FleXible user-CEntric Energy poSitive houseS

Deliverable D4.2 - Evaluation and validation

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Abstract
This deliverable provides a summary of the key findings from the four EXCESS demonstration sites. The outcomes of the PEB solution packages are analysed and validated using the KPI framework from Work Package 4. The technical and economic feasibility is evaluated with reference to the business models and cost-effectiveness of PEB technologies developed in Work Package 5. Additionally, the barriers and challenges encountered at the demonstration sites are described.

Keywords
EXCESS demo sites, feasibility, KPI's, results, monitoring, data, LCA, greenhouse gas emissions

Revision	Date	Description	Author (Organisation)
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More information available at https://positive-energy-buildings.eu/

EXECUTIVE SUMMARY

This report outlines the results and key findings from the four EXCESS demonstration cases across various climatic zones. It includes a detailed analysis of the collected measurement data and provides an overview of the KPI's achieved. The report also discusses the barriers, challenges, opportunities, and lessons learned throughout the design, implementation, and operation phases of the demos. Additionally, it provides a cost analysis covering CAPEX, OPEX, and energy-related costs, along with a global annual cost per square meter of floor surface area. Furthermore, the greenhouse gas emissions for the Austrian and Belgian demo sites are calculated in detail using the life cycle assessment method. A more detailed summary is presented from the unique perspective of each demo case:

Spain

The Spanish demonstrator consist of a deep renovation of a heritage building into PEB. Thin interior insulation is used to comply with façade protection regulation and reduce energy demand. Air source heat pumps with radiant floor provide efficient heating and cooling, while PV compensates the energy balance towards a PEB. Storage tanks for space conditioning and DHW and batteries provide flexibility to the system, to operate more efficiently and increase self-consumption. These flexibilities are activated by the smart energy management system, harnessing the benefits a PEB building offers.

While the PEB deep renovation implies additional upfront cost, operational cost during the building lifecycle is reduced so that in the long run, the PEB renovation is more profitable with a payback period of 30 years. This can be reduced with the smart operation of the energy system, that can reduce the energy bills by 20% each year.

The renovation process was affected by many delays caused by the regulations, building structural difficulties and lack of knowledge of the workforce about the PEB technologies. Despite these problems, the renovation was successfully completed near the end of the project, resulting in a small period for monitoring and evaluation. To overcome this issue, a building energy model was calibrated using the measured data and used to simulate the performance of the demo during a full year. This resulted in a confirmation of the PEB achievement.

Austria

The Austrian demonstrator aims to transform a former industrial structure into a Positive Energy Building (PEB), showcasing innovative renovation technologies. Key advancements included the development and testing of active facade elements that integrate thermal insulation with energy-active layers for heating and cooling, PV-panels and a rapid and non-invasive mounting procedure. Groundwater heat pumps that are integrated into the sites local energy grid are supplying heat and cold to the demonstration building while trying to use locally produced electricity from the facade integrated PVs. A novel energy management system using Model Predictive Control is implemented for an optimized use of thermal flexibilities while maintaining indoor temperature comfort. User-centric applications like the developed OBS app enable user participation and transparent energy management and play a pivotal role in the development of an energy community.

While delays in construction limited the implementation of the developed methods to a smaller part of the building, the scaled-down setup allowed for focused testing and validation of core technologies. The wireless sensor and actor systems that are implemented ensure effective monitoring for the challenging renovation situation. Dynamic building and energy system simulations incorporating the supervisory Model Predictive Control (MPC) algorithm further demonstrated the potential of the technologies, achieving not only PEB standard but also high renewable self-consumption.

Predictive control systems together with user flexibility proved to be a critical enabler, leveraging the building's activated thermal mass for energy storage and load shifting, while aligning energy demand with renewable production. The results of the Austrian demonstrator validate the feasibility of the technologies and their ability to achieve PEB status, providing a concept for reaching PEB status in urban contexts and demanding refurbishments.

Finland

The Finnish demo case is a residential house at Kalasatama, Helsinki, targeting to a building which is producing as much local renewable energy as is needed for heating, ventilation and domestic hot water at yearly level. The Kalasatama house is demonstrating the performance of semi-deep geothermal system integrated with heat pumps, PVs at facades, PVT panels on the roof, ventilation cooling and high COP domestic hot water systems. Demand based ventilation has high efficiency heat recovery and energy systems are controlled with smart control and an optimisation system.

The construction started at end of 2021 at empty plot, and in August 2023 the multi-story apartment building were handed over to housing co-operative, which now owns the building. Due to bankruptcy of the company in responsibility of the construction, the PVs and PVTS could not be commissioned during the EXCESS project. Bankruptcy estate, and trustee in bankruptcy in practice, organises the activities in installations with the financing of deposit set at the beginning of the construction (guarantee fund) and the installation will be finalised in 2025.

The energy system has been running since August 2023, but unfortunately without PVs and PVTs. The system performance has been monitored and the final tuning of the system has been performed since mid-2023. The existing energy system was running at planned performance at end of 2024, and the monitoring results were analysed in this period. The evaluation of the performance was done by using short monitoring period and using this data to tune the model for yearly analysis. The indoor temperatures in the apartments were individually controlled. During the monitored heating season period the temperatures were 19,7…24,5 °C, with an average of 22,1 °C. The heat pumps for space and domestic hot water heating were performing with COP of 2,8…5,0 but due to short measurement period the seasonal COP was not available. The building space and domestic hot water system consumes 77,9 kWh/(m^2, a) heating energy, but when using semi-deep geothermal system with heat pumps for heating the electricity consumption is 22,6 kWh/(m^2,a). The simulated electricity production of façade PVs and roof tilted PVTs was 23,9 kWh/(m^2,a). Based on this analysis, when the PVs and PVTs will be operational, these can provide the electricity for space and domestic hot water heating.

The implemented hybrid semi-deep geothermal heat pump system with special high COP DHW heat transfer components performs quite well already now, but still requires some tuning when PVTs will be operational in 2025. The planned operation principle is to use the PVTs thermal output for heating the geothermal wells and thus improve the COP of heat pumps by increased source temperature.

Belgium

At the Belgian demonstrator, a fossil fuelled heating system was replaced with a multi-source heat pump system. PVT provides low-temperature heat for the heat pump and for regenerating the BTES. The self-consumption of locally generated electricity (PVT and wind) is maximized by exploiting the thermal flexibility of domestic hot water storage units. The measurement data confirms that the EXCESS PEB concept significantly reduces primary energy consumption by working on different levels such as improved heat pump performance, reduction of the overall supply temperature, maximizing local generation and consumption of renewable heat and electricity and by exploiting the thermal flexibility within the heating system.

From a cost perspective, PVT panels have a relatively high installation cost in comparison with other PEB technology packages. The cost analysis confirms that a larger geothermal source in combination with conventional PV is more cost effective than PVT on the condition that sufficient space is available to accommodate more ground heat exchangers. Overall, annual operational expenses decreased by 53%. However, fully eliminating the gas-fired system proved challenging, as its use remained necessary during cold winter days when the BTES and PVT systems could not supply sufficient energy. Although the Belgian demo site is not a PEB today, it is expected to become one when the planned PV installations are installed.

The implementation process faced delays due to a complex design and the risk of budget overruns. This required a redesign to lower installation costs and stay within project timelines. Finding skilled installers for PVT panels also posed difficulties. Despite these challenges, technological advancements in Collindi heat interface units (SOC, P2H, and control systems) were successfully tested and deployed, and the data management platform developed within the EXCESS project delivered positive results. A survey was organized among the building users to gather information on thermal comfort and experiences with the heating concept. The majority of the inhabitants is satisfied with the thermal comfort although attention must be paid to the sizing of the domestic hot water tank for apartments with larger families and to prevent overheating during summer. This can be considered in the building design phase where the option for passive cooling can be used for geothermal energy systems.

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1 Introduction

The overall goal of EXCESS WP4 is to demonstrate the ability of the PEB solutions to fulfil the end user heating and cooling needs with a minimum ecological footprint. WP4 demonstrates the principles of novel technologies and functionalities developed in WP2 and WP3 and uses the extended definition (techno-socio-economic-regulatory) of WP1 for defining the KPIs, which are created to facilitate an efficient comparison, common evaluation and reporting principles.

The key activities of the WP4 are (highlighting in bold the activities presented in this report):

- Definition of qualitative and quantitative indicators KPIs aligned with with T1.1 PEB definition, project's goals, use cases, requirements and harmonised with SmartCity indicators to make them easily adoptable by replication actors;
- Preparation and integration of the validation framework (Setting up the demonstration cases)
- Demonstration of PEB technologies in pilot sites from a broad perspective (technical, environmental, economic and social), showing the user behaviour (context-aware flexibility interactions) & societal impacts and market added benefits (local energy communities peer-to-peer energy transaction and flexibility trading)
- Define and collect the necessary data (monitoring) for the optimization and validation of proposed secure data-handling infrastructure
- Validate the technical and economic feasibility of the EXCESS PEB solutions
- Evaluate the results and make a synthesis of the key achievements of the project

This work focuses on the evaluation and validation of the results at the four EXCESS demo sites.

Purpose and scope of the document

Deliverable D4.2 summarizes the main findings of the EXCESS demo sites. The results of the PEB solution packages are evaluated and validated based on the KPI framework described in Deliverable 4.1. The technical and economic feasibility is calculated with reference to the work carried out in WP5 on the business models and cost effectiveness of PEB technologies. The barriers and challenges experienced at the demo sites are described and discussed.

The task description is cited from the workplan:

Task 4.3 Evaluation and validation (Leader: VITO, Participants: VTT, TAS, CEN, AEE, S5, M14-M46)

"The task will summarize the findings of demonstrations and benchmark cases. The performance of the cases will be reported for future scaling and replication strategies, including:

- *Description of the case study: case summary (VTT- Finland, CEN-Spain, AEE-Austria, VITO-Belgium)*
- *Evaluation of each demonstration case in terms of T4.2 KPIs and comparison with nZEB solutions of same country (VTT- Finland, CEN-Spain, AEE-Austria, VITO-Belgium, main responsible, partners responsible ofT4.2 KIPs will support)*

Description of the case study (case summary) gives a description of the PEB solution demonstrated in different climates, showing the affinity with definition of T1.1. Characteristics of buildings & connected district infrastructure, business use cases, technical energy system, control and PEB solution specific

ICT system architecture, costs (hardware, software, installation, maintenance and running costs), description of encountered challenges and barriers will be included. Informative sheet of each demonstration cases will be prepared by M18.

Evaluation of each demonstration case will be done based on the indicators, defined in T4.2, and the expected impacts for validating the societal, technical and economic feasibility of the EXCESS PEB solutions. Partner will do also Scalability and Replicability analysis (SRA) as well as the cost benefit analysis (CBA), of the demonstrated PEB solutions. Evaluation results will be used in WP5 to evaluate & validate the different developed Business Models and draw policies."

1.1 Structure of the document and role of partners

Chapter 2 includes a comprehensive overview and comparison of the demo sites. A detailed overview of the as-built situation is given and more details on the monitoring system and -data is provided.

In chapter 3 the demos are evaluated based on measurement data and the KPI framework from D4.1. Here we focus on the technical performance and site-specific economic aspects. The methodology for calculating the KPI's is presented per demo case. An LCA analysis for the Belgian and Austrian demo is presented in order to quantify the greenhouse gas emissions.

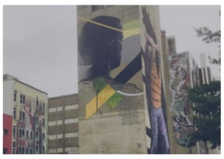
The following partners contributed to the deliverable:

- VITO, AEE, CENER, VTT/TAS – demo case evaluation and validation
- JR – providing input on the demo costs (WP5)
- JR – LCA analysis of the Belgian an Austrian demo

2 Demonstration cases summary

A compact overview of the different demo cases is presented in Table 1.

Table 1: Summary of the four EXCESS demo cases

	SPAIN	AUSTRIA	FINLAND	BELGIUM
				
Climate	Mediterranean	Continental	Nordic	Oceanic
Building type	Residential	Commercial	Residential	Residential
Total floor area	2112 m²	1160 m²	2814 m²	2170 m²
Construction	Renovation	Renovation	New built	New built
Building commissioned	2024	2025	2023	2018
Ownership	Private	Private	Private	Social housing company
Users	Private owners	SME, start-ups	Private owners	Social tenants
Units or dwellings	9 dwellings	26 units	52 dwellings	20 dwellings
Key technologies	• PV • Aerothermal heat pumps • Battery energy storage • Building energy management	• Multifunctional façade • OBS app • MPC • BiPV • Heat pump	• High COP DHW • Semi-deep BTES • PVT • PV • BMS	• PVT • Geothermal heat pump • Power 2 heat • Building energy management
Heating system rated capacity	46 kW	37 kW	162 kW	60 kW
Cooling system rated capacity	40 kW	20 kW	100 kW	/
Local renewable production capacity	58 kW_p	42 kW	67 kW_p PVT 64 kW_p PV	35kW_p

2.1 Spain – Valladolid

2.1.1 Demo site summary

The Spanish demo is a residential building located in the historical center of Valladolid. It is a renaissance palace of the 16th century that was in a state of ruin, and that was renovated maintaining the two historical façades typology, with the existing stone portrait and the Tuscan patio. In 2022 it has been entirely renovated, making the interior layout of the dwellings and improving the building envelope, installing also high-efficiency technologies and control systems.

Stakeholders

The project is being coordinated between the Urbatelier, the architectural firm responsible for the building & design; Cener and Net-X, responsible for the energy technical aspects and control of the energy system of the dwellings and Trycsa, the construction company that is carrying out the building works. Also collaborating as stakeholders are Naven engineering and Audiotec, companies that give support with other technical aspects.

The building offers 9 dwellings of different sizes: a one-bedroom apartment, a two-bedroom apartment and the rest of them of larger dimensions, five of them duplex typology, with three and four bedrooms. Therefore, the building offers accommodation to different kind of tenants and they are expected to be high income families.

Other stakeholders include the energy system installation companies, among which Proyco and Prolar stand out; the high-efficiency insulation company, Actis; the marketing and sales company, Engel & Völkers and the property manager Salvador Díez Valbuena.

Other stakeholders have been involved in the project as a result of the workshops held in Valladolid, especially the Chamber of Architects of Valladolid, several architects, and other representatives of the City Council.

Business model

The building is privately owned and the apartments are going to be sold to individuals that will all together own the building common facilities. Therefore, the relation of the individual dwelling owners with the energy supply and management will be decided by them. However, the most reasonable setup will be that they constitute a shared self-consumption scheme where they benefit from the PV generated electricity based on their share's percentage and or energy consumption.

In this sense, the business model of the PEB would be that the initial overcost compared with a business-as-usual building is compensated through the building lifecycle due to the reduced energy cost and energy exchange revenues.

Challenges and barriers encountered during implementation

Over the course of EXCESS project, different barriers and challenges have arisen. The most important ones are summarized below:

Barrier or challenge	Category	Impact on project and replication
1. Coordination of PEB technologies and controller	Technical and financial	High
2. Envelope insulation	Technical and financial	High
3. Systems commissioning	Timing and technical	Medium
4. Permits and licenses	Timing	Medium
5. Commercialisation and sales	Timing	Medium

The main difficulty we have encountered in relation to the implementation of the different technologies to make the building meet the requirements of being a PEB, has been in coordinating the different technologies, sensors and controllers in the building. The complexity of the energy system defined, requires that many of the elements work together towards the same objective. By using new and complex technologies, it was complicated to find qualified companies, and the installers did not have sufficient knowledge. Many doubts and discrepancies have arisen throughout the work to ensure that all the systems were flexible with each other. The costs were also very high and higher than initially estimated since several modifications had to be made to make the system and the controllers flexible and compatible.

Problems also arose when installing the high-efficiency insulation to make the building envelope very efficient. As it is a heritage protected building, it had to be installed on the inside. The types of insulation used are not standard, so the installers have had many difficulties to place them, especially when they were placed on the roof because of the difficulty of fixing them to the slab to ensure a continuous insulation and to guarantee the minimum heights according to the regulations. It has also had a significant impact on the costs compared with a conventional insulation.

Related to the commissioning of the systems, it has also been quite complex, mainly because there have been many different installers involved and because of the complexity of coordinating all the different technologies.

In terms of permits and licenses, there have not been many delays, but there have been some difficulties in complying with the regulations, given the restrictions imposed by governments to preserve local cultural heritage.

In terms of commercialisation and sales, difficulties are also being experienced. Sales prices are higher than conventional ones because of the technologies and systems installed. Interested parties are sometimes distrustful as the dwellings include new and unknown systems and technologies. This is leading to a slower progress in sales than initially expected.

