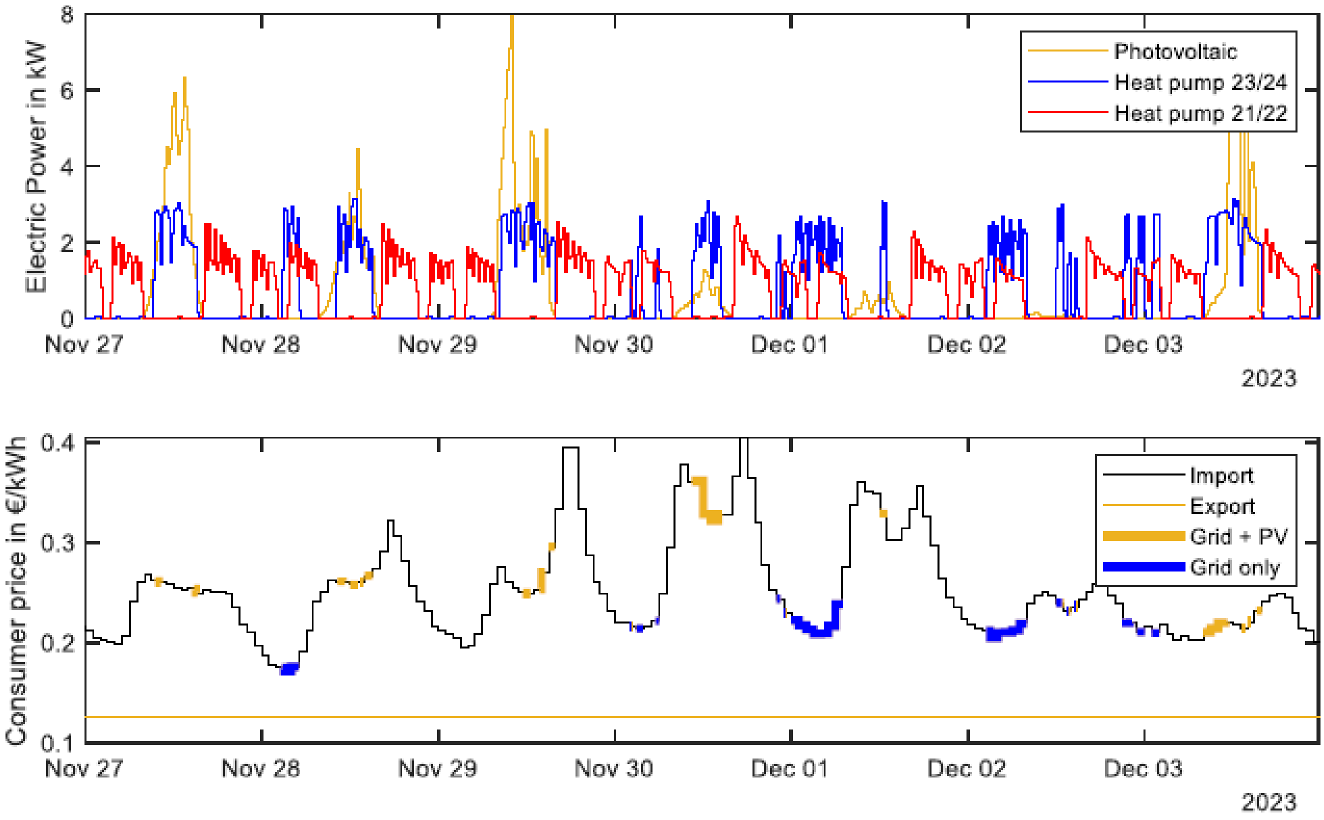

Figure 20: Qualitative comparison of heat pump consumption profiles under PnP control (2023/24) and standard control (2021/22) (Source: FH Burgenland, 2024).

The results show that the PnP control strategy systematically shifts heat pump operation towards periods with high photovoltaic availability or low electricity prices. In contrast, standard outdoor-temperature-based control largely bypasses photovoltaic potential and benefits from low electricity prices only incidentally. Even a single representative week highlights the significant potential of demand-side management for residential heat pump systems.

A more detailed analysis over a six-month heating period is shown in Figure 21. The mean daily load profile reveals a pronounced shift in operation times under optimized control. The cumulative load curves further indicate that cost-optimized operation can increase peak loads if no explicit load-limiting constraints are applied. This finding is relevant for grid operation and highlights the importance of combining price-based incentives with appropriate grid fee structures.

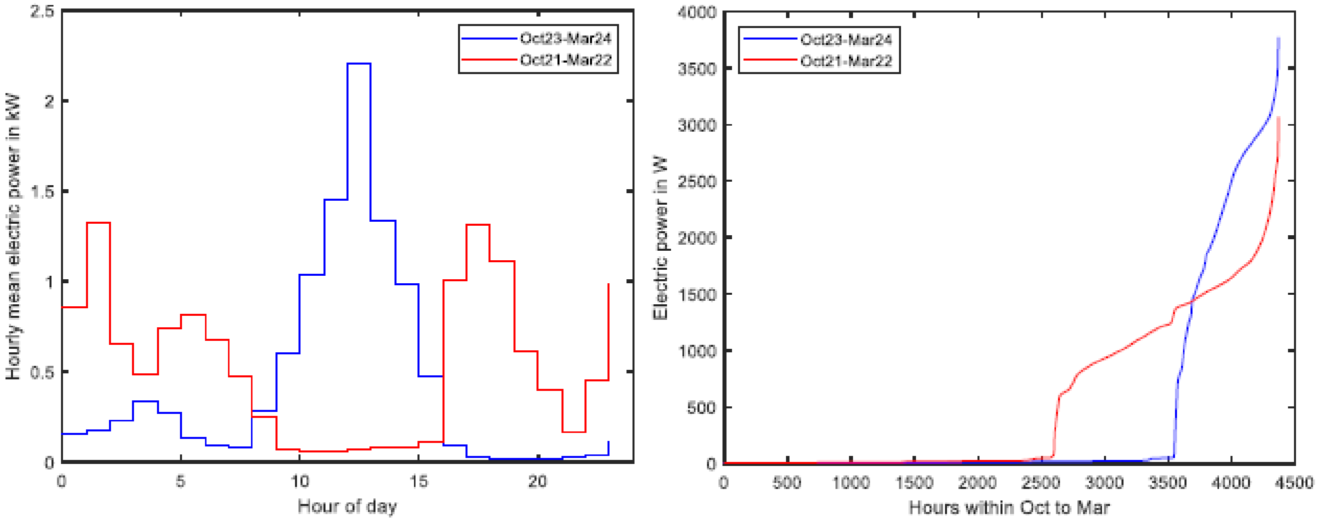

Figure 21: Analysis of optimized and standard heat pump operation over a six-month heating period (Source: FH Burgenland, 2024)

The quantitative comparison in Table 7 demonstrates the overall performance improvements. For consistency, photovoltaic generation and electricity prices from 2023/2024 were applied to the 2021/2022 reference profile. Direct photovoltaic self-consumption increased from below 10 % to over 70 %. Although the building includes a battery storage system, only direct photovoltaic consumption was considered in this analysis.