2.1.2 Energy system innovations

Thin interior insulation for heritage facade

The PEB refurbishment of the Spanish Demo involved improvements in the envelope and the energy system. The facade features a thin insulation at the inner side of the walls and roof to preserve the existing exterior aesthetics while improving the performance of the envelope. This type of insulation is not widely used, especially in Spain due to the climate, and presents a key innovation to refurbish heritage buildings. To further reduce energy usage, a mechanical ventilation system with heat recovery units were installed independently for each dwelling.

Smart Building Energy Management System

The energy system features 58 kW_p PV with 30 kWh battery energy storage combined with a 46 kW heat pump installation providing heating and cooling through radiant floor system. Although the technologies used are widely used nowadays, the main innovation in this building lies in the integration and coordination of the different devices and equipments to achieve the maximum efficiency while activating energy flexibility. This has been accomplished through a smart building energy management system.

All the different equipments have been integrated in the NETx Building Management System (BMS), providing a centralised monitoring and control platform. Using this BMS to interface with all the building devices, a smart controller coordinates the behaviour of the system by modifying control set-points to optimize energy performance and self-consumption. The smart controller uses a Model Predictive Controller (MPC) to optimize user comfort and heat pumps efficiency, generating at the same time a consumption prediction that allows the optimization of the battery energy management to optimize self-consumption. This combination of MPC and Energy Management System (EMS) increases overall system efficiency and flexibility to minimize costs and maximize revenues.

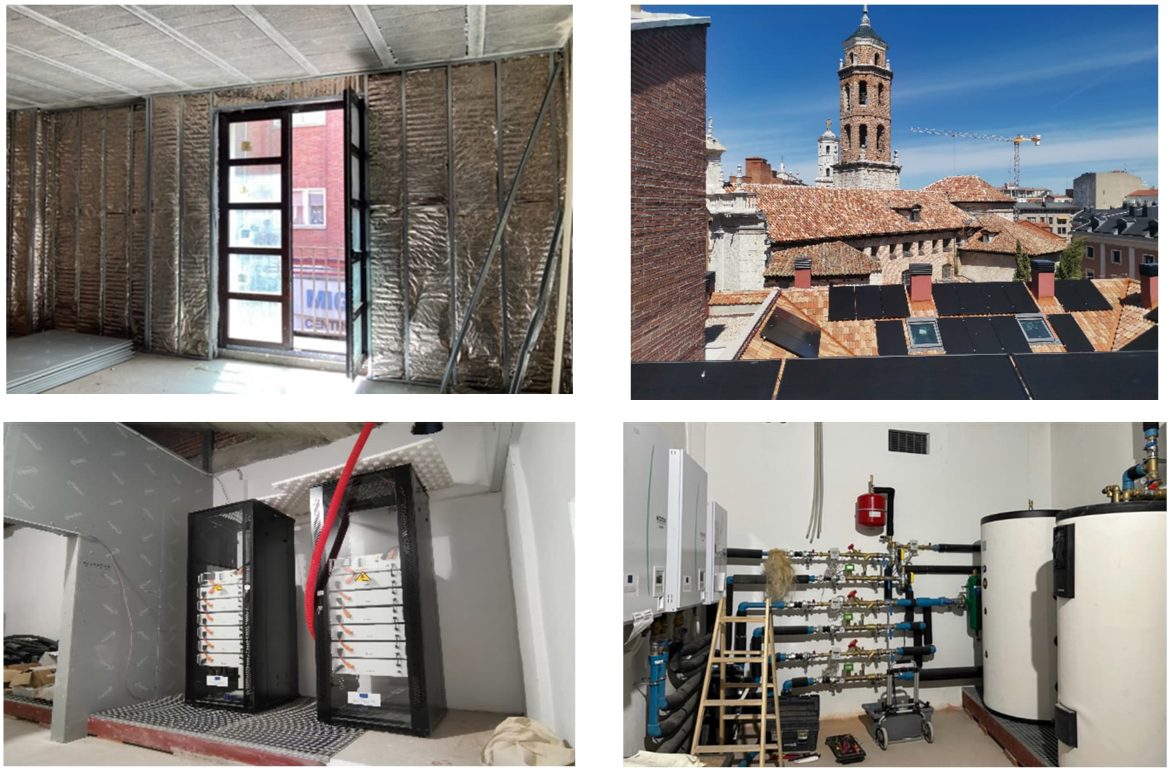


Figure 1: Key components of the Spanish Demo energy system: high performance thin insulation (upper left), PV installation (upper right), battery energy storage (lower left) and air-source heat pumps with storage tanks (lower right)

The main difference with the initial plans was that the Smart Converter that CENER was developing was not ready to be installed in the building at the end of the project due to detection of parasitic currents that made it impossible to license it on time. Therefore the system was redesigned to include standard PV inverters that could be used to provide similar level of control over the energy management that was originally intended. The smart controller that was intended to be running physically inside the Smart Converter has been installed in the building but instead of controlling the Smart Converter, it controls the installed PV inverters.

2.1.3 Measurement data and ICT framework

The building infrastructure is monitored by several sensors and meters so that we can keep track of the energy consumption breakdown over different services and uses. All the data is centralised in the NETx platform that acts as a Building Management System. This data is then available for the Smart Controller to use in the MPC algorithms and for the EXCESS data management platform through a secure API.

Table 2: Measurement data overview for Spanish demo case

Dataset name	Spanish demo site
Data owner	The building community
Data purpose	KPI calculation, evaluation and validation of energy concept
Type of data	Time series metrics e.g. temperatures, flows, energy consumptions etc.
Metrics and scope	+/- 120 points sampled each 1h (dwellings). +/- 80 points sampled each 15 min (facilities)
Data access CENER	Local BMS (source) and over secured API
Data access EXCESS partners	Over secured API
Data access other parties	Data not available for other parties
Metadata	Embedded in the data structure
Data preservation beyond end of project	To be discussed
GDPR compliance	Data owner and user agreements pending (signed consent forms)

The EXCESS Data Management Platform has been set up with multiple data collection jobs that periodically fetch the building data through a secured API. The results of the analytics are then made available in the DMP for the MPC component to use the predictions in the control algorithm.

As the data is only available from the end of September 2024, a building model has been calibrated with the available data and used to simulate the behavior of the demo site during the whole year 2024. The available datasets are described in Table 3.

Table 3: Measurement data availability

Technology related data	KPI domain(s)	Measured	Simulated	Period
PV	Energy, Economy	X	X	10/2024 – 11/2024
BES	Energy, Economy	X	X	10/2024 – 11/2024
Heat pumps	Energy, Economy	X	X	10/2024 – 11/2024
Electricity consumption	Energy, Economy	X	X	10/2024 – 11/2024

Meteorological data	KPI domain(s)	Measured	Simulated	Period
Local weather conditions	Energy, technology	X		01/2024 – 11/2024

User data	KPI domain(s)	Measured	Simulated	Period
Energy consumption	Energy	X	X	
Comfort	Social	X		
Comfort (temperature)	Energy	X	X	

2.2 Austria – Graz

2.2.1 Demo site summary

Situated in the south of Graz the, former industrial site "Tagger-Werk" holds the Austrian demo site of the ECXESS project. This site covers roughly 31,000 m² of gross floor space and is repurposed into a Plus Energy Quarter, showcasing cutting-edge energy concepts and a strong focus on sustainability. The redevelopment retains and integrates elements of the original industrial architecture into a vibrant, mixed-use complex, maintaining visible reminders of the site's heritage. So far, about one-third of the 19 buildings shown and labelled in Figure 2 have been modernized to meet low-energy standards. Among the standout features is the old feed production silo (building 10), which is set to be transformed into a mixed use commercial site and an EXCESS demonstration model, aiming for positive energy building standards.

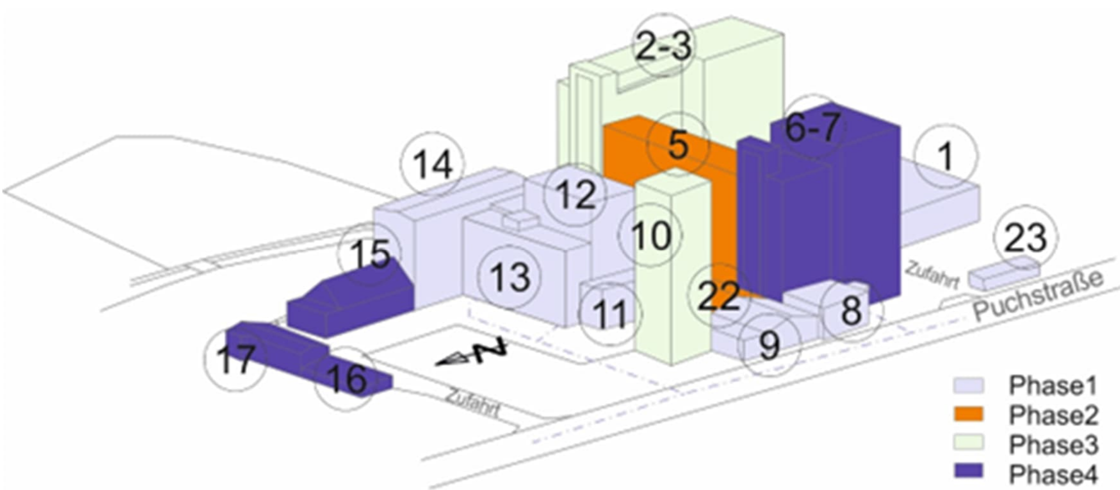


Figure 2: Whole building complex Tagger-Area and buildings related to refurbishment phases one to four (Source: BAR Vermögensverwaltung GmbH)

Figure 3: View on the partly transformed industrial area from the south, showing the EXCESS demonstration building no. 10 to the far left

Stakeholders

The innovative renovation project at the former industrial site involves multiple key stakeholders. BAR Vermögensverwaltung GmbH, as the site owner and main stakeholder, oversees and conducts the renovation, focusing on innovative facade elements and using Tower 10 as a testing ground for scalable methods across the site. They are also responsible for renting out the renovated spaces to suitable tenants. AEE INTEC provides scientific support in developing energy systems and facade technologies, aiming to generalize and disseminate the knowledge for application beyond the site. TSI utilizes the site to test innovative hardware and software for energy management refurbishment, emphasizing user participation to refine and implement systems. Users and tenants are active stakeholders, engaging in the energy system's flexibility trading and reward mechanisms, contributing feedback to ensure usability and efficiency. Finally, the City of Graz supports the project as a pioneer initiative, looking to apply lessons learned to similar redevelopment efforts within and beyond the city. Together, these stakeholders combine expertise, innovation, and strategic vision to revitalize the site as a model for sustainable urban development.

Business Models

The business model for the demo project is rooted in transforming a formerly uninhabitable building owned by BAR Vermögensverwaltung GmbH into a highly functional, revenue-generating asset. By developing and testing innovative renovation concepts such as the multifunctional facade, wireless control components, and user participation apps, the project creates a replicable model for the entire site. The test tower not only becomes rentable space but also serves as a pilot for applying advanced technologies across the property. Additionally, the building's exterior functions as a photovoltaic (PV) power plant, enhancing its energy-generating potential.

Revenue streams include energy sales from the integrated PV systems, monetization of flexibility within the thermal energy system, and earnings from user flexibility through participation in the energy ecosystem. These are complemented by increased rental income due to the improved building quality and its appeal to tenants. By combining cutting-edge technologies with sustainability-driven energy solutions, the business model ensures economic viability and scalability while maximizing the building's value. This approach demonstrates how innovation can unlock the latent potential of underutilized properties, creating financial and environmental benefits.

Challenges and barriers encountered during implementation

Throughout the implementation of the demo site, various challenges were encountered leading to a delay in construction, which hindered progress. The challenges are mainly based on the very special construction of the tower and the special industrial equipment that was installed for the former usage and had to be gutted to transform it to a habitable space. Also, various legal hurdles including fire protection regulation and permits for non-industrial use on the site necessitated some deviations from original plans. These delays affected the timeline and necessitated strategic adjustments, prompting a reliance on alternative methods to maintain momentum.

The project team had to remain adaptable and continuously revise plans to ensure that the project remained on track despite setbacks. This required robust contingency planning, a proactive approach to problem-solving, and the use of simulation tools. By employing virtual dynamic building models and using lab and on-site tests the team could augment the real-world conditions, which provided critical data inputs for optimizing the planned systems and developing components. This ultimately made it possible to reach project goals thus facing delays in the construction work.

2.2.2 Building infrastructure

The Austrian EXCESS case study is a former feed production silo seen in Figure 4, which is renovated into a positive energy building with mixed usage. The positive energy house standard will be achieved by activating the existing thermal mass of the building structure via pre-fabricated multifunctional facade elements including integrated PVs to supply the heat, cold and electricity demand of the building.

Figure 4: Original state of the feed production silo tower (left) and 3D rendering of the planned refurbishment (right)

The building is be heated and cooled via groundwater heat pumps that are integrated into the sites heating, cooling and energy grid trying to use locally produced electricity from the facade integrated PVs. The heat pump charges the domestic hot water storage or the space heating storage that provides energy to the consumers. In summer cooling as free-cooling, directly from the water-well is foreseen and simultaneously cooling with DHW preparation is performed. Figure 5 shows the scheme of the hydronic system in detail with its design parameters. For the circulation pumps high efficiency pumps are assumed and the set points are 52 °C/48 °C for the storages DHW and SH, and 6 °C /12 °C for the cold storage. The heights of the sensors are 10 % for DHW and SH, and 95 % for space cooling (SC) based on max. high of the tank. The linkage part between building and plant is the multifunctional facade with the active layer to transfer heat to or from the existing wall that conditions the room behind.

User-centric applications will play a pivotal role in fostering the development of an energy community. These applications enable continuous monitoring and verification of energy savings at both the prosumer and building levels. They also ensure a transparent allocation of benefits from energy optimization among prosumers, based on precise energy measurements.

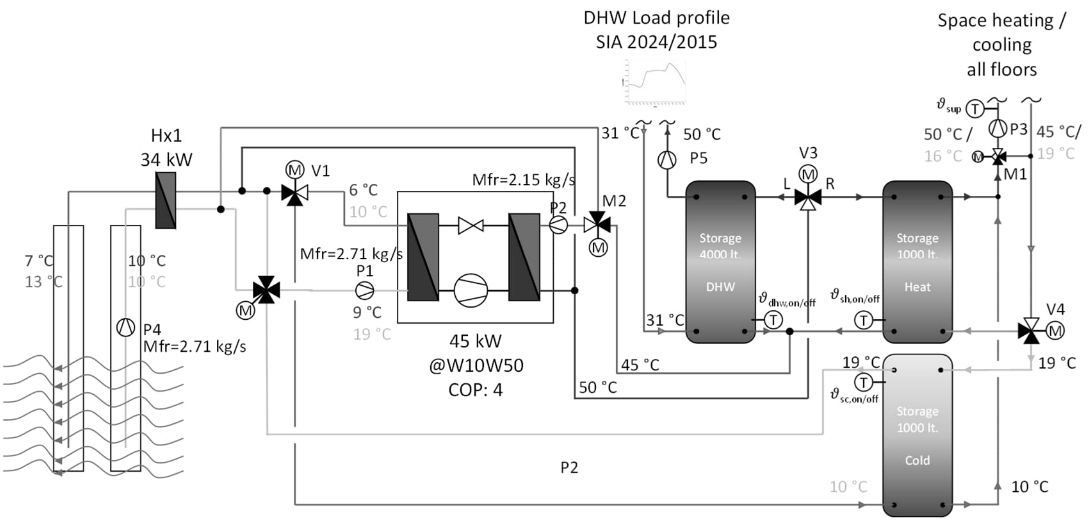


Figure 5: Overall scheme of the hydronic system with heat pump, water-well as source, storages (DHW and SH and cold) and distribution system

2.2.3 Energy system innovation

Energy active Façade

The facade technology developed in this project represents a comprehensive thermal-energetic renovation solution with a high degree of industrial prefabrication. The approach focuses on activating the thermal mass of existing buildings using multifunctional, modular facade elements. These elements combine thermal insulation with an energy-active layer that enables heating and cooling from the exterior. Designed for rapid, non-invasive installation, the system concept, depicted in Figure 6 transforms existing building structures into efficient energy storage and distribution systems for heating and cooling. The large surface areas of the facade enable an effective transition to low-temperature energy systems. Combined with the added storage capacity, this allows for the integration of volatile renewable energy sources with maximum efficiency and reliability. The implemented design of the active layer (see Figure 7) and the perused assembly process ensures optimal thermal contact between the surface heating system and the existing wall, enabling the entire wall depth to be utilized for heating or cooling storage. This innovative solution was iteratively tested on site and improved to overcome practical hurdles during the installation, resulting also in novel mounting mechanisms. A picture of partly installed facade modules at a dedicated testing room in the tower is shown in Figure 8.

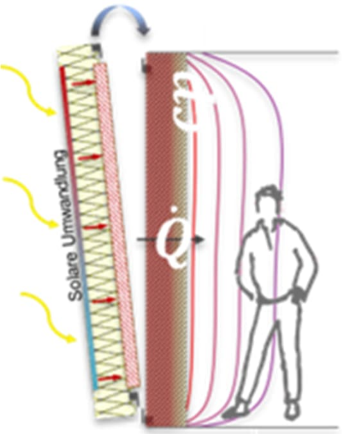


Figure 6: Renovation concept with thermal activation of the existing building envelope

Figure 7: Active heating and cooling layer design applied to the outside of the existing building facade

Figure 8: Partly installed multifunctional facade modules at the Austrian demonstration building

Smart Room Control

The Smart Room Energy Control System is an advanced solution designed to optimize energy usage, enhance comfort, and reduce operational costs. Built with state-of-the-art technology, it provides a seamless and intelligent approach to energy management for modern homes and buildings. Key features of the system include: The system incorporates ULE-WB (Ultra-Low Energy Wideband) technology to ensure direct and efficient communication with sensors and actuators within the room. This minimizes latency and maximizes energy efficiency by enabling real-time data exchange. The system allows precise power control for individual zones, ensuring that energy is allocated where it is needed most. This personalized approach optimizes comfort while significantly reducing energy waste. Leveraging machine learning (ML), the system adapts dynamically to room conditions, learning user habits, thermal patterns, and environmental factors. By using historical data, it continuously refines its operations to achieve maximum efficiency. With MPC (Model Predictive Control), the system optimizes energy usage by targeting key performance indicators (KPIs) such as energy efficiency, cost minimization, and user comfort. MPC ensures that the system operates proactively rather than reactively, delivering consistent performance improvements. The system supports external forecasts, including weather conditions, energy prices, and energy consumption trends, to make informed decisions. By anticipating future conditions, the system adjusts its operations to maximize efficiency and minimize costs. Users can connect to the system through a dedicated app, enabling direct input of user demands, flexibility preferences, and usage patterns. This intuitive interface ensures that users remain in control of their energy environment. The system continuously monitors its conditions and performance. In the event of anomalies or inefficiencies, it provides alerts and maintenance notifications, ensuring long-term reliability and optimal operation. By leveraging past operational data, the system enhances its machine learning capabilities and predictive accuracy. This robust data usage enables the system to adapt to changing conditions and user preferences effectively.

Supervisory MPC

At the demo site in Graz, a supervisory Model Predictive Control (MPC) system has been implemented to optimize the entire building's energy system while maintaining occupant comfort. This advanced system oversees the temperature state of the building envelope's thermal mass, ensuring efficient energy use across the structure. The MPC integrates seamlessly with individual smart room controls, creating a multi-layered energy management solution.

By accounting for the entire energy ecosystem, including photovoltaic (PV) systems and heat pumps, the MPC system dynamically adjusts heating and cooling operations. Its predictive capabilities rely on analyzing diverse inputs such as historical energy use, real-time occupancy data, and weather forecasts. Data driven forecast algorithms together with semi-physical building models enables the system to anticipate energy needs and system states and make proactive adjustments to enhance efficiency and reduce costs. Figure 9 shows the structure of the MPC-internal building model which is used for forward optimization and continuously updated by a Moving Horizon Estimation. This enables the constant adaption to changing physical and environmental factors while maintaining robustness of a physical model.

The coordination of PV energy production, heat pumps, and thermal storage ensures maximum utilization of renewable energy, reducing dependence on external energy sources. Through its integration with smart room controls, the MPC system aligns localized comfort settings with overarching energy strategies, creating a holistic, sustainable approach to building energy management.

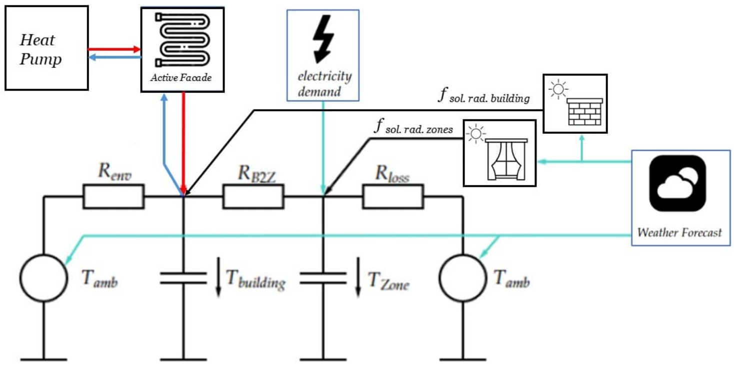


Figure 9: RC-equivalent representation of the used thermodynamic building model for predicting the demonstration buildings temperature and heat/cold demand

IoT Devices

In the demo project, innovative IoT devices were developed to meet the unique challenges of smart energy systems in renovations. These sensors and actuators were specifically designed for rapid installation while maintaining advanced control capabilities. Seamlessly integrated with the Smart Room Control and supervisory MPC system, they enhance monitoring and optimization of energy consumption across the building. A dedicated OBS app is planned to facilitate real-time data analysis and sensor performance monitoring.

Key features include versatile connectivity options such as ULE-WB, WLAN, and BLE. The ULE-WB technology boasts an impressive outdoor range of over 1 km and indoor performance of up to 82 meters, even through one concrete and two brick walls. These devices support both REST API and MQTT protocols for seamless communication with external systems. Additionally, the sensors are equipped with a High Availability (HA) feature, ensuring robust and reliable operation. This innovation in IoT technology goes along with the goal of the demo to show that high quality, fast, serial renovation is possible.

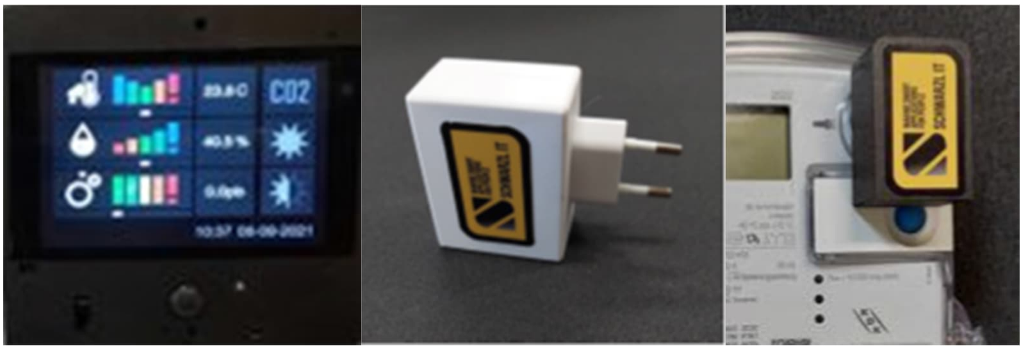


Figure 10: User-interface and sensor devices

User Engagement App

In the demo project, the Objective Benefit Sharing (OBS) app was developed as a critical tool for integrating IoT devices and control systems, placing a strong emphasis on user engagement and energy efficiency. The app addresses key user needs, enabling consumption planning and promoting behaviour change through incentivization and active engagement. By encouraging users to adjust their energy usage patterns, the app helps reduce overall energy demand and maximizes flexibility within the system.

One of its core objectives is to increase the self-consumption rate of energy produced on-site, leveraging flexibility to enhance system efficiency. The app provides external visibility into the building's energy demand and production forecasts, offering users a clear understanding of their energy impact. This transparency fosters trust and satisfaction, empowering users to actively participate in energy management. By combining incentives with real-time insights, the OBS app enhances user readiness for behaviour change while supporting the overall energy ecosystem of the demo project.

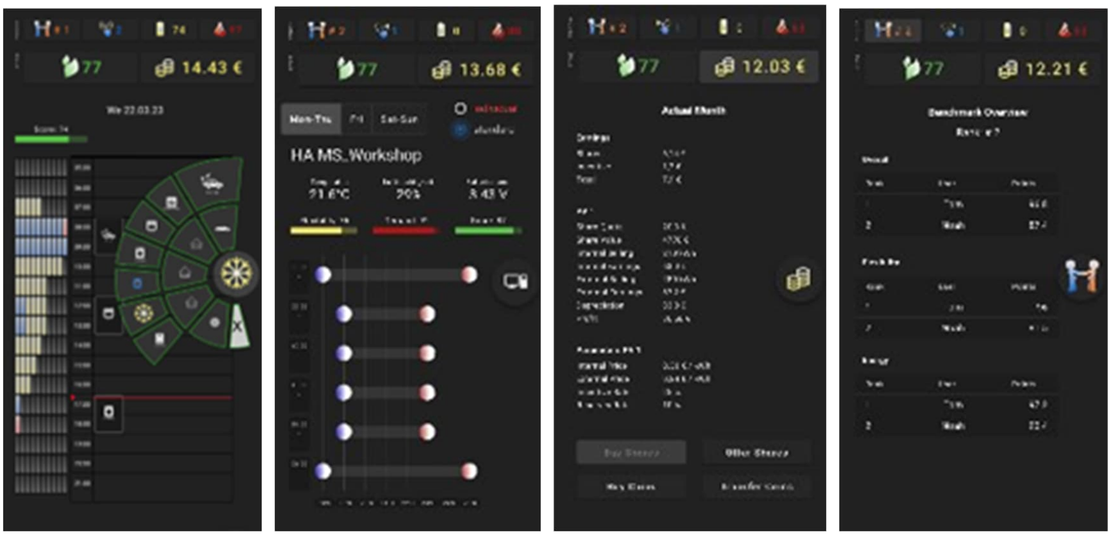


Figure 11: Screen shots of user engagement application

2.3 Finland – Helsinki

2.3.1 Demo site summary

The Finnish EXCESS positive energy building is located at Kalasatama district, in the city of Helsinki. The project has two separate buildings including 145 apartments. The total floor area is almost one hectare. The plot is located in the centre of Helsinki, in the new fast developing area at Kalasatama close to sea. The city centre area is typically served with district heating network and buildings are mixture of residential and commercial buildings. The demo building is similar since it includes residential apartments, commercial spaces and a restaurant at the first floor.

The project is developing new type of housing solutions aiming at positive energy buildings, producing at least the same amount of energy than they are using, when looking at the yearly energy balance. The project at Kalasatama has two separate houses, one 8 floor and one 13 floor building. The lower one participates in the EXCESS EU Horizon project and the higher one participates in HYBGEO Business Finland financed project.

Kalasatama area is a perfect place to demonstrate PEBs: it is a part of City of Helsinki's Re-thinking Urban Housing programme, which aims to increase the quality and appeal of living in blocks of flats and integrate new personalised solutions into it. The programme provides developers with the opportunity to try new things and receive valuable guidance from city experts for the development efforts.

The key info of the Finnish EXCESS demo building is presented in Figure 12 and Table 4.

Figure 12: EXCESS demo building in Kalasatama, Helsinki, December 2024.

Table 4: Key figures of Finnish EXCESS demo building and energy system.

Building:	Energy system:
• 2 buildings, EXCESS demo in lower one • 2-13 floors • 145 apartments / 8254 h-m^2 • House AB (As Oy Aurinkoamppeeri) 52 apartments / 2814 h-m^2 • House CD (As Oy Geowatti) 93 apartments / 5440 h-m^2 • Apartments 26,5 – 100 m^2, average 57m^2 • Restaurant and 4 commercial spaces, 456 m^2 • parking for 56 cars, underground space • 2 shared cars, by shared car services • Spaces for bikes inside 234, outside 97 • Solar panels at facades and at roof • Challenging underground conditions, due to location in dense living area near harbour	• Deep boreholes 3-5x800m (drilling technology and heat exchangers collector) • 67 kW_{el} DualSun PVT panels, 315 m^2 • for multisource ground source heat pump with defrosting function • PVs at facades, 348 m^2 • Seasonal borehole storage. PVT heat surplus will be used to charge the ground during transitional months, while during summer the HP condenser using the PVT as thermal source will dump heat to the ground. • Multisource ground source heat pump system for deep boreholes with high COP for DHW with 2x500 litre and 2x300 litre short term tanks and remote heat pump monitoring, on-line commissioning and fault diagnostics. • Utilisation of the EXCESS heat of exhaust ventilation • Smart control and optimisation

The design values for the energy efficiency of the Finnish demo building are presented in Table 5.

Table 5: Energy efficiency design values of the Finnish demo house

Envelope	A (m^2)	U (W/m^2K)	UA (W/K)	share of heat losses
External walls	2075,4	0,16	327,9	29 %
Roof	643,7	0,09	59,9	5 %
Floor	643,6	0,14	89,5	8 %
Windows	849,5	0,60	510,5	45 %
Cold bridges			144,1	13%
Air leakage q50		1,0 $m^3/(h\ m^2)$		
Heated net area		4069 m^2		
Windows at facades	A (m^2)	U (W/m^2K)	g-value	
North	20,2	0,60	0,50	
North-East	15,1	0,60	0,50	
South-East	374,9	0,60	0,50	
South-West	116,3	0,60	0,48	
North-West	322,8	0,60	0,48	
Ventilation system		mechanical supply and exhaust with heat recovery		
	Air flow rate supply / exhaust (m^3/s) / (m^3/s)	SFP ($kW/(m^3/s)$)	Heat recovery efficiency	Defrosting limit (°C)
Main ventilation machines	2,75 / 2,75	1,52	83 %	-10
Heating system		Geothermal heat, floor heating		

PVs and PVTs

The following design values have been used for PV and PVT panels (Table 6).

Table 6: Energy efficiency design values of the Finnish demo house

Location	Efficiency %	m^2/kWp	kWh/ kWp	kWh/ m^2	Area m^2	Electricity production kWh
PV South façade	18,5	5,4	677,6	125,4	100,2	12561
PV West, blue panels, south end	18,5	5,4	478,1	88,5	79,1	6993
PV West, green panel	18,5	5,4	478,1	88,5	79,1	6993
PV West, blue panels	18,5	5,4	478,1	88,5	53,8	4755
PV West, green panels, North end	18,5	5,4	478,1	88,5	35,6	3151
PV Roof, South tilted 45 degrees	21,3	4,7	972	207,0	315	65216
Total					663	99669

The total electricity production of the PV and PVT panels is 99669 kWh (23,9 kWh/m^2,floor,a).

Stakeholders

The following key business stakeholders were involved in the Finnish demo case:

Basso Building Systems Oy (BAS) is the developer of the houses in the Finnish demo and hosts the planning, constructing and monitoring of the EXCESS demo case at Kalasatama, Helsinki. Basso gathers the external stakeholder network (e.g. City of Helsinki planning section authorities and Kehittyvä Kerrostalo project) around the project supplementing the excellence of the full project partners. Basso co-creates and co-innovates the PED housing concepts for different client types and sizes of buildings aiming at conceptualization of PEB and nZEB houses that enable PED creation. Basso studies the financing models and new methods of making PEDs economically viable, e.g. by binding mobility solutions in house design economics.

Tom Allen Senera Oy (TAS) develops the solutions for hybrid geothermal systems, integrating semi-deep geothermal boreholes and associated ground collectors with solar thermal, solar PV and heat pump systems and smart building control system. TAS develops hybrid concepts harvesting heating and cooling energy from building energy process, ground source and storages. TAS aims at conceptualizing the hybrid energy systems for different building types and consumption levels. TAS develops and co-innovates heat pump systems utilising multiple heat sources and improves COP of systems. TAS has an integrator role in designing energy technology system for PEDs.

Muovitech Oy (MUO) develops the flexible collectors for semi-deep boreholes. The R&D focuses on ground collectors and collector optimization for combination of heat pump, borehole and hybrid energy systems. Muovitech optimizes hydraulic performance collector system & circulation pump, collector solution and connection to borehole wall. Muovitech aims at high performance collectors for semi-deep geothermal systems.

Gebwell Oy (GEB) develops the high COP heat pump systems for semi-deep borehole system of PEBs and nZEBs. Gebwell optimizes the details of heat pumps, multisource heat pump systems and associated ICT/IoT solutions enabling fluent integration of heat pumps in hybrid energy systems. Gebwell makes acoustic development of heat pump and associated space systems. Gebwell develops the remote control, monitoring and associated services related to heat pumps and enables the heat pumps for the demand response activities and integration in electricity markets.