The primary optimization objective was cost reduction, accounting for photovoltaic opportunity costs and variable electricity tariffs (OEMAG, 2024). Total operating costs over the six-month period were reduced by approximately 50 % when opportunity costs were considered, and by up to 75 % when opportunity costs were neglected. Depending on assumptions, specific electricity cost reductions between 40 % and 70 % were achieved. These results were obtained with minimal installation effort and without continuous data transfer from the building to the optimization server.

Table 7: Quantitative performance analysis of optimized and standard control strategies at STBG

	Oct 2023 – Mar 2024		**Oct 2021 – Mar 2022**	
Heat pump electricity consumption	**1,861 kWh**	**(100.0 %)**	**2,351 kWh**	**(100.0 %)**
from grid	536 kWh	(28.8 %)	2,171 kWh	(92.3 %)
from photovoltaic system	1,326 kWh	(71.2 %)	180 kWh	(7.9 %)
Photovoltaic generation	6,828 kWh	(366.8 %)	6,828 kWh	(290.4 %)
Operating costs				
incl. opportunity costs of PV	212.29 €		423.86 €	
excl. opportunity costs of PV	94.34 €		411.70 €	
Specific electricity costs				
incl. opportunity costs of PV	0.1141 €/kWh	(62.3 %)	0.1803 €/kWh	(100.0 %)
excl. opportunity costs of PV	0.0507 €/kWh	(29.9 %)	0.1751 €/kWh	(100.0 %)

Finally, thermal comfort was assessed qualitatively using indoor temperature measurements at two representative locations Figure 22. Indoor air temperatures remained comparable for both control strategies, indicating no negative impact on thermal comfort. However, occupants reported noticeable changes in floor surface temperatures, which were not captured by air temperature measurements alone. This observation highlights a key project finding: air temperature alone is insufficient to fully describe thermal comfort, particularly under dynamic load-shifting conditions.

This insight supported the decision to exclude indoor temperature measurements from the final PnP control logic, improving scalability and reducing hardware requirements. Thermal comfort assurance is instead delegated to local control systems, while the PnP algorithm operates as a high-level energy management layer.

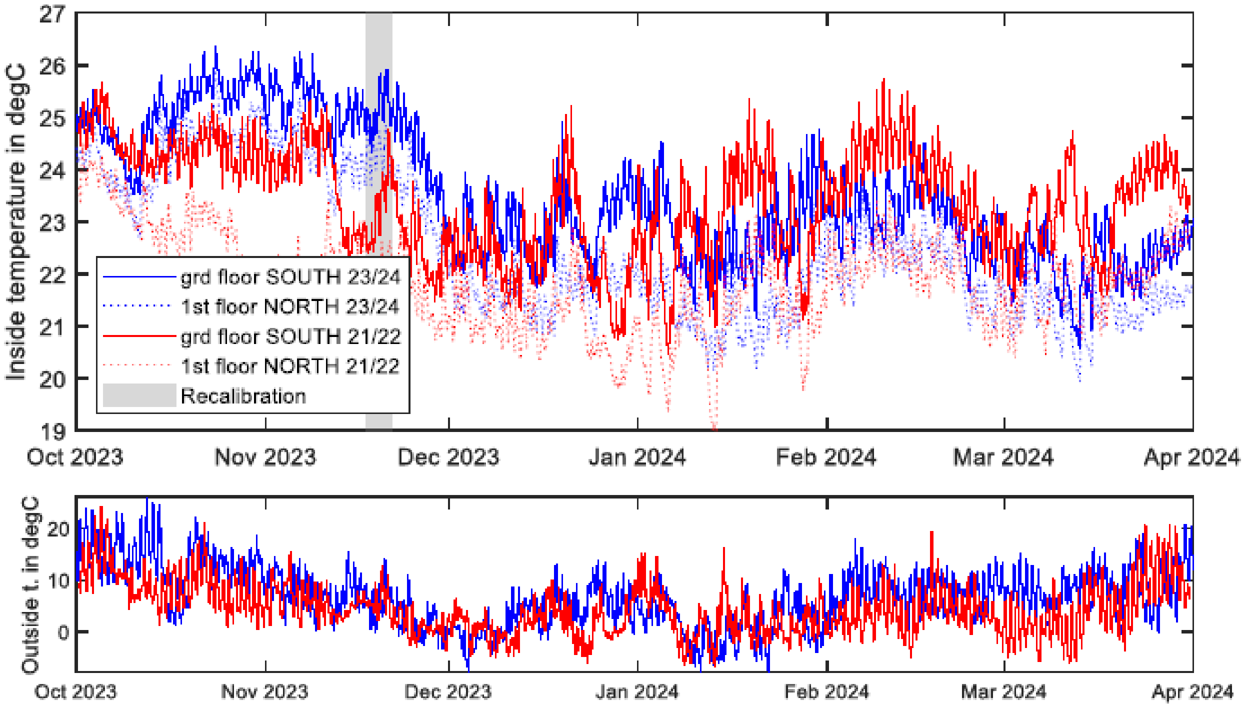

Figure 22: Comparison of indoor temperatures under optimized and standard control strategies (Source: FH Burgenland, 2024)

3.5 Results demonstration site No. 4 (URBZ)

The demonstration site URBZ (Figure 23) was used in the project as a reference case to assess the performance of control strategies that do not rely on forecasting or optimization-based decision making.

Figure 23: Visualization of demonstration site No. 4 (URBZ) (Source: FH Burgenland, 2024)

The building is equipped with a sufficiently sized photovoltaic system and a ground-to-water heat pump with near-surface ground collectors. Both systems are integrated into a local Loxone-based building automation and smart home environment, which includes a sophisticated energy management system (EMS) developed and operated by the building owner.

The EMS adjusts heat pump operation based solely on real-time surplus photovoltaic power at the grid connection point. When surplus power is available, temperature setpoints for space heating and domestic hot water are increased to maximize photovoltaic self-consumption. Compared to manufacturer-provided surplus heating functions, the applied control settings are relatively aggressive, supported by fallback strategies and priority rules to ensure thermal comfort.

From a control perspective, the system operates close to the technical performance limits of static, rule-based control, without requiring forecasts, numerical optimization, or continuous historical data. All decisions are based on real-time measurements, and the EMS runs locally without any internet connection.

Due to system security constraints, the installed Loxone automation did not allow external access from the project’s optimization server, and integration of the PnP control logic was therefore not possible. Nevertheless, the available monitoring data supported algorithm development, and the URBZ site serves as a benchmark for alternative demand-side management strategies.