DualSun (DS) develops PVT panels, which will be integrated to the energy and geothermal systems. In Kalasatama Finland demo building, Dualsun has assisted in designing and installations of hybrid PVT solar modules.

VTT Technical Research Centre of Finland (VTT) coordinates the meetings of Finnish demo site partners in the EXCESS project. VTT performs the initial simulations and modelling for the energy system, defines the key performance indicators for the system performance evaluation, and develops the MPC control strategies. VTT arranges stakeholder workshops for dissemination and feedback gathering.

Sweco Oy has acted as design partner under supervision of Basso, and has completed the building design documents for Basso Building Systems Oy. Sweco has not been partner in EXCESS.

Rototec Oy performed the drilling of boreholes, with special drilling rig for semi-deep boreholes. Rototec has not been partner in EXCESS, but participated in the sister project HYBGEO.

Helsinki City has accepted Bassotalo case for "Kehittyvä Kerrostalo" programme (Evolving multi-storey building).

Business model

The apartment pricing will be done according to Hitas I rules. Hitas is a system for regulating the price and quality of apartments in Helsinki, Finland. The system is intended to provide affordable owned apartments to Helsinkians. Apartments within the Hitas system are set a maximum selling price already when the lot is signed over for construction, and this maximum selling price may not be exceeded even when selling the apartment afterwards.

The technological innovations have been developed and integrated with each others: Smart integration of geothermal deep boreholes and geothermal collectors, heat pumps, solar PV and PVT panels, energy efficient envelope and ventilation with heat recovery. Intelligent BMS with smart control and forecasting strategies.

Exploitation and replication of PEBs requires good examples and proof-of-concept. The Finnish demo case at Kalasatama will bring monitoring and evaluation results for public discussion. First time implementation of new RES solutions solves unexpected challenges, e.g. fire and safety aspects related to PVs, and technical challenges of deep boreholes and collectors.

As key figures, EXCESS PEB at Kalasatama is producing as much local energy as is needed for heating, ventilation and domestic hot water at yearly level. Target electricity consumption is 27 kWh/m^{2}a, PV&PVT electricity production is 24 kWh/m^{2}a, with self-sufficiency ratio 88 %.

Challenges and barriers encountered during implementation

The challenges and barriers of Finnish demo case have been analysed taking into account the difference between design phase and implementation phase. The following design phase challenges were recognised: target setting, key performance indicators in target setting, how to find the final design, what kind of technologies were implemented and challenges in energy design with several phases.

The implementation (construction) and start-of-operation phases included several challenges: management of the timetable, underground construction below the sea level, technology implementation (semi deep drilling, installation of collectors, control strategies of PVT, control system in general, new heat pump models, >1200 measurement points etc.) and approvals needed during the construction. At the final state of the construction works, one of the key companies faced financial challenges and went bankrupt. In this face the building was already in use, and only some final installations were delayed. Bankruptcy estate, trustee in bankruptcy in practice, organises the activities in installations with the financing of deposit set at the beginning of the construction/guarantee fund.

Experiences and lessons learned

The importance of the Finnish demo case as offering proof-of-concept of energy efficient local RES solution has been noticed. The monitoring and evaluation results are needed to confirm the stakeholders and bring experiences to publicity. The pioneer attitude has been required from stakeholders of the project (new requiring technology PV, PVT, construction below sea level, semi deep boreholes, control strategies). Co-creation, co-operation and communication has been important part in the project implementation.

2.3.2 Building and district infrastructure

The building is located at Helsinki, Kalasatama, next to harbour of the Baltic sea (Figure 13).

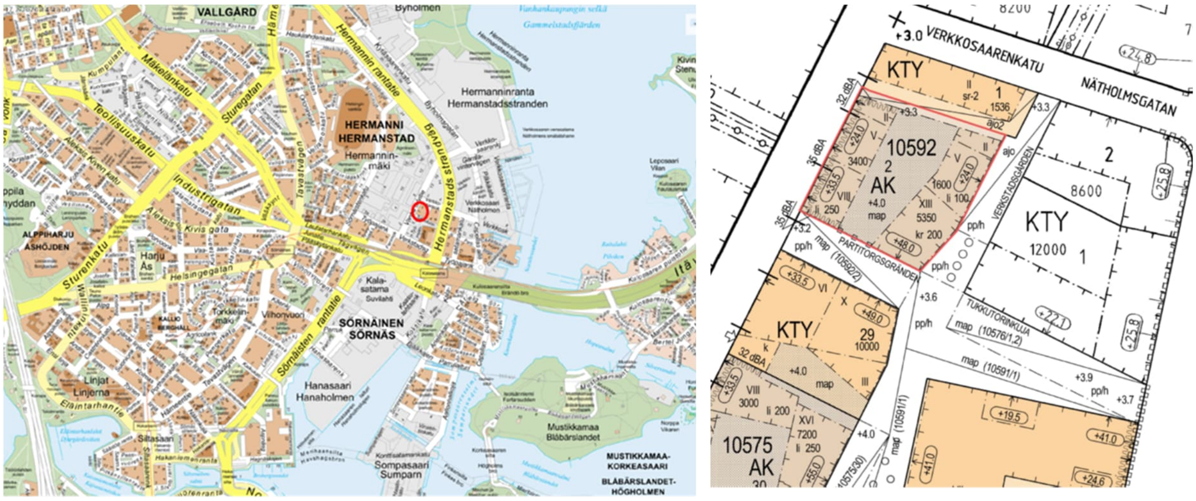


Figure 13: The location of the EXCESS demo building at Kalasatama, Helsinki. EXCESS building plot number 10592

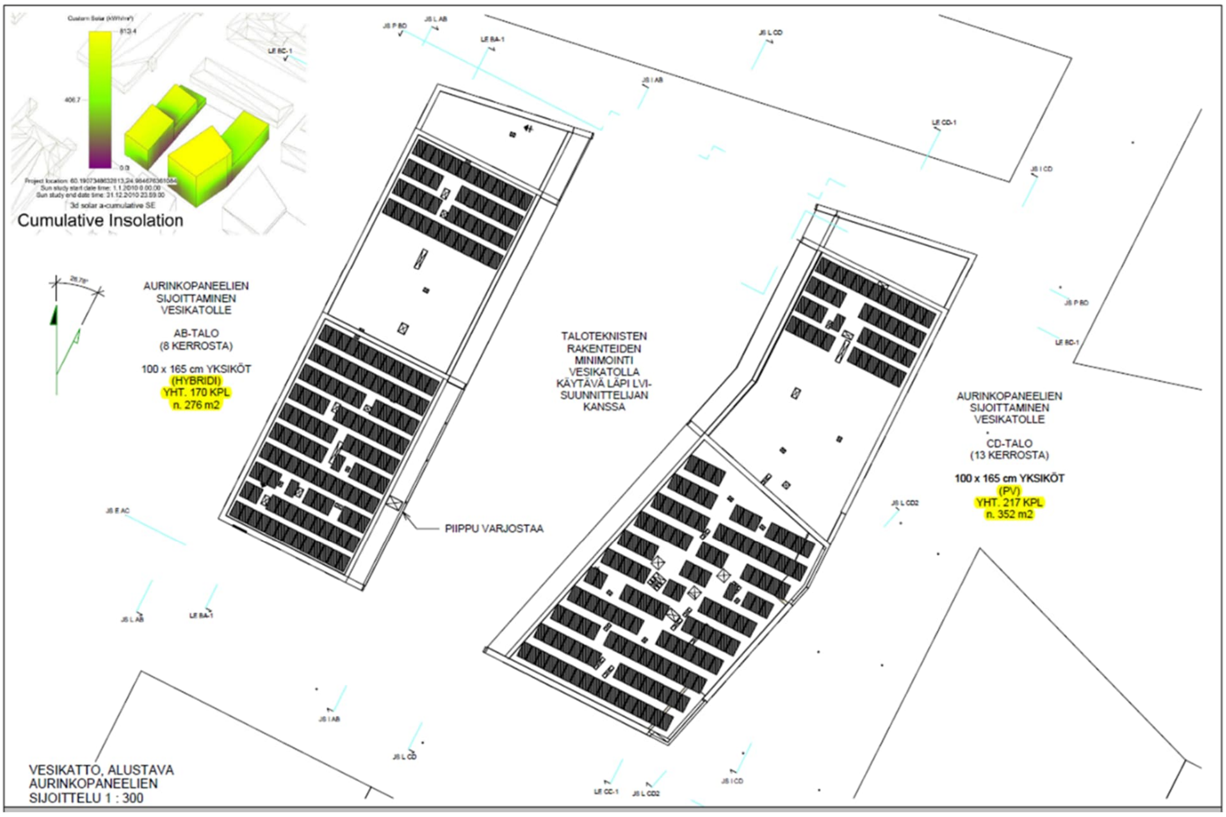


Figure 14: The location of the EXCESS demo building (in right, front building) at Kalasatama, Helsinki

The section views are presented in Figure 15.

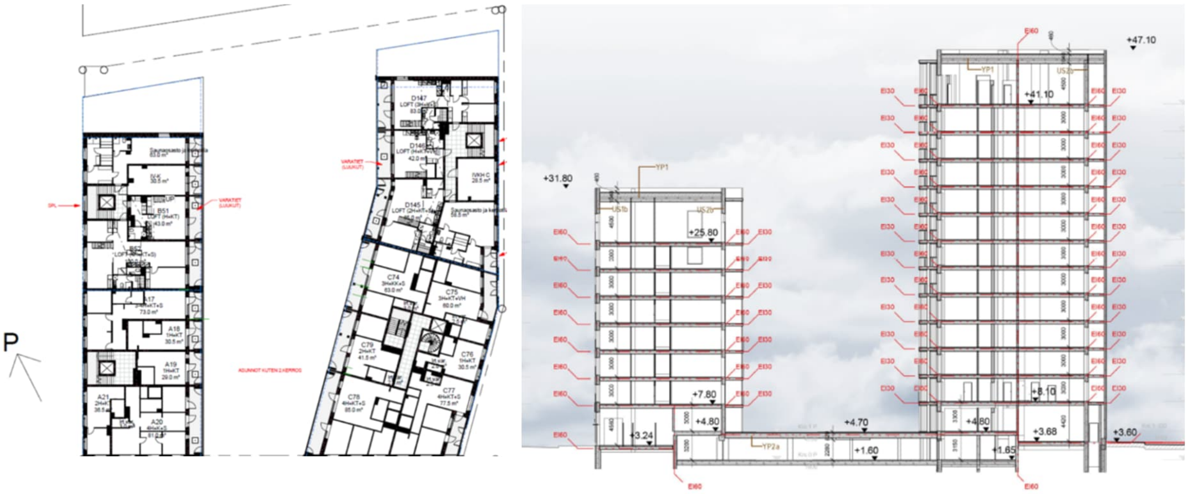


Figure 15: The section views of EXCESS demo building (in left, lower building)

The final shape of the building (before PV-installations) is presented in Figure 14. The PVs have not been installed and PVT panels are not connected to the energy system. The building is in use by Inhabitants, who have moved in August 2023.

2.3.3 Energy system innovations

Boreholes and collectors

Figure 16: BHE TC55 designed for semi-deep boreholes(SDR17/SDR11)

The special drilling rig for semi-deep boreholes was delivered and used by Rototec under separate contract by Basso.

Heat pumps and domestic hot water system

Two Gebwell Taurus 80 EVI heat pumps (Figure 17) are used for heating and cooling. The boreholes and PVT are used as heat source.

The technical performance of the Taurus EVI:

- Heating capacity 81 kW [5°/35°]
- COP 5,0 [5°/35°]
- Tandem (2pcs) EVI scroll compressors
- High COP due to EVI compressor technology
- Simultaneous space heating and DHW production due to desuperheating heat exhanger
- Maximum forward temperature with full capacity 65°C
- Dimensions: 1300 x 700 x 1860 mm

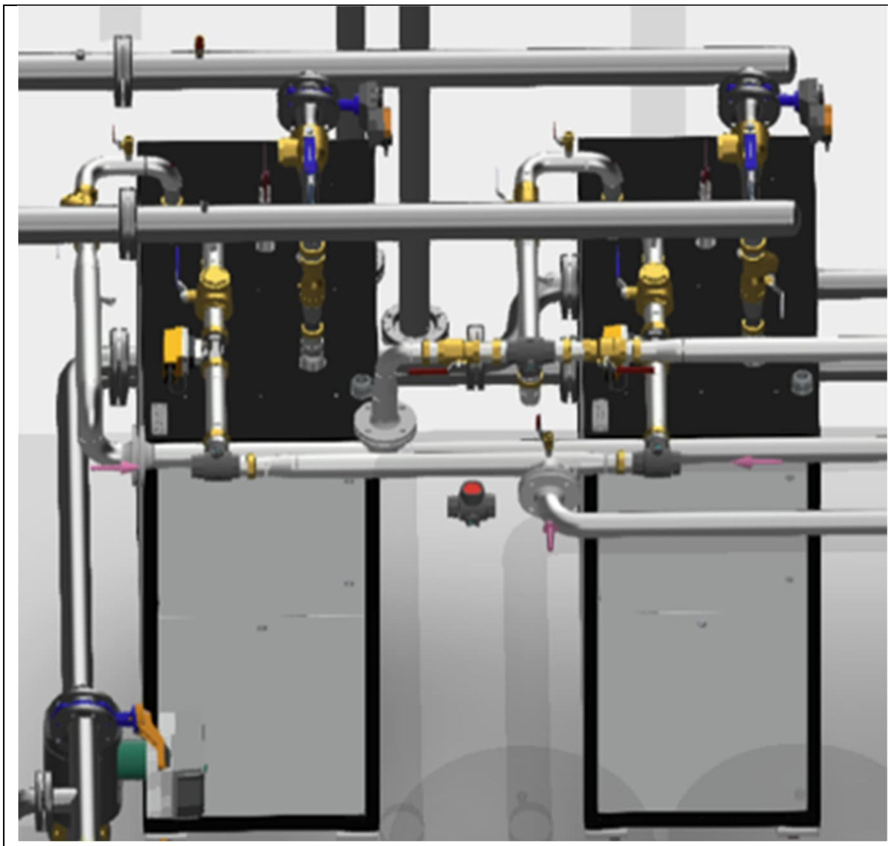
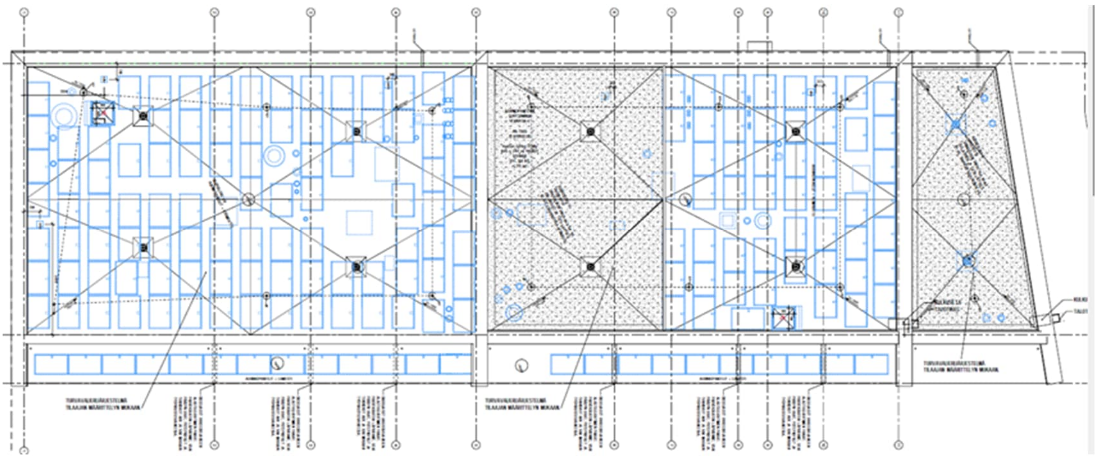


Figure 17: Taurus 80 EVI heat pumps

Solar PVT panels

In Kalasatama Finland demo building, Dualsun has assisted in designing and installations of hybrid PVT solar modules. 145 PVT panels, total area 315 m^2 and 60 kW$_p$ has been installed (Figure 18).



a. *Installation plan*

b. *PVTs at roof, general view*

a. *PVTs at roof, details*

Figure 18: PVT solar modules at Kalasatama Finland demo building

Overall energy system

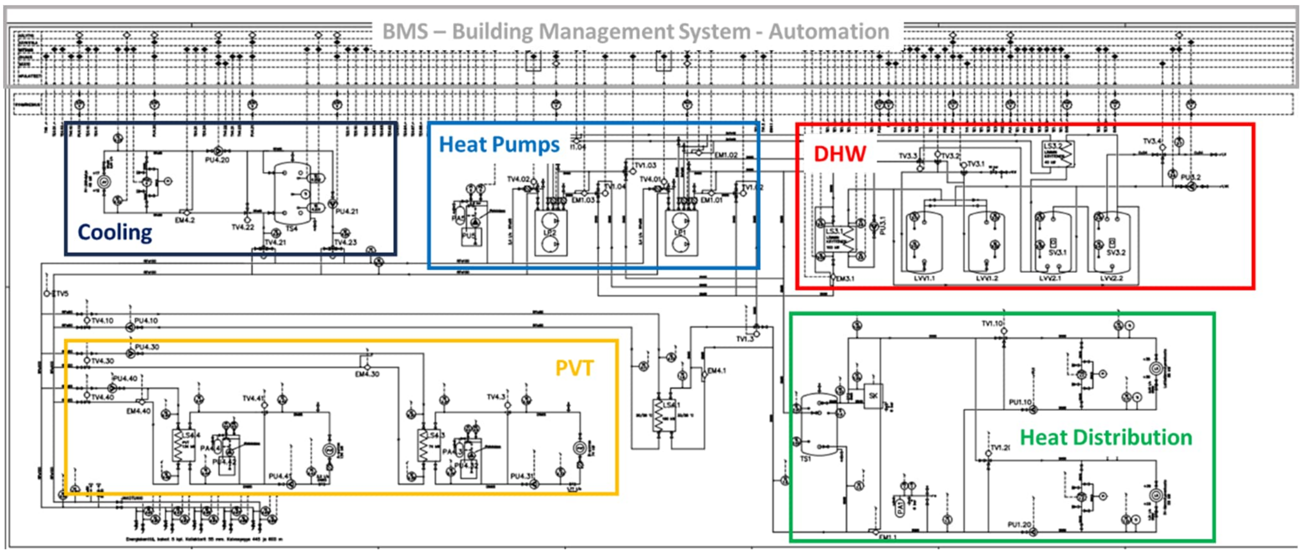


Figure 19: The general view of energy system hydraulics and measurements

2.3.4 Measurement data and ICT framework

Automation, control and measurements

Each one of the apartments have their own automation unit controlling the apartment level functions and measurements, targeting to optimize room temperatures without losses. All the apartment level automation units are connected to the main BMS unit through Modbus (Figure 20). The main BMS unit performs all the functions of heating, cooling, DHW and ventilation.

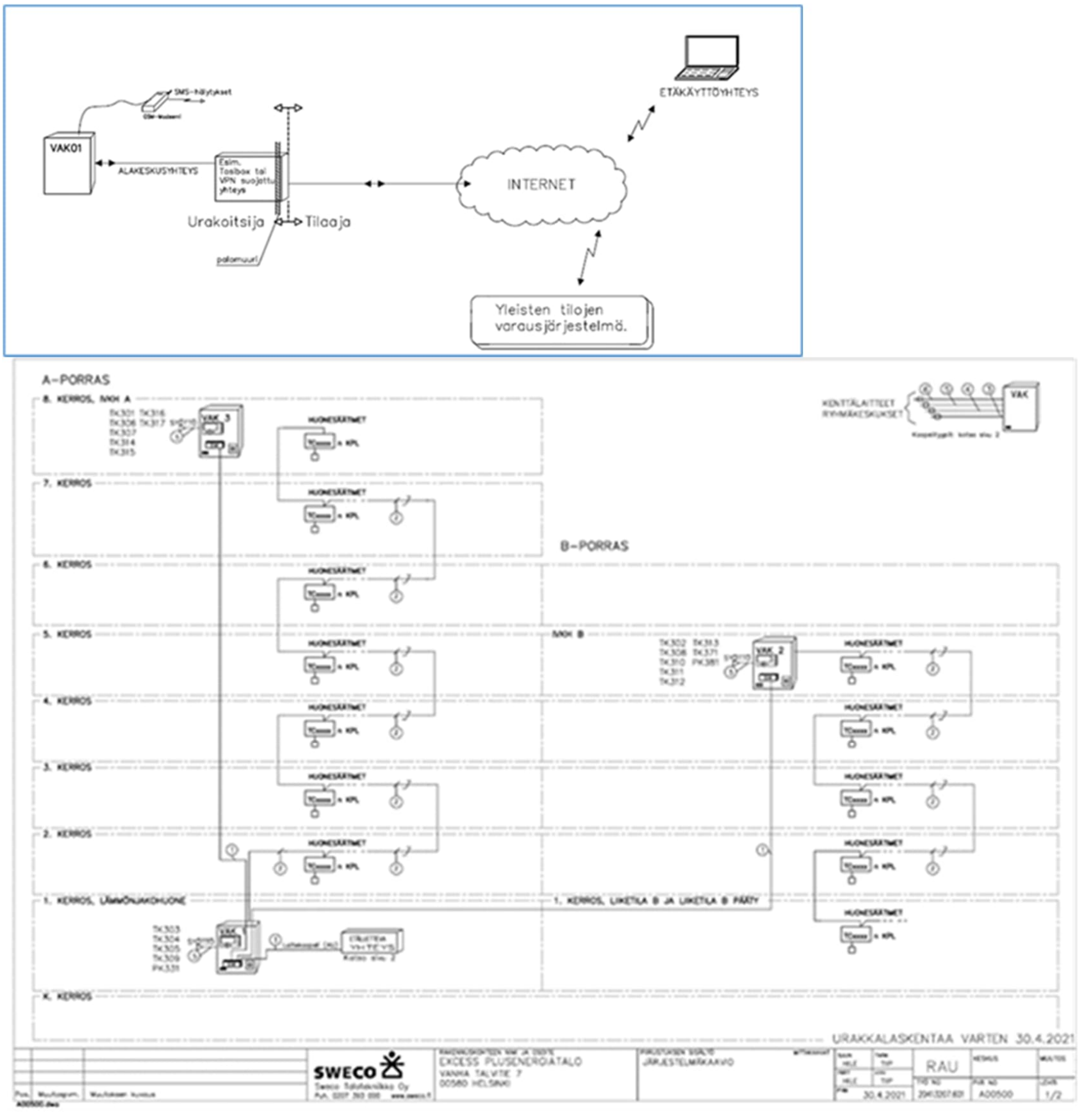


Figure 20: Automation system layout

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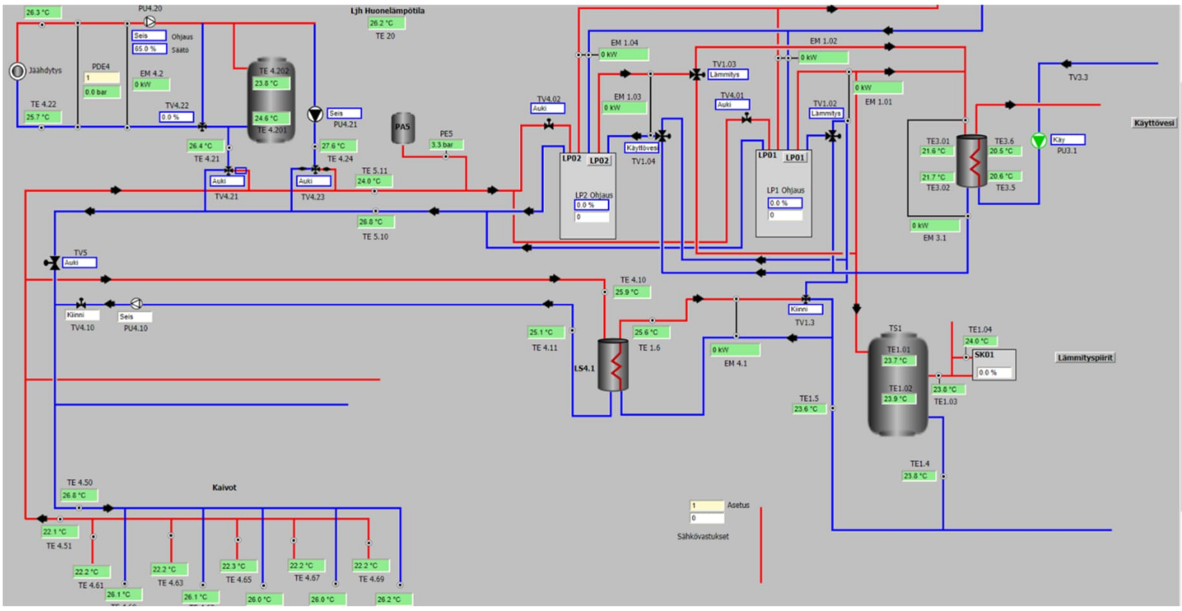

Figure 21: Layout of building management system view in Fidelix system

Some key figures of the BMS:

- Three main BMS units connected by bus
- Appr. 50 apartment level automation units connected by bus
- Appr. 1200 automation points altogether
- 1-4 automation specialists have been working on the site for more than a year
- Testing, validation and approval of the system took appr. one month

Table 7: Measurement data overview for Finnish demo case

Dataset name	Finnish demosite
Data owner	Housing cooperative Aurinkoampeeri (Solar Ampere) & TAS Tomallen Senera
Data purpose	KPI calculation, evaluation and validation of energy concept
Type of data	Time series metrics e.g. temperatures, flows, electricity consumptions, heat consumptions etc.
Metrics and scope	+/- 1.200 points sampled each minute
Data access VTT	Local BMS (source) and over secured API, limited access to VTT, only data not under GDPR
Data access Excess partners	Data not available for other parties
Data access other parties	Data not available for other parties
Metadata	Embedded in the data structure
Data preservation beyond end of project	To be decided by data owners
GDPR compliance	Data owner and user agreements in place

The selected data of Finnish demo case was linked with Excess data management platform as off-line data, by exchanging csv files. The available data sets for the evaluation phase are presented in Table 8.

Table 8: Measurement data availability

Technology related data	KPI domain(s)	Measured	Simulated	Period
PVT	Energy, Economy		X, PVGIS-5	one year, monthly PV data
PV	Energy, Economy		X, PVGIS-5	one year, monthly data
Heat pumps	Energy, Economy	X		8/2023-12/2024, optimal performance data 20.12.24-20.01.25
Electricity consumption	Energy, Economy	X		8/2023-12/2024, optimal performance data 20.12.24-20.01.25
Heat consumption	Energy, Economy	X		8/2023-12/2024, optimal performance data 20.12.24-20.01.25
Meteorological data	KPI domain(s)	Measured	Simulated	Period
Local weather conditions	Energy, technology	X		
User data	KPI domain(s)	Measured	Simulated	Period
Air humidity	Social	X		14.9-13.11.2024
Ventilation control	Social	X		14.9-13.11.2024
Comfort (temperature)	Energy, social	X		14.9-13.11.2024

The detailed electricity and heat energy data of heating, domestic hot water and heat pumps has been downloaded from BMS system, in form presented in *Table 9*, schematic presentation of energy flows in Figure 22. The total heat output of heat pump is sum of heat energy from condenser and heat energy from hot gas heat exchanger, and these are measured separately for two heat pumps in demo house. The principle of heat pump clarifying these two energy outputs is presented in Figure 23.

Table 9: The measured electricity and heat energy data of heating, domestic hot water and heat pumps

Symbol	Description	Unit
EM1_1_MW_FM	Cumulated heat energy from heat pumps to heating network	MWh
EM3_1_MW_FM	Cumulated heat energy from heat pumps to DHW	MWh
EM4_1_MW_FM	Cumulated heat energy from free cooling storage to heating	MWh
EM4_2_MW_FM	Cumulated energy from ventilation cooling network	MWh
EM1_101_MW_FM	Cumulated heat energy from condenser of HP1	MWh
EM1_104_MW_FM	Cumulated heat energy from hot gas heat exchanger of HP2	MWh
EM1_102_MW_FM	Cumulated heat energy from hot gas heat exchanger of HP1	MWh
B_LP01_SYS_KWH_FM	Cumulated electricity consumption of heat pump 1	kWh
EM1_103_MW_FM	Cumulated heat energy from condenser of HP2	MWh

B_LP02_SYS_KWH_FM	Cumulated electricity consumption of heat pump 2	kWh
LP_SM_KWH_FM	Cumulated electricity consumption of appliances in heat distribution room	kWh
SK_SM_KWH_FM	Cumulated electricity consumption of electric boiler of heating	kWh
SV_SM_KWH_FM	Cumulated electricity consumption of electric heater of DHW	kWh

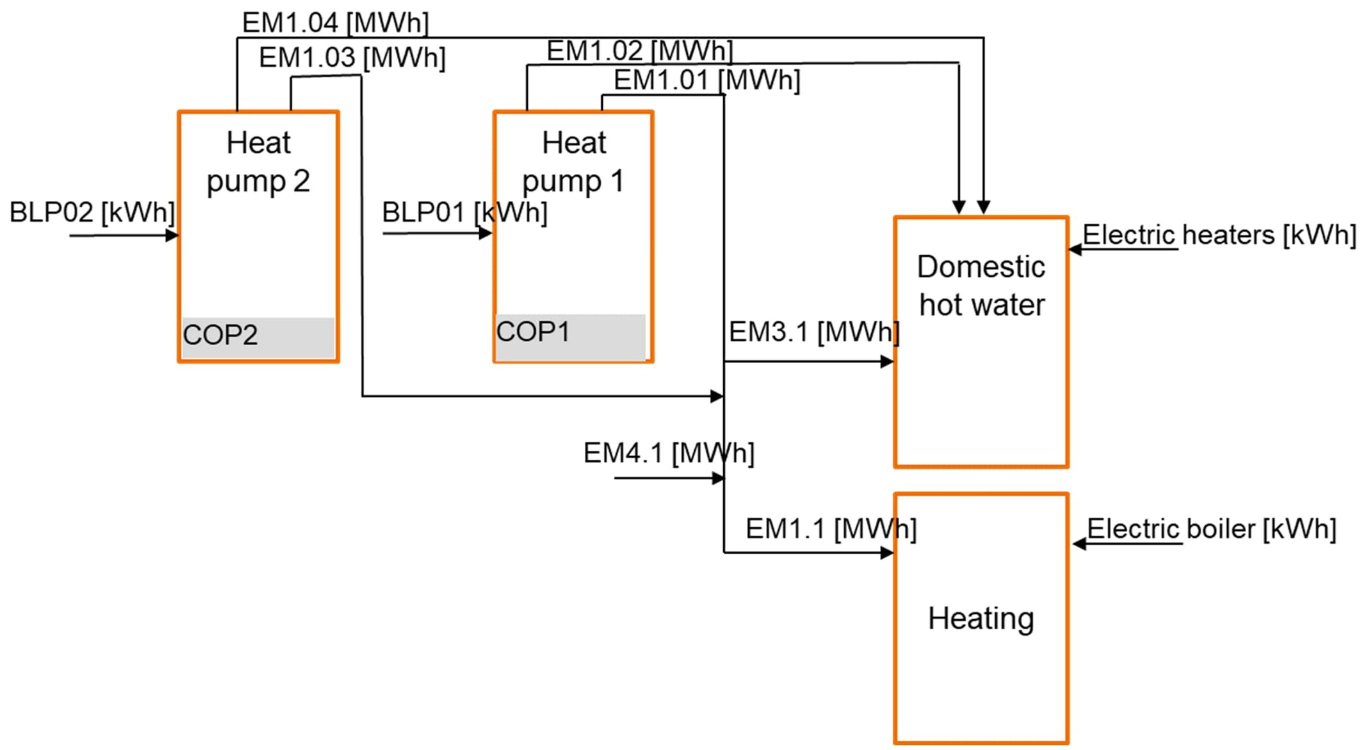

Figure 22: Schematic presentation of energy flows in heating system

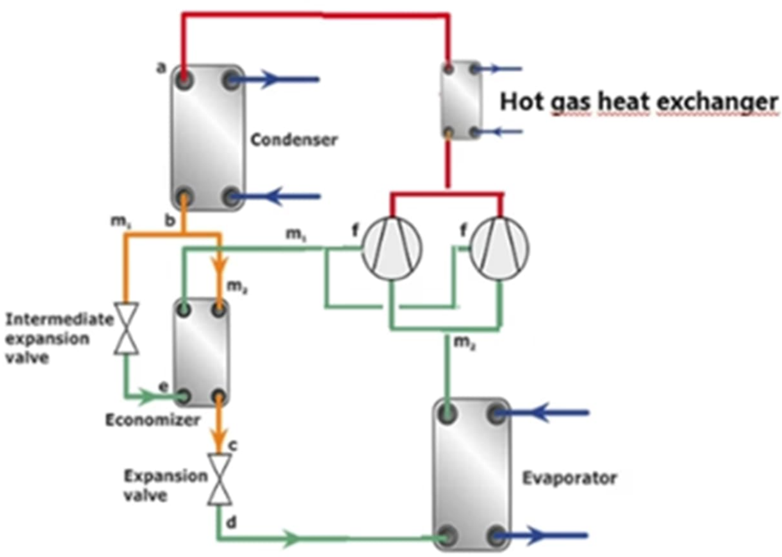

Figure 23: The principle of the heat pump in the Finnish demo

2.4 Belgium – Hasselt

2.4.1 Demo site summary

Stakeholders

The social housing company WIL (Wonen In Limburg) is building owner and responsible for managing the Belgian demo site. This includes technical operations, user administration, social services and support for their tenants. WIL has a total portfolio of approximately 24.000 dwellings in the region of Limburg. While the Flemish Society for Social Housing provides guidelines for new construction and renovation projects, support on technical aspects such as renewable energy technologies and PEB concepts is not included. As a result, the social housing company is responsible for knowledge and capacity building in these areas. Therefore, WIL considers the PEB concept as a good practice example of how to use energy technology optimally. WIL is also energy supplier since they generate, distribute and sell heat to the tenants.