Figure 24 shows a time-series analysis of heat pump electricity consumption and photovoltaic generation during two representative weeks: a “warm” week at the beginning of the heating season and a “cold” week in December. In both cases, heat pump operation aligns closely with photovoltaic generation, resulting in high self-consumption rates. During periods of low heating demand, the heat pump is almost entirely supplied by photovoltaic energy. As demand increases, operation shifts to early morning hours, driven by outdoor-temperature-based control. Coincidentally, these hours often correspond to low electricity prices, although this effect is not explicitly considered in the control logic.

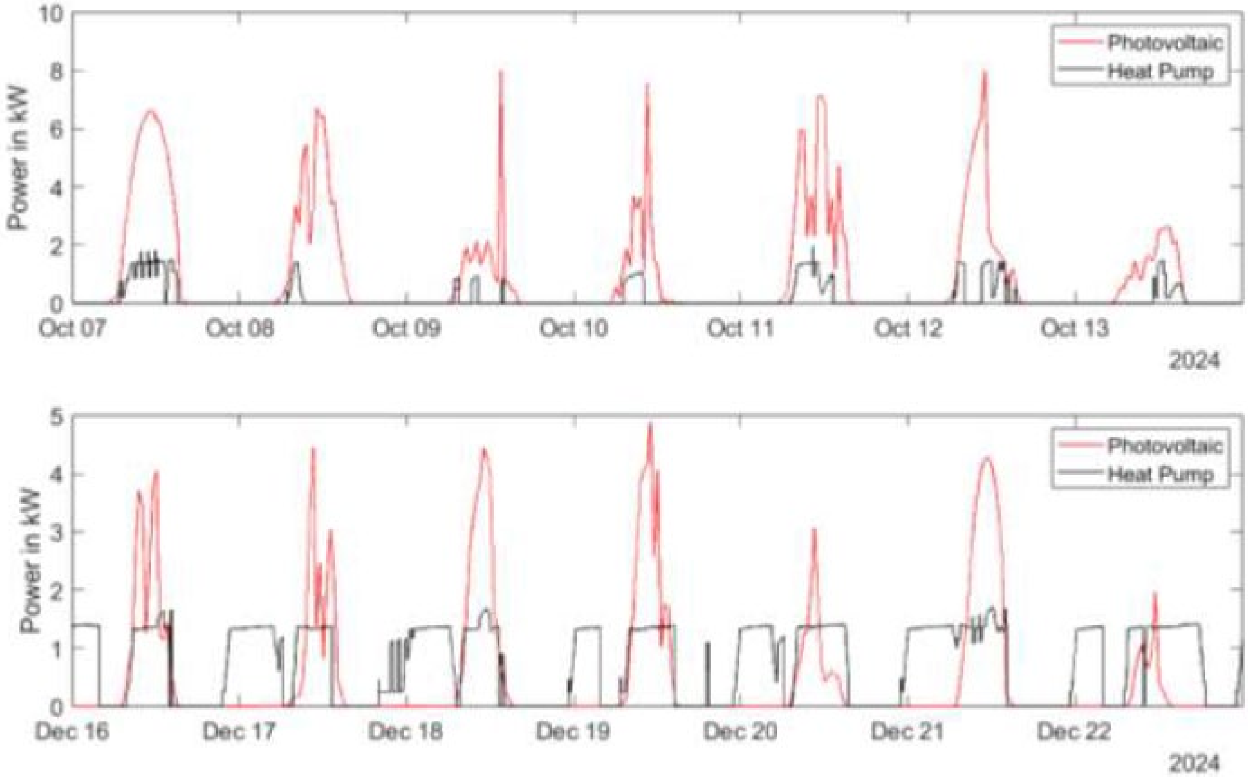

Figure 24: Time-series analysis of photovoltaic generation and heat pump consumption at URBZ during representative warm and cold weeks (Source: FH Burgenland, 2024)

A key project finding is that maximizing photovoltaic self-consumption alone can be effectively achieved using simple, locally operated control strategies without forecasts or optimization. As shown in Table 8 the heat pump achieved approximately 40 % photovoltaic self-consumption over two heating periods from October to February.

Table 8: Quantitative performance analysis of two heating periods using the reference control strategy at URBZ.

Category	**Oct 2023 – Feb 2024**		**Oct 2024 – Feb 2025**	
Heat pump electricity consumption	**1,852.5 kWh**	**(100.0 %)**	**2,352.8 kWh**	**(100.0 %)**
from grid	1,001.8 kWh	(54.1 %)	1,419.1 kWh	(60.3 %)
from photovoltaic system	850.7 kWh	(45.9 %)	933.7 kWh	(39.7 %)
Photovoltaic generation	**2,595.6 kWh**	**(100.0 %)**	**2,373.6 kWh**	**(100.0 %)**
used by heat pump	850.7 kWh	(32.8 %)	933.7 kWh	(39.3 %)

From a cost–benefit perspective, this simple and robust approach is highly effective and helps explain why more complex optimization-based control strategies have so far seen limited market adoption. Nevertheless, comparison with optimized operations at other sites (e.g. STBG) shows that additional savings are achievable when multiple objectives are considered.

As of early 2025, photovoltaic self-consumption remains the most economically attractive single objective. However, with increasing price volatility and higher electricity price levels, multi-objective control strategies will become increasingly important. The developed PnP algorithm addresses this need by combining photovoltaic self-consumption, flexible tariffs, efficiency optimization, and grid-friendly operation within a single, scalable control framework that goes beyond the capabilities of purely local, rule-based controllers.

3.6 Results demonstration site No. 5 (PLBG)

The demonstration site PLBG (Figure 25) was used to exclusively investigate the use case “flexible electricity tariffs”, as no photovoltaic system is installed. The site demonstrates the plug-and-play integration of the PnP control setup into an approximately 15-year-old heat pump system.

Figure 25: Visualization of demonstration site No. 5 (PLBG) (Source: FH Burgenland, 2024)

The building is equipped with a ground-to-water heat pump using near-surface ground collectors. Due to an outdated insulation standard and a large heated floor area, the building exhibits a high heating energy demand. At the beginning of the project, an extensive long-term monitoring campaign was initiated to analyse heat pump operation and building dynamics.

For the final demonstration, a minimal hardware and software setup was applied (Figure 26). The optimization results were transmitted from the PnP server to the heat pump via a Shelly smart relay (Shelly smart relay, 2024), which controlled the EVU contact to block selected operating hours.