The apartments offer accommodation to different kinds of tenants e.g., families with children, single person households and to people who need additional support. There are in total 20 apartments available within the four demo buildings.

Other stakeholders include the energy system installer VoltedgeSolar and Equans. Voltedgesolar installed and commissioned the technologies from the EXCESS concept and integrated them into the existing HVAC system. Equans is the maintenance service provider for the district heating network operated by WIL.

VITO is responsible for the definition of the concept, the ICT framework with monitoring and control and data analysis.

Business model

The reference business model for producing and selling heat to the tenants used by WIL is based on a reference model with natural gas boilers. The tenants will not pay more than they would pay in case of a conventional gas boiler. Therefore, the heat tariff follows the gas-price although heat can be generated by an electrical heat pump. With the EXCESS technology packages, the cost for heat production is reduced due to the increase in system efficiency and by applying load shifting. Here we refer to UC1 – load shifting with PV and fixed electricity tariff in EXCESS Deliverable 5.3 on Business Models:

<u>UC1 - Load shifting with PV and fixed electricity tariff:</u> This use case uses the thermal mass of PEBs and shifts the heat pump in order to increase self-sufficiency rate of the building. In this UC, electricity prices for purchasing and selling are assumed to be fixed (no hourly changes). As the electricity price for consumption is typically higher than the electricity price for electricity feed-in, costs reduction are possible if the heat pump load is shifted to those hours where electricity from PV is available. This means that costs get reduced through an increased self-sufficiency rate.[1]

The storage capacity of the domestic hot water tanks in the apartment satellites is used as a primary source of flexibility extended with the central storage tank.

[1] EXCESS Deliverable 5.3: Business Models for PEBs

Challenges and barriers encountered during implementation

During the course of the EXCESS project, different barriers and challenges related to the successful implementation of the PEB technologies were identified. Here we summarize the most important ones for the Belgian case:

Barrier or challenge	Category	Impact on project and replication
1. High installation costs for PVT	Financial	High
2. System design too complex	Technical	High
3. Timing installation process	Timing	Medium
4. Permitting procedures	Timing	Low

The high installation costs for the PVT installation was the most important barrier for the Belgian case. This is also linked with the second barrier referring to the complexity of the initial system design. VITO took the original system design back to the drawing board in order to simplify the system (reduce number of components, adapt control strategy) with the goal to reduce the installation and maintenance costs drastically.

It proved to be very complex to find qualified installers with sufficient knowledge on PVT, PV, heat pumps and HVAC in general. Smaller installation companies offer flexibility in terms of a more tailored and integrated installation process while the installation progress advances significantly slower due to the limited number of workers that can perform different tasks simultaneously. The commissioning of the system progressed smoothly without major problems. Also, the ICT infrastructure development and implementation did not cause significant delays.

Permitting procedures related to the electrical grid connection should be taken into account in the planning. As a results of the significant changes made to the electricity system, the as-built files of the installation had to be updated and the system had to be reinspected.

2.4.2 Energy system innovations

Heat pump prototype

The heat pump prototype was manufactured and provided by Gebwell. The heatpump uses a scroll compressor with inverter drive and allows for direct external control. The rated thermal heating capacity is $40kW_{th}$. This is sufficient to provide more than 95% of the annual heat load. In combination with the buffer capacity from the central storage tank, it is expected that the heat pump will cover almost the entire heat load of the building. The modulation range is 25 – 100%.

Figure 24: Heat pump prototype

Figure 25: Low-temperature storage tank which connects HP, PVT and BTES

Figure 26: Overview of heat pump with high temperature storage and control cabinets

Modulation tests were performed to characterise the modulation speed and response from the heat pump's compressor drive. The results of such test cycle are presented in Figure 27. In general, the HP response is well within expectations (5sec resolution).

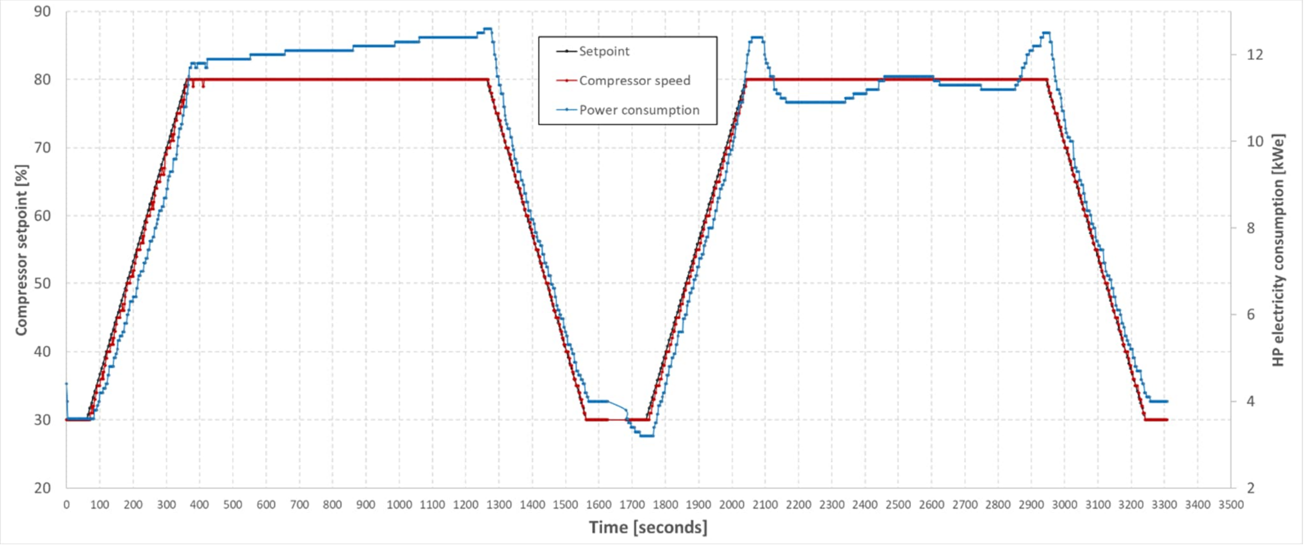

Figure 27: Results from modulation test to illustrate responsiveness of heat pump to external control signals

PVT installation

The installation process of the PVT panels was finalized in the beginning of 2024. Some modifications to the original design had to be made in order to stay within the foreseen project budget. Less panels were placed, however, with a higher electrical power output compared to the original panels. Therefore, the electrical output is similar, the thermal output is slightly less than foreseen. The panels are placed under an inclination angle of 30 degrees and an azimuth angle of 30 degrees facing South-southwest.

In total 85 panels with an electrical output of max. 35kW are installed. The installation is filled with a 30% glycol solution to prevent freezing. Heat is transported to the cold storage tank in the boiler room via insulated underground pipes (Figure 29).

Figure 28: Overview of PVT installation

Figure 29: Solar heat transport pipes to boiler room

DHN satellites

The heating satellites (Figure 30) in the apartments provide space heating and domestic hot water to the tenants. The units are equipped with a 90-litre domestic hot water boiler with integrated heat exchanger and P2H. VITO performed extensive tests in their lab in order to improve digital controllability of these units.

Figure 30: District heating satellite unit

The BEMS at the demosite determines the setpoint for domestic hot water in order to exploit the thermal flexibility from the storage tanks.

Power to heat

Power to heat is applied in the central storage tank and in the hot water storages within the satellite units. The central power to heat unit has a maximal electrical load of 6kW$_e$, it is controlled by a three-phase power controller connected with the BEMS. Power to heat is used at times when there is an EXCESS of PV energy and when the evaporator temperatures of the heat pump would be too high. In practice, this typically occurs on hot summer afternoons. In addition, P2H can be used for legionella prevention by increasing the temperature in the domestic hot water tanks periodically.

Figure 31: Phase angle controller for P2H control via BEMS

2.4.3 Measurement data and ICT framework

An overview of the measurement data is presented in Table 10.

Table 10: Measurement data overview for Belgian demo case

Dataset name	Belgian demosite
Data owner	Wonen In Limburg (WIL)
Data purpose	KPI calculation, evaluation and validation of energy concept
Type of data	Time series metrics e.g. temperatures, flows, energy consumptions etc.
Metrics and scope	+/- 1.600 points sampled each 5-15min.
Data access VITO	Local BMS (source) and over secured API
Data access EXCESS partners	Over secured API
Data access other parties	Data not available for other parties
Metadata	Embedded in the data structure
Data preservation beyond end of project	To be discussed with WIL
GDPR compliance	Data owner and user agreements in place (signed consent forms)

The available datasets are described per category in Table 11, Table 12 and Table 13. The data collection will continue after the end of the project.

Table 11: Technology measurement data availability

Technology related data	KPI domain(s)	Measured	Simulated	Period
PVT	Energy, Economy	X		04/2024 – 31/12/2024
BTES	Energy, Economy	X		04/2024 – 31/12/2024
Heat pumps	Energy, Economy	X		04/2024 – 31/12/2024
DHN satellites with P2H	Energy, Economy, Social	X		04/2024 – 31/12/2024
Electricity consumption	Energy, Economy	X		04/2024 – 31/12/2024

Table 12: Meteorological data availability

Meteorological data	KPI domain(s)	Measured	Simulated	Period
Local weather conditions	Energy, technology	X		2023 - 2024

Table 13: User-related data availability

User data	KPI domain(s)	Measured	Simulated	Period
Energy consumption	Energy	X	X	2023 - 2024
Comfort	Social	X		2023 - 2024
Comfort (temperature)	Energy	X		2023 - 2024

3 Evaluation

3.1 Spain

3.1.1 Methodology

In the Spanish Demo the monitoring started in September 2024, but only for the dwellings data due to delays in the commissioning of the facilities in the building. The monitoring of the facilities started in November 2024. Therefore, while we have some monitoring data to make the evaluation, it comprehends only a few winter months. In order to attempt to provide an unbiased evaluation of the performance of the technologies installed, the measured data has been compared with simulation data, and thus extended to a full year to cover different seasons.

To validate the simulation, the results of the building model has been compared with the available monitored data. From the comparison, the building model was slightly adjusted to match the simulation data and be able to derive the KPI's with a full year simulation. However, as no inhabitants are living there yet, variables like home appliances and plug loads electric consumption are not possible to estimate and therefore will not produce realistic scenarios for the KPI's.

3.1.2 Case specific analysis and results

Although the delays in the construction, commissioning of the systems and integration of sensors and controls prevented the evaluation of the MPC and the EMS, we have measured the impact of such systems in the real building through a simulation.

The main objective of the MPC is the reduction of consumption through a smart operation of the building HVAC systems. This result in a different temperature of the storage tanks, letting the temperature drop when heating is not needed and pre-heating when there are favourable conditions as shown in Figure 32. The MPC achieved a net energy saving of 5% through the year, which proves the potential of its use, however the control strategy didn't fully manage to avoid large deviations in temperature setpoints, which shows that it still needs improvement.

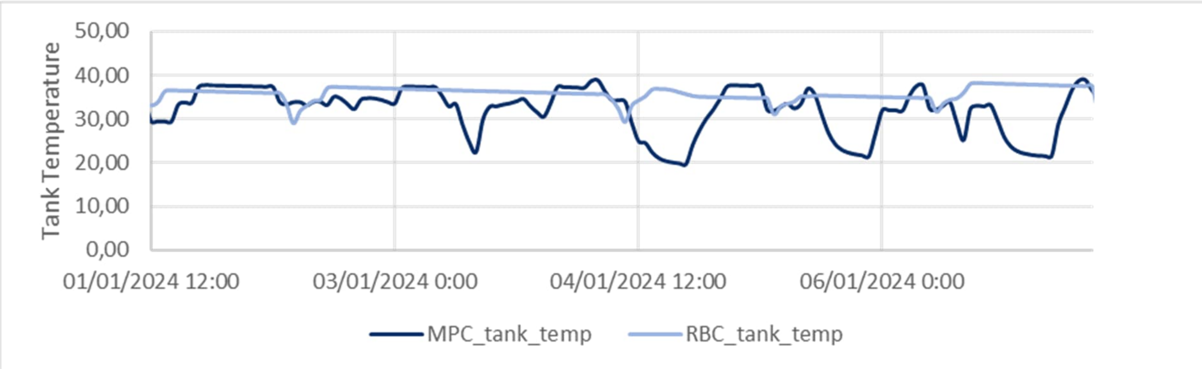

Figure 32: HVAC storage tank temperature using RBC and MPC during a winter week

he main objective of the EMS is the activation of energy flexibilities to reduce the energy bill. To evaluate the performance of the system we have compared the cost of the electricity between a standard battery charging strategy prioritizing self-consumption and the EMS designed strategies. The results represented below to show the benefit of the different system control alternatives, taking the following scenarios as a reference:

- Base case (Rule Based Control): both the aerothermal system and the batteries are managed by RBC, without any optimisation algorithm.

- Thermal MPC: the decisions for the control of the aerothermal system are calculated by a Model Predictive Control, which optimises the efficiency of the system taking into account factors such as the outdoor temperature and the COP curves of the equipment. The batteries remain in RBC mode.
- EMS: battery control decisions are calculated by Model Predictive Control, which optimises battery charging and discharging based on the electricity price profile and PV generation and demand forecasting.
- Thermal MPC + EMS: both the decisions for the control of the aerothermal system and the batteries are calculated by a Model Predictive Control.

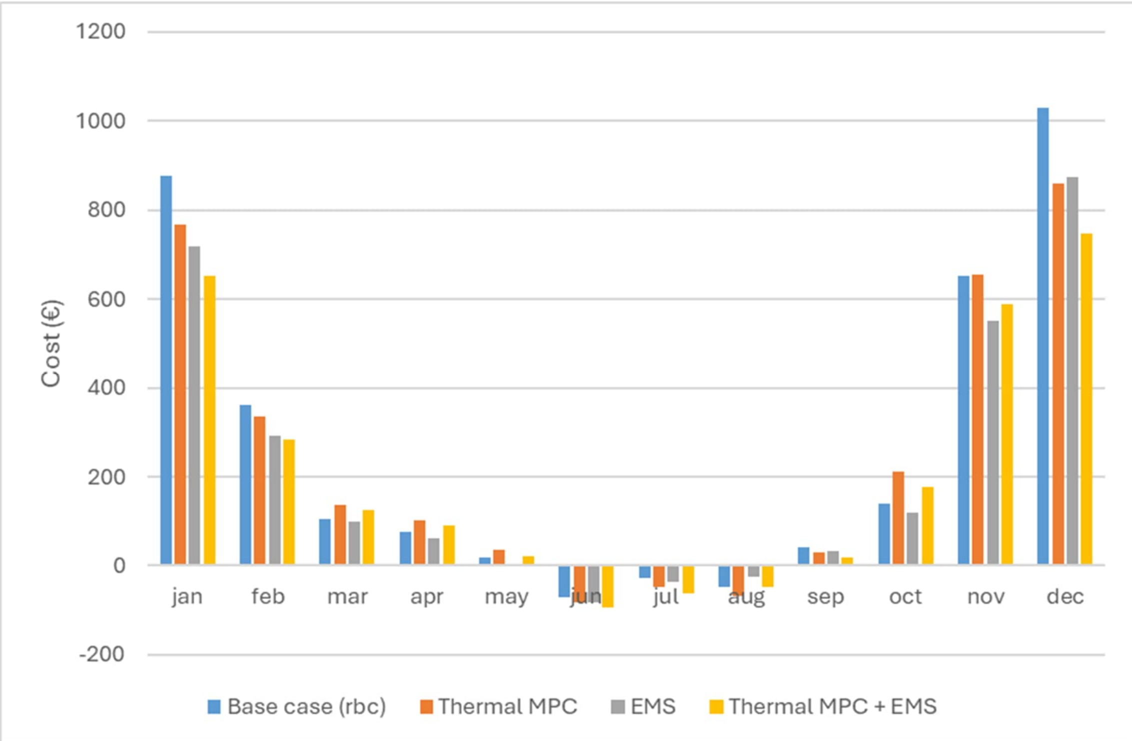

Figure 33: Comparison of system operating costs by month in the scenarios considered

As the figure shows, energy costs are much higher in the winter months due to the higher thermal demand in the dwellings and the lower generation of the photovoltaic system. In the months where there is a higher cost in the electricity bill, the progressive savings achieved by including the different control layers implemented in the Integrated Controller are more noticeable. During the summer months there is a positive balance on the bill due to the sale of photovoltaic surpluses. Although the different devices were dimensioned to obtain a positive energy building, the generation-demand balance varies significantly seasonally.