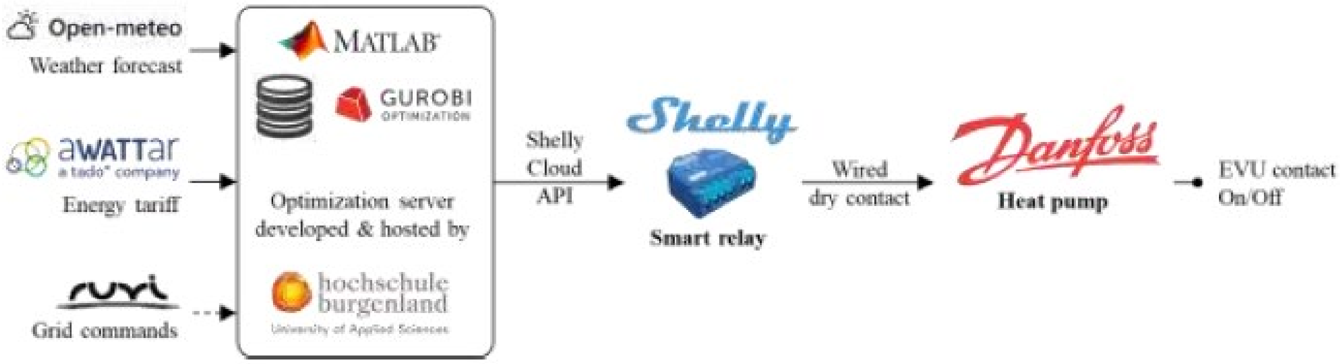

Figure 26: Automation and communication setup for the final PnP control demonstration in the PLBG building (Source: FH Burgenland, 2024)

The final demonstration was conducted over approximately three months during the 2024/2025 heating season. During this period, two server failures occurred, causing unplanned heat pump shutdowns for several hours and leading to thermal discomfort for the occupants. After the second incident, participation in the project was discontinued. These failures were caused by the experimental software infrastructure and not by the optimization algorithm itself, which was the main focus of the project.

The incidents highlighted the importance of robust local fallback strategies for a future market-ready plug-and-play solution:

- The optimization typically generates an operation plan covering several days. If communication fails, this plan can bridge short outages.
- For outages exceeding the control horizon, a fallback mode should release the EVU contact and allow the local controller to maintain minimum thermal comfort.

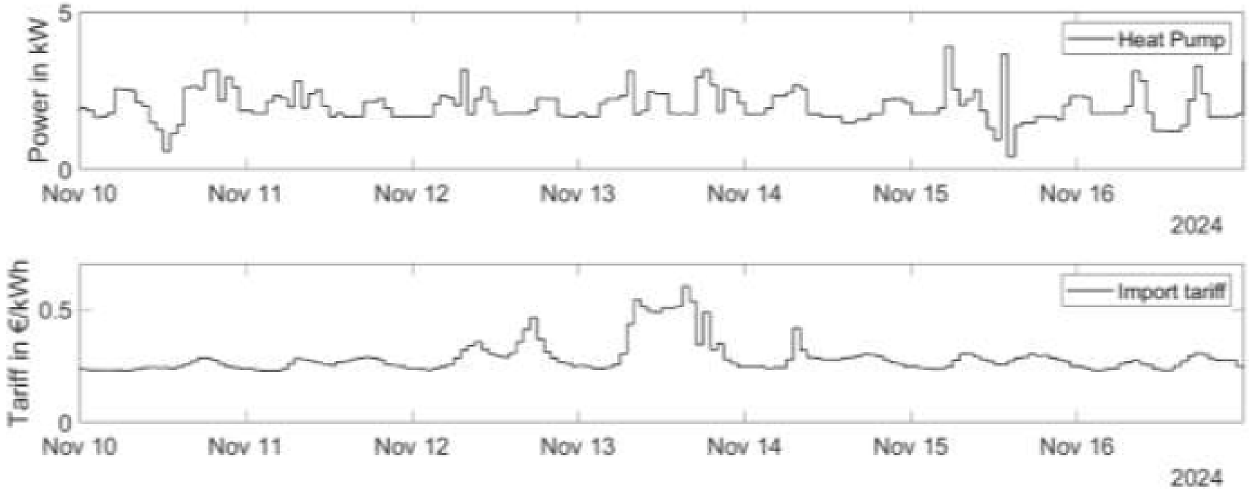

Figure 27: Heat pump operation without PnP control at PLBG (Source: FH Burgenland, 2024)

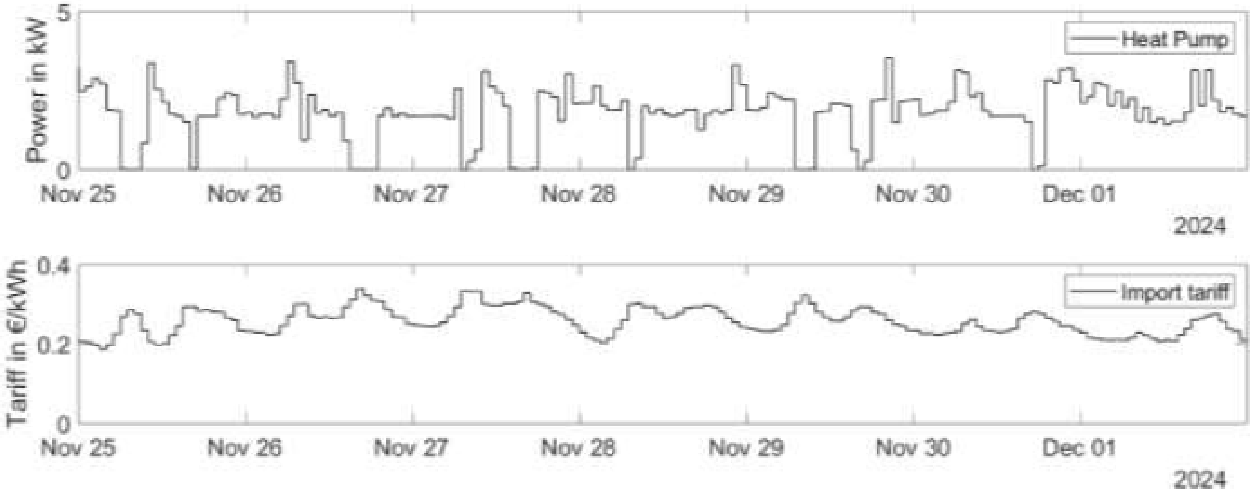

Figure 28: Heat pump operation with PnP control during moderate tariff variability (Source: FH Burgenland, 2024)

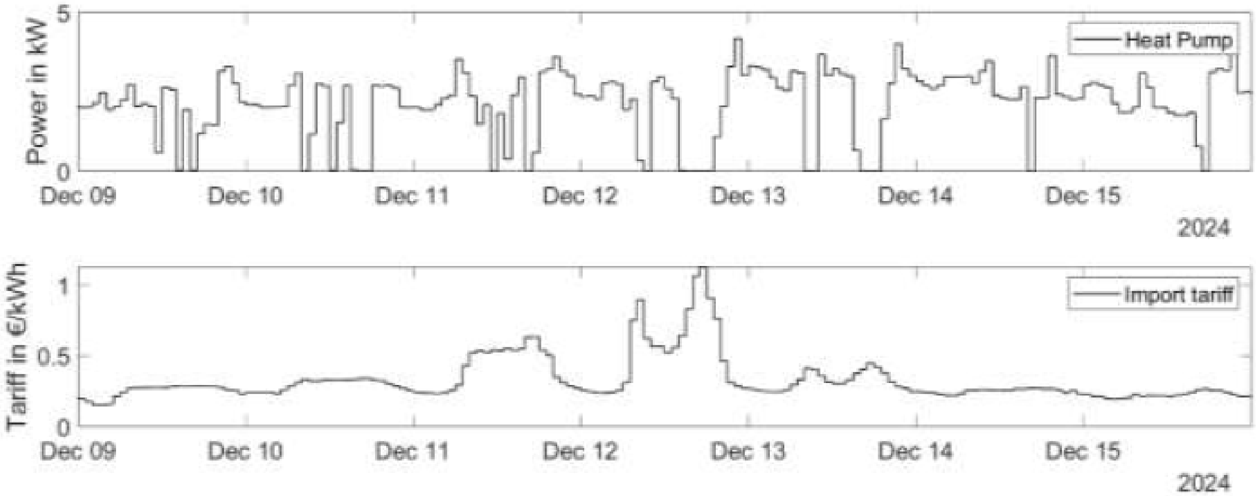

Figure 29: Heat pump operation with PnP control during high tariff variability (Source: FH Burgenland, 2024)

Figure 27, Figure 28 and Figure 29 present representative time-series analyses of heat pump electricity consumption and variable electricity tariffs. In the first week shown (November), the PnP control was inactive, resulting in near-continuous heat pump operation. In the following week, with active PnP control and moderate tariff variability, operation during high-price periods was blocked, leading to more pronounced load peaks. In December, when electricity prices exceeded 1 €/kWh, the PnP control reliably blocked heat pump operation for several hours, already approaching the comfort limits of this less flexible building.

Overall, the PLBG demonstration shows that in buildings with limited flexibility and high heating demand, the PnP control strategy can only block operation during a small number of very high-price hours. Consequently, the achievable cost-saving potential is limited, estimated at below 10 % for heat pump operating costs over the winter period. In addition, fluctuations in wholesale electricity prices are dampened at the consumer level by fixed grid fees, charges, and taxes, further reducing the economic impact of tariff-based load shifting.

3.7 Results demonstration site No. 6 (HERZ)

The HERZ demonstration building (Figure 30) was included in the project to demonstrate the interaction between the PnP control logic and the internal building automation of a new generation of HERZ heat pumps.

Figure 30: Visualization of demonstration site No. 6 (HERZ) (Source: FH Burgenland, 2024)

The interface between the PnP optimization server and the internal HERZ heat pump controller was implemented using Shelly smart relays, as shown in Figure 31 Due to the digital nature of the PnP control signal, simple On/Off switching was sufficient. The Shelly cloud infrastructure had already been successfully used in other demonstration sites.

To control both space heating and domestic hot water preparation, two Shelly relays were connected to dedicated digital inputs of the HERZ heat pump controller. A third relay was connected to the EVU contact, but this interface was not used in the final demonstration.

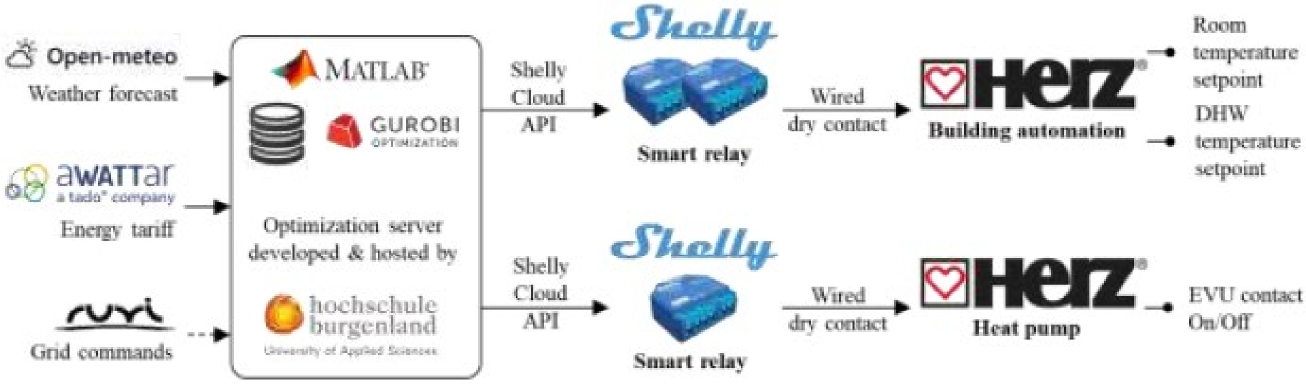

Figure 31: Automation and communication setup for the final PnP control demonstration in the HERZ building (Source: FH Burgenland, 2024)

Figure 32 shows a screenshot of the software implementation within the HERZ heat pump controller, illustrating the integration of the external PnP control inputs.

X52 Boiler SG Üh x001 0 °C
X54 HK SG Raum-Soll Üh x002 2 °C x003 0 °C
X54 HK SG VL-Soll Üh x002 0 °C x003 0 °C
X45 Externer Halt
X46 Smart Grid 1
X47 Smart Grid 2

Figure 32: Software implementation of the PnP control logic in the HERZ heat pump controller (Soure: ruvi e.U., 2024)

As monitoring data from the local photovoltaic system were not available, solar generation was estimated using historical radiation data for the site and a simple steady-state model scaled to the installed module capacity.

Figure 33 presents two representative weeks of heat pump operation. During the first week, the heat pump operated under the standard HERZ control strategy, showing near-continuous operation with regular defrosting cycles and periodic domestic hot water preparation. In the second week, the PnP control logic was activated. The optimization aimed to increase photovoltaic self-consumption and improve operational efficiency based on a predefined correlation between the coefficient of performance and outdoor temperature. As a result, the heat pump load profile changed noticeably, indicating increased load shifting and higher solar utilization.