The figure below shows the resulting cost differences at each hour of the day. Notably, the operation of the EMS system (grey and yellow bars) uses storage capacity to take advantage of price differences in the market throughout the day. Thus, it increases the cost of the system in the early and middle hours of the day in order to reduce it in the early and late hours of the day.

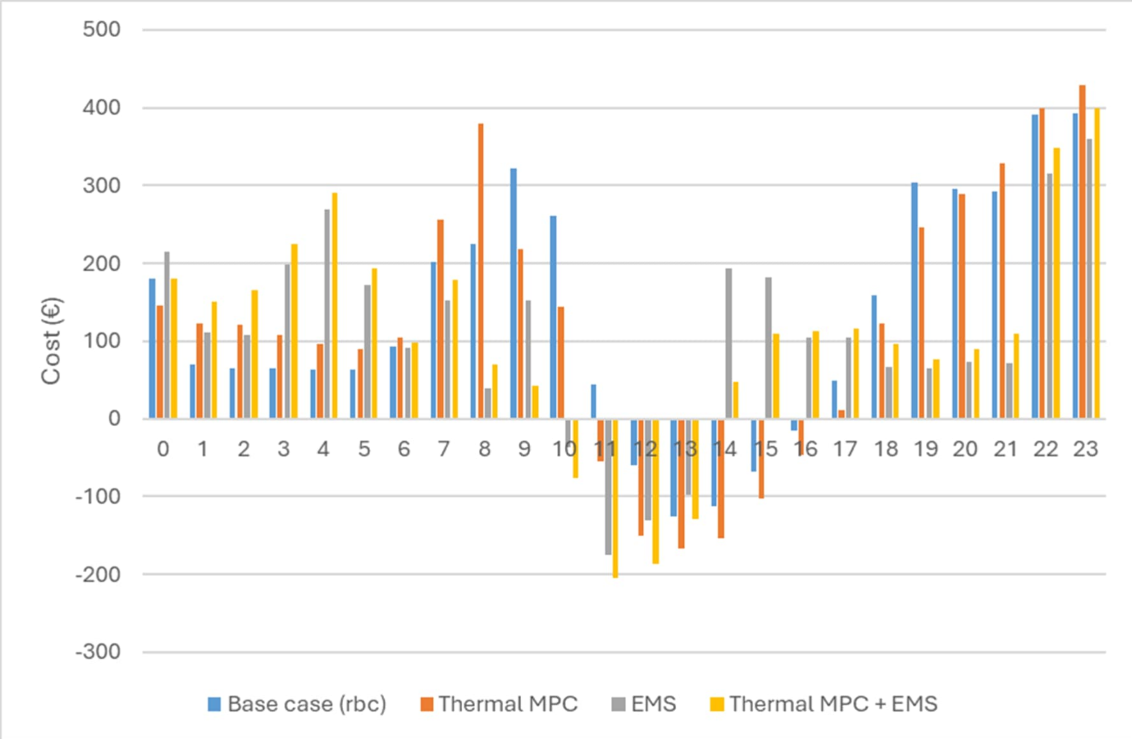

Figure 34: Comparison of system operating costs by time of day in the scenarios considered

The figure below shows the average purchase and sale prices in Spain in 2024, used in the simulations, as well as the local renewable energy generation in the building. The price variation caused by the charging and discharging behaviour of the batteries discussed above can be clearly seen.

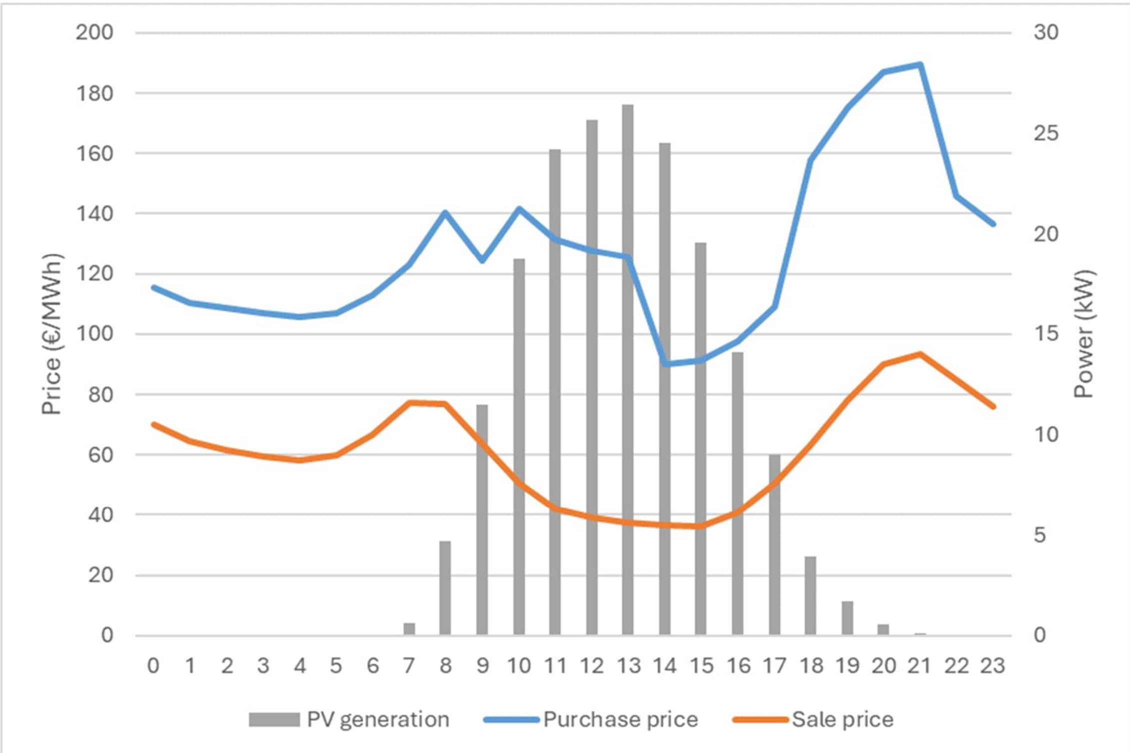

Figure 35: Average purchase and sale prices of the electricity market and photovoltaic generation in the building

The table shows the result of the total costs in each scenario, where it can be seen that the combined system of thermal MPC and economic MPC achieves the greatest savings, reaching a reduction of 20.7% in the cost of the electricity bill at the end of the year.

Table 14: Total electricity costs per simulated scenario

	Base case (RBC)	Thermal MPC	EMS	Thermal MPC + EMS
Total cost (€)	3,159.20	2,940.09	2,609.70	2,504.86
Savings (%)	-	6.94%	17.39%	20.71%

.

3.1.3 Cost analysis

The major investment in the Spanish demo involved envelope improvements, a centralized aerothermal heat pump, PV systems (51.4 kW), and energy storage (30 kWh battery). The detailed CAPEX and OPEX costs are outlined in Table 15.

This subsection outlines the investment costs and operational and maintenance cost of the Spanisch demo project Valladolid. The major investment in the Spanish demo involved envelope improvements, a centralized aerothermal heat pump, PV systems (51.4 kW), and energy storage (30 kWh battery). The detailed CAPEX, OPEX and energy costs are outlined in table 1. Total net energy costs are calculated as the difference between electricity consumption costs and revenues from grid feed-in.

Table 15: Cost of Demo Spain

Investment costs (CAPEX)	Envelope renovation with heat recovery unit	318 k€
	PV (375kW$_p$ – 137 panels)	96 k€
	Aerothermal heat pump and floor heating system	156 k€
	Battery (30kWh)	53 k€
	Advanced Building Energy Management System	25 k€
Operation costs (OPEX)	Maintenance of PV	1 812 €/year
	Maintenance of heat pump	1 460 €/year
Energy costs	Net primary energy demand	-47 kWh/m2a
	Net energy costs	-1 €/m2a
Overall life time costs (global costs)		664 €/m2a
Payback time compared to conventional renovation		30 years

It can be seen that the main part of the investment cost comes from the envelope renovation. Due to heritage protection, the insulation had to be mounted on the inner side of the wall which led to higher costs compared to conventional renovations.

Overall, the heritage protection of the building led to additional construction costs as heritage protection regulations had to be fulfilled. Therefore, it is important emphasize the multiple additional benefits of the renovation. The main aspects are an enhanced property value, increased comfort as well as reduced electricity costs and revenues from renewable energy production. Additionally, the buildings thermal system and the battery storage could be used to gain savings and additional revenues from implicit and explicit flexibility activities.

The economic analysis in D5.1 showed that the building renovation to PEB level has a payback time of around 30 years. This means that the reduced energy costs and the revenues from electricity feed-in could fully compensate the investment after 30 years. For more details on the calculation method and calculation parameters, see D5.1. This deliverable also shows a comparison of the Spanish demo technology package with other technology packages.

3.2 Austria

3.2.1 Methodology

For the Austrian demo building, a total renovation of the entire building was not feasible within the project timeline. It became apparent that only one demo room could be finished until the end of the project. However, the relevant interfaces between façade segments, the joints and mounting strategies (horizontal and vertical mounting, corners, hydraulic connections, cladding) could be sufficiently tested. In order to produce meaningful results on the systems performance and behaviour that provide a strong basis for replicability, the demo leader developed a measurement-data augmented digital twin of the entire building that is based on more detailed monitoring data than initially planned. This allows to extrapolate the effects of the renovation and all connected technical innovations like the active facade technology, smart energy management system and supervisory model predictive control for the entire building and furthermore other building typologies and designs.

The only partial refurbishment affects the amount of collectable data and requires additional effort and a change of methodology for the estimation of thermodynamic façade parameters. Therefore, the research team decided to adapt the foreseen measurement strategy from a monitoring based on data points that would be available within a smart control system to a much more detailed in-depth measurement for the controlled demo room, including additional measurement values like heat fluxes, thermography scans and sophisticate indoor climate assessment. A visualisation and listing of the data points is shown in Figure 36. Figure 37 shows pictures of the temporary installation of additional measurement equipment on site. The IoT technologies and devices developed within the project are also installed in the test room and deliver the monitoring data of the heating and energy system, external variables and room temperatures. The included databases and data handling are running as planned.

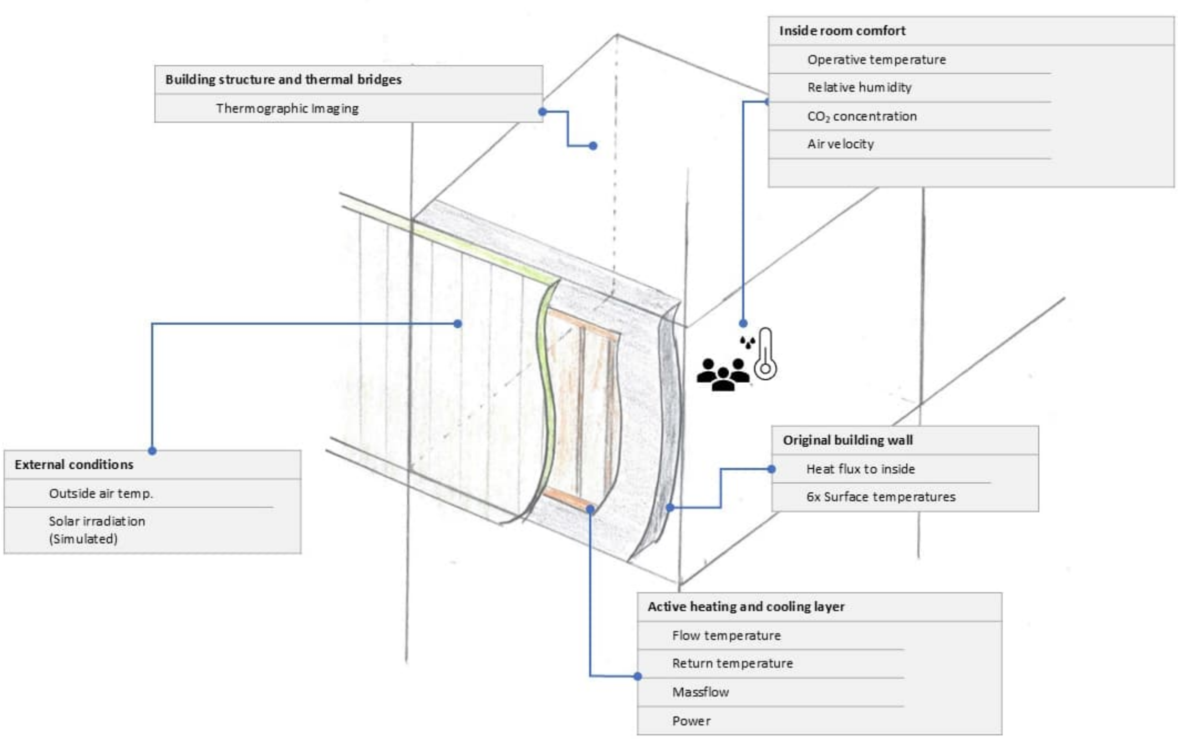

Figure 36: Sketch of Demo Room with a list of measurement point at the according components

Figure 37: Realized demo room setup from the inside with comfort and heat flux measuring equipment

The measurement-data augmented digital twin is based on a dynamic white box model simulation of the whole building that requires data from the real physical system for parametrization. The finished twin, is used for whole year simulations with reference climate data for the city of Graz, including the virtual implementation of the supervisory MPC. The evaluation criteria, KPIs and data visualization for reporting is mainly based on these simulations.

3.2.2 Case specific analysis and results

On site measurements

Thermography measurements have confirmed that heat transfer from the active facade layer to the interior of the test room is functioning as intended, validating the novel concept. Inconsistencies in the wall material significantly affect local heat transport. Concrete columns within the structure act as both heat dissipators and thermal storage units as visible in Figure 38. The system's large-area, low-temperature heat dissipation capability enables radiative heating of the opposite interior walls (see Figure 39), contributing to a more balanced thermal environment, than the retrofitting of low temperature radiators would have.

Further thermographic images underscored the critical role of detailed elements, such as proper insulation around window sills, in mitigating thermal bridges. The experiments were conducted at lower-than-normal room temperatures, as the partitioned test room is situated in the middle of an active construction site with limited insulation from the unconditioned areas of the building. Despite these constraints, heat transfer rates of up to 20 W/m² were achieved (scaled to design temperature conditions and at average T_fluid = 35°C), demonstrating the system's effectiveness. These results confirm that the approach is well-suited for full-scale renovations, particularly given that all floors above level 2 are constructed entirely of concrete, which enhances thermal storage and heat transfer efficiency.