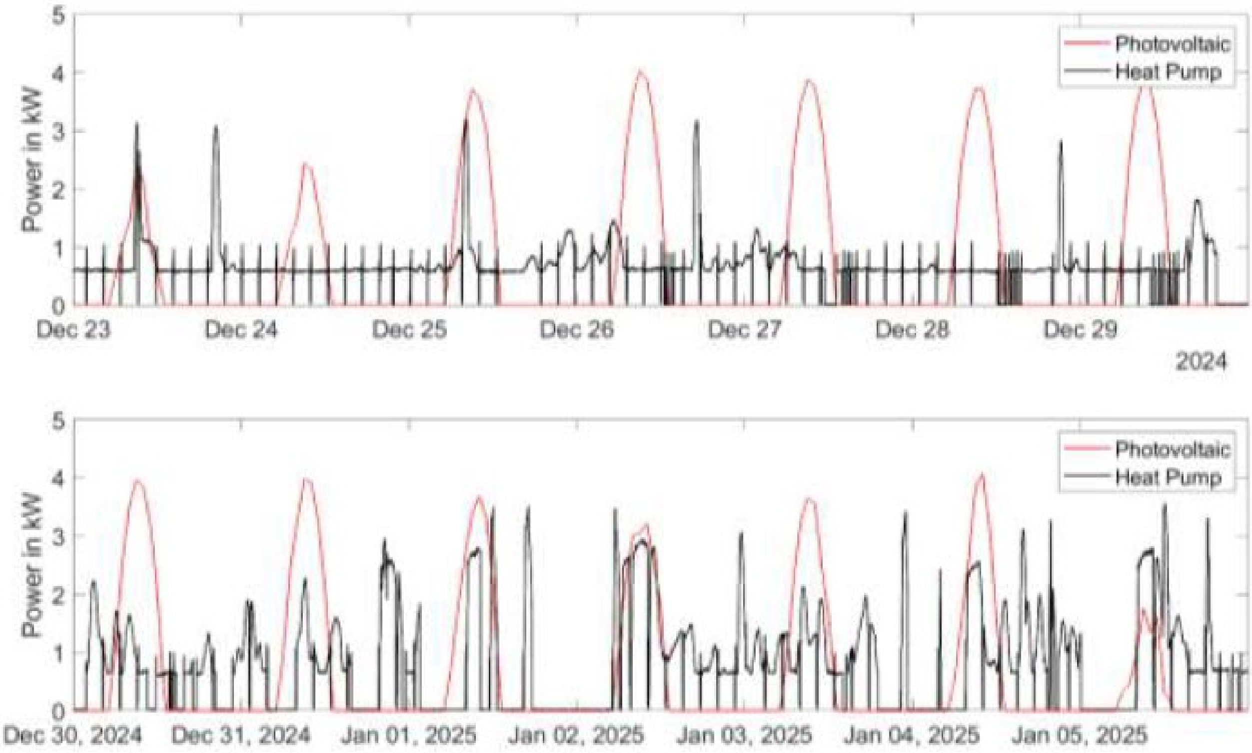

Figure 33: Comparison of heat pump operation before and after activation of the PnP control logic at the HERZ site (Source: FH Burgenland, 2024)

The final demonstration at the HERZ building was conducted over several weeks during the 2024/2025 heating season. Overall, the results were limited. To avoid potential thermal comfort violations, the PnP control parameters were configured conservatively. Consequently, the degree of thermal load shifting remained small and the resulting effects were modest.

In addition, occupant interaction with the control settings significantly influenced the outcome. In several cases, users manually overrode or modified parameters suggested by the PnP control logic. For example, proposed night-time operation during cold periods was rejected by occupants, and changes to domestic hot water setpoints led to unintended operating conditions. As no feedback loop from the heat pump to the PnP optimization server was implemented, these interventions could not be automatically detected or compensated.

These experiences provided an important project insight: although load-shifting strategies are designed to operate transparently, user perception and interaction remain critical factors. Even small changes in operating behaviour can affect acceptance and system performance. Continuous user communication and clarification therefore represent an important complement to technically sound control strategies, particularly for market-ready implementations.

4 Tendering Approaches and Relevance for the Project

Depending on the specific project context and the objectives of the client, tendering procedures can generally be classified as either **constructive (prescriptive)** or **functional (performance-based)**.

Constructive (Prescriptive) Calls for Tenders

Constructive calls for tenders are based on standardized specifications or predefined templates, typically issued by public authorities or professional institutions. In Austria, such templates are provided, for example, by the Federal Ministry for Economic Affairs in the form of the standard specification for building services engineering (LB-HT, 2021) for HVAC systems or the standard specification for building construction:

This approach allows for a precise and transparent definition of all required services and components. For the technologies addressed in this research project—particularly heat pump systems, control components, and instrumentation—the existing standardized templates already provide a suitable and comprehensive basis for preparing a tender. However, the effective use of constructive tendering requires that planners possess sufficient expertise in building services engineering and control systems, as all specifications must be defined in detail in advance.

Functional (Performance-Based) Calls for Tenders

Functional calls for tenders are applied when a detailed technical specification of services is not required, not desired, or not feasible. Instead of prescribing how a solution must be implemented, this approach focuses on defining the functional objectives and performance targets to be achieved.

In this case, bidders are given the freedom to propose their own technical solutions, provided that the defined goals are met. The key distinction between functional and constructive tendering therefore lies in the degree of technical prescription: while constructive tenders specify the means, functional tenders specify the outcome.

Implications for the Project Scope

With regard to the topics addressed in this research project, the use of functional tendering requires that planners and clients are able to clearly and unambiguously formulate the expected system behavior, performance criteria, and operational objectives. This is essential to enable bidders to accurately assess the scope of work and propose suitable solutions.

While all technical components required for the implementation of the project outcomes can be found in existing standardized templates for constructive tenders, no comparable standardized framework currently exists for functional tenders in this domain. To address this gap, the project developed a generic example of a functional tender description, intended to serve as guidance for planners and contracting authorities.

The tender-relevant information developed within the project is provided in Annex 1.

5 Summary and Conclusions

5.1 Control Strategy Development

Within the project, a plug-and-play (PnP) control strategy for heat pumps combined with thermally activated building systems (TABS) was developed, implemented, and evaluated. The overarching objective was to increase the energy flexibility of buildings, enable cost-efficient operation of heat pumps, and improve the integration of local renewable energy sources while maintaining thermal comfort for occupants.

The control concept is based on a predictive, data-driven approach that combines weather forecasts, photovoltaic generation estimates, electricity price signals, and simplified thermal building models. Different scenarios for thermal comfort assessment and heat pump control interfaces were systematically analyzed to ensure broad applicability across residential buildings with varying technical configurations.

A key methodological step was the transition from temperature-based to energy-based building models. This simplification improved numerical stability and robustness in the optimization process, enabling the use of mixed-integer linear programming (MILP) within a receding-horizon model predictive control (MPC) framework. The resulting control strategy determines optimal heat pump operation schedules at 15-minute resolution over multi-day horizons, balancing operational costs, renewable energy availability, and comfort constraints.

The approach was validated using an extensive experimental database from a well-instrumented demonstration building. Long-term, high-resolution operational data supported model identification, testing, and refinement of the control strategy. The final system architecture allows cloud-based optimization without continuous on-site computation and can be integrated with existing building automation systems using minimal hardware interfaces.

The project demonstrates that plug-and-play, forecast-based control strategies for heat pumps and thermally activated building systems are technically feasible, scalable, and well suited for real-world residential applications. By leveraging the inherent thermal storage capacity of buildings, significant flexibility can be provided to the energy system without compromising occupant comfort.

The use of simplified, energy-based building models in combination with MILP optimization proved to be an effective trade-off between model accuracy, computational efficiency, and robustness. This approach enables stable operation even under variable boundary conditions such as fluctuating electricity prices, changing weather forecasts, and intermittent photovoltaic generation.

A central finding is that many advanced demand-side management objectives—such as increased photovoltaic self-consumption and cost-optimized heat pump operation—can be achieved without intrusive sensor installations or complex local control hardware. The reliance on standardized forecasts and limited on-site signals strongly supports the plug-and-play philosophy and lowers barriers for market adoption.

At the same time, the results highlight the importance of hierarchical control structures. While high-level optimization provides economic and system-level benefits, local room temperature controllers remain essential to ensure thermal comfort and to compensate for model uncertainties and forecast errors.

In conclusion, the developed control strategy represents a robust and transferable solution for increasing energy flexibility and supporting the integration of renewable energy sources. It contributes directly to the objectives of decarbonization, sector coupling, and grid-friendly operation and provides a solid foundation for further demonstration, standardization, and market-oriented implementation within the Austrian and European energy transition context.

5.2 Data Exchange Platform

Within the PnP Controls TABS research project, a standardized and secure communication framework for the exchange of energy-related data between grid operators, energy suppliers, and flexible energy consumers was developed. This framework, referred to as the Grid Data Manager, addresses the growing need for interoperable, vendor-independent data exchange in increasingly flexible and decentralized energy systems.

The Grid Data Manager provides a server-based, open-source platform that enables bidirectional communication of forecasts, price signals, load curves, and flexibility information. It relies on state-of-the-art security concepts, including encrypted VPN-based connectivity and application-level encryption using established cryptographic libraries. A clear separation between network security (VPN) and data encryption ensures a robust and scalable architecture.

By introducing standardized terminology, clearly defined roles, and a unified data record structure, the developed concept establishes a transparent and extensible basis for future grid-oriented applications. The approach supports both user-centric use cases, such as optimized heat pump operation, and system-level objectives, such as data aggregation for energy suppliers.

Overall, the Grid Data Manager serves as an enabling infrastructure for the integration of predictive, optimization-based control strategies in buildings and other flexible energy assets, while maintaining a high level of cybersecurity and interoperability.

The results demonstrate that a standardized, secure, and open communication layer is a key prerequisite for the large-scale deployment of demand-side flexibility solutions. The Grid Data Manager successfully bridges the gap between local energy systems and higher-level grid and market actors by providing a technically robust and conceptually clear interface for data exchange.

From a technological perspective, the separation of responsibilities between communication, encryption, and application logic proved to be an effective design choice, allowing the system to remain adaptable to different use cases and future extensions. The use of open standards and open-source components significantly lowers entry barriers for additional stakeholders and supports technology transfer beyond the scope of the project.

From a system integration perspective, the developed solution highlights that reliable fallback mechanisms, clear identification procedures, and strict security policies are essential for operational robustness in real-world deployments. While the current implementation serves as a proof of concept, it provides a solid foundation for further validation with grid operators and energy suppliers.

In conclusion, the Grid Data Manager represents a crucial building block for future energy systems in which buildings act as active, flexible participants. Its integration with predictive control strategies such as the PnP algorithm enables cost-efficient, grid-friendly, and user-transparent operation of flexible energy assets, contributing directly to the objectives of decarbonization, sector coupling, and increased renewable energy integration.

5.3 Demonstration Sites

The report "D5.1 – Report of Experiences of Demonstration Projects" summarizes the results of implementing the Plug-and-Play (PnP) control strategy at six demonstration sites. The overall objective was to optimize heat pump operation in order to increase energy efficiency, maximize photovoltaic self-consumption, and reduce operating costs through forecast- and optimization-based control.

Six demonstration buildings participated in the project, each fulfilling a specific role:

- **ENRG** served as a development and testing environment with extensive monitoring capabilities. While not fully representative of real-world applications, it provided valuable insights and data for the early development of the control algorithm.
- **LWRG** demonstrated the combination of flexible import tariffs and photovoltaic self-consumption in a complex non-residential setting. Despite delays in commissioning and limited data availability, the site illustrated the potential of optimization-based control under flexible tariff structures.
- **STBG** was the primary experimental and validation site. Equipped with an air-to-water heat pump and a photovoltaic system, it demonstrated significant cost reductions and increased photovoltaic self-consumption through optimized load shifting.
- **URBZ** functioned as a reference case using a local, rule-based energy management system without forecasting or optimization. The results showed that simple control strategies can already achieve high photovoltaic self-consumption under suitable conditions.
- **PLBG** focused exclusively on the use case of flexible electricity tariffs in an older heat pump system. Due to high heating demand and limited building flexibility, the achievable cost savings were modest. Operational issues highlighted the importance of robust fallback strategies for practical deployment.
- **HERZ** showcased the interaction between the PnP control logic and a new generation of heat pumps. The demonstration emphasized the importance of user interaction and clear communication, as manual interventions and parameter changes significantly influenced system performance.

In conclusion, the project results confirm that the PnP control strategy offers substantial potential for improving heat pump operation and reducing costs. However, successful real-world implementation requires careful consideration of user acceptance, system robustness, and fallback mechanisms. Continuous user information and engagement are essential to ensure reliable and accepted operation of advanced control strategies in residential and commercial buildings.

6 Outlook and Recommendations

The results of this project demonstrate that plug-and-play, forecast-based control strategies for heat pumps and thermally activated building systems are technically mature and suitable for broader deployment. The developed control approach and the associated Grid Data Manager provide a solid foundation for future energy systems in which buildings act as active and flexible participants.

From a technological perspective, further development should focus on extending the robustness and scalability of the control architecture. While the current implementation has proven effective as a proof of concept, future iterations should increasingly consider fault tolerance, automated fallback mechanisms, and long-term operational stability under real-world conditions. This includes reducing dependencies on external services where possible and ensuring seamless transition to local fallback operations in the event of communication or server failures.

The Grid Data Manager concept shows high potential for wider application beyond the demonstrated use cases. Its open-source, vendor-independent design makes it well suited for integration with additional flexible assets such as electric vehicle charging infrastructure, stationary battery systems, and sector-coupled applications. Further validation in cooperation with grid operators and energy suppliers will be an important next step toward standardization and market uptake.

On the application side, the demonstrated results indicate that the greatest benefits of optimization-based control can be achieved in buildings with sufficient thermal storage capacity and moderate heating demand. Future research and demonstration activities should therefore explore differentiated control strategies tailored to specific building typologies, climate zones, and user profiles.

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8 Appendix

8.1 List of Figures

8.2 List of Tables

9 Glossary

DWD	Deutscher Wetterdienst
EMS	Energy Management System
EVU	Energy Provider
HVAC	Heating, Ventilation and Air-Conditioning
JSON	JavaScript Object Notation
MILP	Mixed-Integer Linear Programming
MPC	Model Predictive Control
NWP	Numerical Weather Prediction
PV	Photovoltaic
SOC	State of Charge
STC	Standard Test Conditions
TABS	Thermal Activated Building Systems
UFH	Under Floor Heating
VAT	Value-Added Tax

Annex 1: Tender relevant Information

Ausschreibungstexte MSR
Für funktionale Leistungsbeschreibung. Konstruktives Leistungsverzeichnis mittels LBHT-Standard-positonen weitgehend abgedeckt.
Angelehnt an die Leistungsgruppen der LBHT werden die benötigten Anlagenkomponenten kategorisiert.

LG84 – GA-System Raumautomation (RA)
Automation raumweiser Funktionen aller TGA-Gewerke.
Raumbediengeräte
Die Raumbediengeräte mit Temperaturregler sind für den Heiz- und Kühlbetrieb geeignet. Die Raumtemperaturregler ermöglichen es dem Nutzer, neben einer Solltemperatur, ein Temperaturband zu definieren, in dem Abweichungen vom Sollwert akzeptiert werden.
Dies kann beispielsweise in der Praxis so aussehen:

- Solltemperatur Winter: 22°C
    - Abweichung: - 1 K, +2 K – Temperaturband 21 °C – 24 °C
- Solltemperatur Sommer: max. 26 °C
    - Abweichung: -3 K, +1 K Temperaturband 23 °C – 27 °C

Das Temperaturband und die Sollwerte Heizen/Kühlen können entweder zentral von der GLT vorgegeben sein und ein Offset vom Zentralwert auf den Raumbediengeräten eingestellt werden, oder Sollwert und Abweichungsband sind vollständig ohne Zentralvorgabe je Raumbediengerät zu definieren (Projektabhängig und vom Fachplaner vorgegeben).

LG85 – GA-System Anlagenautomation (AA)
Zentrale Komponenten und Software
Wärmepumpenregelung Software
Die Wärmepumpe wird in erster Priorität bedarfsgeführt geregelt. Darüber hinaus ist eine Regelungslogik zu implementieren, welche auf Basis der Witterungsverhältnisse, Stromnetzauslastung und Photovoltaikertrag einen Demand-Side-Management-Betrieb ermöglicht. Dabei soll basierend auf einer prädikativen Regelung ein Heiz- (Winter) bzw. Kühlbetrieb (Sommer) der Wärmepumpenanlage stattfinden, auch wenn momentan kein direkter thermischer Energiebedarf besteht. Sofern die Wetterprognose es zulässt, kann auf einen Betrieb der Wärmepumpe verzichtet werden, wenn die gebäudeseitigen Temperaturen noch innerhalb des definierten Abweichungsbandes liegen und es im Stromnetz momentan einen hohen Bedarf aber niedrige Erzeugung gibt.
Ziele:

- Überschussstrom aus dem Netz in Form von thermischer Energie zu speichern
- (Betonkernspeichermasse) und (zeitversetzt) zu nutzen
- Ausnützen der thermischen Trägheit des Gebäudes, Lastspitzen abfedern, thermische Energiebereitstellung zu netzdienlichen und ökonomisch optimalen Zeiten

- Erhöhung des Eigenverbrauchs einer etwaigen PV-Anlage
- Ökologischer Betrieb, CO2-optimierte Beladung der Speicher
- Gebäude nimmt am Regelenergiemarkt teil
- Gebäude als thermischer Speicher

LG86 – GA-Management (GA-M)

Mensch-Maschine-Interface, Bediengeräte MSR, Überwachung und Einbindung der Funktionen

Schnittstelle Wetterprognose

Es ist eine elektronisch-kommunikative Schnittstelle herzustellen, mittels derer auf Wettervorhersagen zugegriffen werden kann. Die Wetterprognose wird dem Regelalgorithmus der Wärmepumpenanlage zur Verfügung gestellt.

Folgende Wetterdaten sind in mindestens stündlicher Auflösung (besser: 15-minütig) für zumindest die nächsten 48 Stunden abzurufen:

- Außenlufttemperatur
- Luftfeuchtigkeit
- Solare Einstrahlung

Schnittstelle Netzbetreiber Strom / Stromlieferant

Es ist eine elektronisch-kommunikative Schnittstelle herzustellen, mittels derer mit dem Netzbetreiber des Stromnetzes ein Datenaustausch stattfinden kann. Mittels dieser Schnittstelle wird auf den Betrieb der Wärmepumpenanlage Einfluss genommen.

Folgende Betriebsfälle sind in Abstimmung mit dem jeweiligen Netzbetreiber zu ermöglichen:

- Überschüssiger Strom im Netz: zur Entlastung des Netzes wird die Wärmepumpenanlage betrieben indem Strom in thermische Energie umgewandelt wird
- Hohe Stromnachfrage im Netz bei niedriger Erzeugung: zur Entlastung des Netzes wird auf Wärmepumpenbetrieb verzichtet, sofern gebäudeseitige Temperaturen im Toleranzband sind und die Wetterprognose keine Verschlechterung der Situation meldet.

LG87 – GA-System Feldgeräte

Feldgeräte, Messgeräte, Messwertgeber

- Außentemperaturfühler: Es ist mindestens ein Außentemperaturfühler vorzusehen und in die GLT einzubinden.
- Temperaturfühler Betonkerne: Je Registerfläche / Zone der thermischen Bauteilaktivierung ist ein Temperatursensor in der Betondecke vorzusehen und in den Regelalgorithmus der GLT einzubinden.
- Einbindung Raumtemperaturfühler: Die Raumbediengeräte bzw. Raumtemperaturfühler sind in die GLT einzubinden.
- Smarter Wärme-/Kältemengenzähler mit Tarifen oder Timelog:
  Die Wärmemengenzähler je Nutzungseinheit sind sowohl für den Heiz- als auch für den Kühlbetrieb geeignet (Messtoleranz unter 1 K). Die Wärmemengenzähler verfügen zur Abrechnung über eine Tarif- oder Timelog-Funktion (bzw. ist diese Funktionalität über die GLT sicherzustellen), um nachvollziehen zu können, welcher Wärme- bzw. Kältetarif anzuwenden ist.

Es ist sicherzustellen, dass in jenen Betriebsfällen, in denen im Sinne der Netzdienlichkeit elektrischer Strom aus dem Netz mittels Wärmepumpe als thermische Energie im Gebäude gespeichert wird, obwohl gerade kein direkter Bedarf besteht, ein anderer Tarif zur Abrechnung herangezogen wird und der Nutzer in diesen Fällen nicht den normalen Wärme- bzw. Kältepreis zahlt (sondern einen stark rabattierten bzw. Nulltarif). Die Wärme-/Kältemengenzähler sind in die GLT einzubinden und es ist sicherzustellen, dass folgende Informationen pro Zählpunkt ausgetauscht werden können:

- Energieverbrauch Wärme
- Energieverbrauch Kälte
- Jedem Energiebezug ist der anzuwendende Abrechnungstarif zuzuordnen
    - Normalbetrieb
    - Demand-Side-Management-Betrieb

LG88 – GA-System Verteiler

Die Positionen der Verteilerschränke sind den Ausschreibungsplänen zu entnehmen. Die MSR-Zentrale befindet sich in der Technikzentrale. Zusätzlich existieren Verteilschränke in den Stockwerken. Die Verteilerschränke sind ausreichend groß zu bemessen und mit einer 20-%-igen Reserve zu versehen.

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