Figure 38: Thermographic image (left) of the thermally activated facade seen from the inside of the demo room and visible spectrum reference image (right)

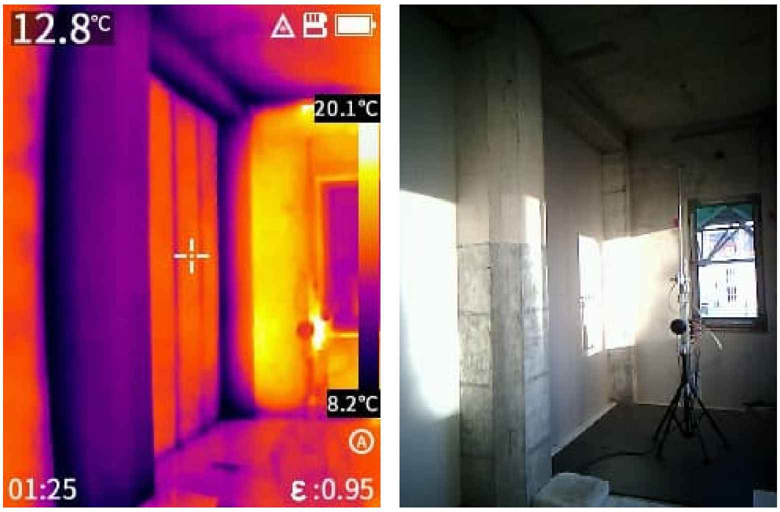

Figure 39: Thermographic image (left) of the thermally activated facade and opposite inside wall seen from the inside of the demo room and visible spectrum reference image (right)

Digital Twin Simulation Results

A dynamic building and system simulation was developed using physical parameters obtained from on-site measurements and prior facade lab tests. This simulation was employed to virtually replicate the renovation, including the integration of the developed MPC control mechanisms, across the entire demonstration building, which also makes use of temperature flexibilities for load shifting. Simulations for a full year of operation revealed that the active facade renovation concept can consistently maintain room comfort. As illustrated in Figure 40, none of the residential rooms operative temperature dropped below 21°C during winter, while worst-case summer temperatures peaked at 28°C, even without accounting for active nighttime window ventilation. The temperature deviation for the first and second floor are based on the vertical coring brick sections in the facade compared to a pure concrete structure for the rest of the tower and are more pronounced during cooling season.

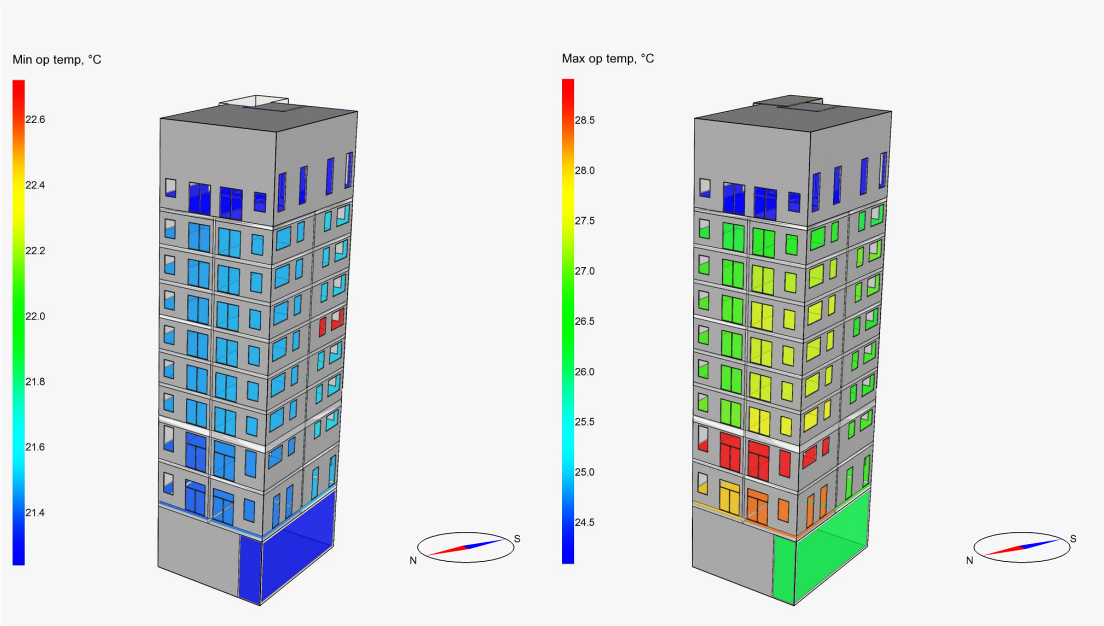

Figure 40: Visual representation of operative temperature extremes for heating (left) and cooling (right)

Impact of Model Predictive Control

The shift towards detailed simulation for the demonstration building has introduced a significant advantage: the ability to conduct repeated, comparable experiments under identical boundary conditions. This capability enabled a thorough assessment of the performance of Model Predictive Control (MPC) algorithms compared to conventional rule-based energy management systems and standard control methods without load-shifting capabilities.

The decision to implement MPC was driven by the unique challenges posed by the building's large thermal time constants, a result of thermally activating its facade. Standard heating controls struggle to manage these delays and the interference of boundary conditions like weather and occupancy. However, the activated thermal masses also serve as substantial energy storage, allowing energy usage to be shifted to periods of renewable production while maintaining user comfort.

This multi-objective optimization is ideal for MPC, which was extended in this project to also address electricity grid relief. Co-simulation experiments revealed that MPC significantly enhances load-shifting capabilities for the heat pump system, as illustrated in Figure 41. Comparisons of energy demand among Standard Control, Conventional EMS, and MPC show that MPC prioritizes electricity from the BiPV system while maintaining comfortable indoor temperatures, further detailed in Figure 42 and Figure 43 for an exemplary winter week. It was found that an indoor temperature flexibility of around 2°C is enough to significantly increase the energy performance of the Building.

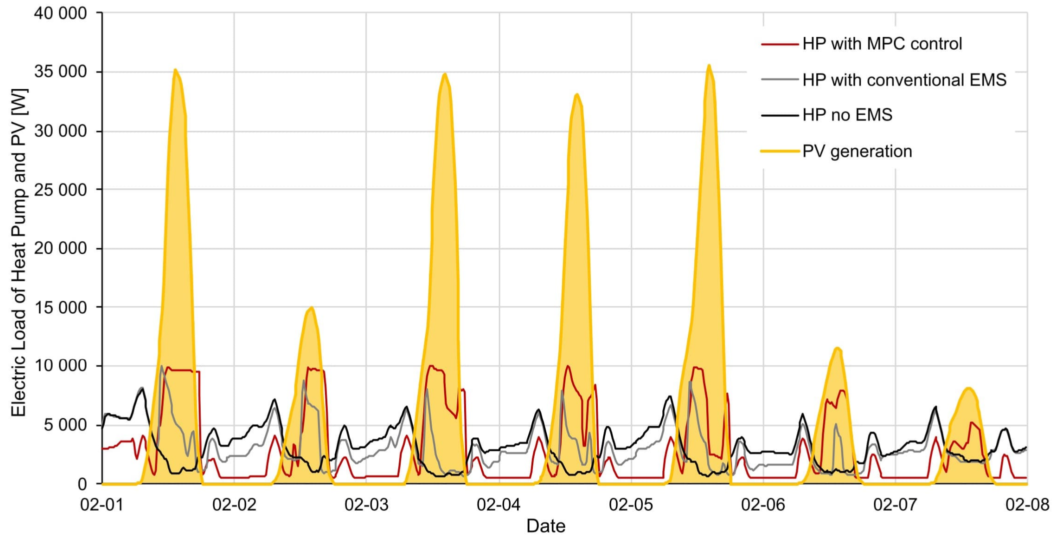

Figure 41: Comparison of heat pump electricity demand for different control systems tested with the Austrian demonstration building in relation to available PV-generation for an average winter week in February.

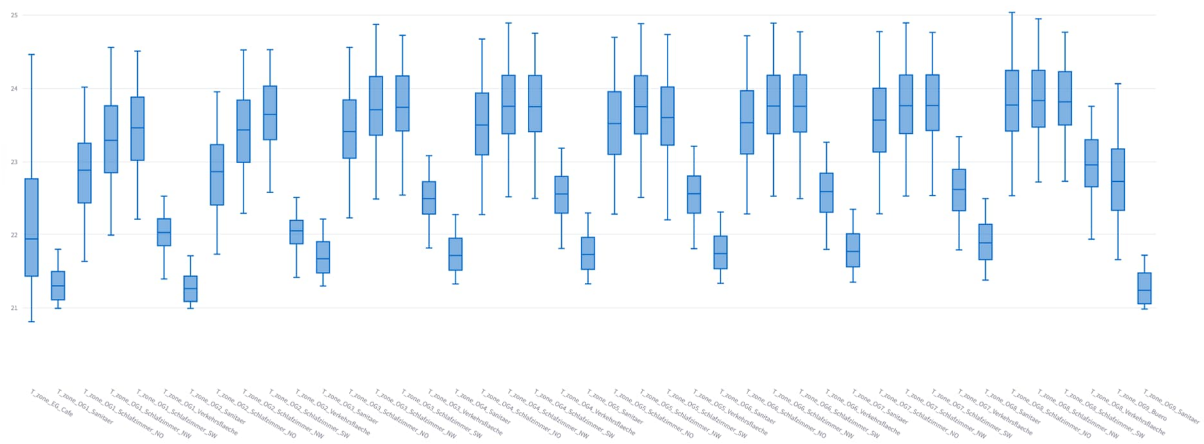

Figure 42: Box Plot of the room wise operative temperature range in the Austrian demonstration building for an average winter week in February

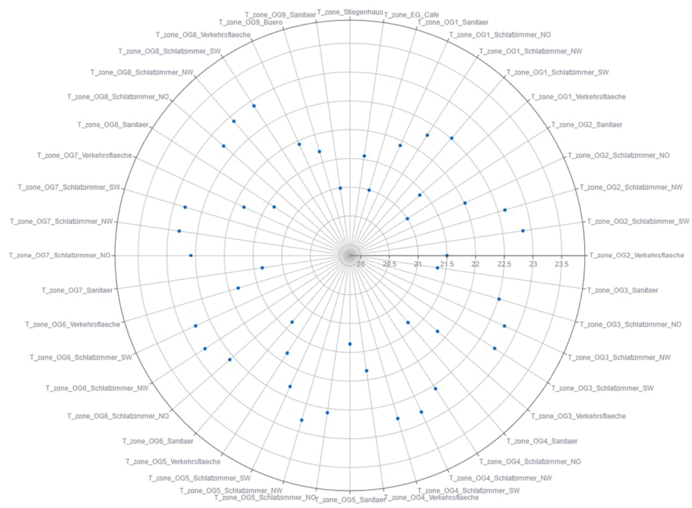

Figure 43: Visualization of minimally occurring operative temperatures in the Austrian demonstration building during an average winter week in February.

The implementation of the MPC algorithm developed within EXCESS demonstrated significant improvements across all evaluated aspects. In terms of absolute energy demands, as shown in Table 16, the energy usage for heating and cooling was notably reduced. By utilizing predictions of room and outdoor temperatures, the system effectively avoided scenarios of overheating or undercooling, optimizing energy consumption in various conditions.

Additionally, the MPC system achieved a further reduction in grid-imported and grid-exported energy. This improvement was driven by enhanced load matching, aligning energy demand more effectively with renewable energy supply.

Table 16: Absolute energy demands and production of the Austrian Demonstrator for different control systems

	Total Generation [kWh/a]	Electricity Demand Heating + DHW [kWh/a]	Electricity Demand Cooling [kWh/a]	Household Electricity Demand [kWh/a]	Grid Import [kWh/a]	Grid Export [kWh/a]
No EMS	62006.0	15743.8	4508.3	21858.8	22090.6	42092.8
Conventional EMS	62006.0	16943.1	4752.5	21858.8	21263.2	39821.9
MPC Control	62006.0	13270.7	4505.5	21858.8	16707.8	39079.2

The findings in Table 17 further highlight the benefits of the implemented MPC algorithm, showcasing significant improvements in the On-Site Energy Ratio, which underscores the Positive Energy Building (PEB) status of the demonstration case. Delving into the Load Cover Factor for heating and domestic hot water (DHW) production, a remarkable improvement over standard control and conventional EMS is evident, achieving nearly 60% on-site renewable energy coverage for heat production. Additionally, the building's overall Load Cover Factor increased to 57.8%, reflecting the efficiency gains enabled by the system.

Table 17: Energy related KPIs of the Austrian Demonstrator for different control systems

	On Site Energy Ratio	Load Cover Factor Heating + DHW	Load Cover Factor Cooling	Load Cover Factor Household Electricity	Total Load Cover Factor	Total Supply Cover Factor
No EMS	147.5%	32.2%	69.3%	54.1%	47.5%	32.2%
Conventional EMS	142.6%	42.7%	70.8%	53.5%	51.2%	35.9%
MPC Control	156.4%	59.9%	73.0%	53.5%	57.8%	37.0%

By leveraging multi-objective optimization, an additional goal of reducing power peaks in the electricity grid was achieved. As illustrated in Figure 28, a 12.3% reduction in the highest 1% of grid load situations (calculated using a 15-minute average) was managed for grid import. This is particularly valuable as it frees up capacity for other applications, such as charging electric vehicles, further demonstrating the system's ability to contribute to a more balanced and sustainable energy ecosystem.

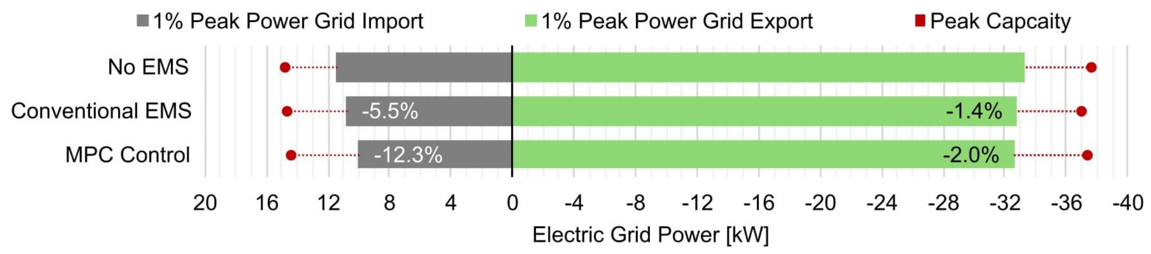

Figure 44: Impact of different control systems on the electrical grid behaviour of the Austrian demonstration building

3.2.3 Cost analysis

The detailed CAPEX and OPEX costs of the Austrian demo building are outlined in Table 18. Total net energy costs are calculated as the difference between electricity consumption costs and revenues from grid feed-in.

Table 18: Cost of Demo Austria

Investment costs (CAPEX)	Renovation of façade with multifunctional façade elements	610 830 k€
	Ground Water Heat Pumps	92 196 k€
	BiPV (520m2, 88 kWp)	200 k€
Operation costs (OPEX)	Maintenance of multifunctional facade	6 106 €/year
	Maintenance of heat pump	1 507 €/year
	Maintenance of BiPV	1 265 €/year
Energy costs	Net primary energy demand	-36 kWh/m2a
	Net energy costs	0,18 €/m2a
Overall life time costs (global costs)		843 €/m2a

It can be seen that the main part of the investment cost comes from the multifunctional façade element. The elements contain insulation and wall heating as well as the mounting system for the BiPV. The building renovation of the Austrian demo is more expensive than a conventional renovation. However, the renovation with multifunctional façade elements exhibits many additional benefits such as:

No floor heating system needed: The wall heating system of the multifunctional façade element replaces existing heat distribution systems with radiators and does not need a change to a floor heating system, which is one of the main advantages of a renovation with the multifunctional façade element. No revenue is lost for the owner due to empty and therefore unused flats.

Non-intrusive renovation process: One central benefit is the non-intrusiveness of the renovation process. This means that tenants do not have to move out during the renovation process, as the multifunctional façade element is placed on the outside of the building. Renovation with multifunctional façade elements therefore save the cost of relocation of tenants.

Speed of renovation: Another financial benefit of the serial renovation approach is the speed of renovation. As the façade elements are prefabricated, the renovation process onsite is faster (around 50-60% time saved) compared to conventional renovation processes.

<u>Flexibility revenues:</u> Buildings with wall heating systems activate a high thermal mass, and therefore, have a high potential for heat energy demand shifting. Flexible demand shifting could lead to additional revenues sold to markets.

For more details on the calculation method and calculation parameters, see D5.1. This deliverable also shows a comparison of the Austrian demo technology package with other technology packages.

3.3 Finland

3.3.1 Methodology

The performance of EXCESS demo case in Finland has been evaluated based on measurements and simulations. The energy performance was monitored since August 2024, but the heat pump system was not operating in the final model, and this long period data cannot be used for the final performance evaluation. Now at the end of 2024 the heat pump system is performing as planned. PV and PVT systems are not operational and PVT electricity production is evaluated based on simulations. Overall analysis is combining measurements and simulations. The electricity and heat consumption measured during the operational periods has been used for evaluation of a full year period, and the simulated PV/PVT electricity production has been evaluated together with these. The yearly energy cost has been estimated.

The evaluation results consist of

1. Heat consumption of space heating and domestic hot water heating
2. Electricity consumption heat pumps of space heating and domestic hot water heating
3. Performance evaluation of heat pumps based on 1) and 2)
4. Indoor air temperatures in 6 randomly selected apartments
5. Yearly and monthly PV and PVT electricity production
6. Yearly and monthly net electricity consumption vs. production and utilisation rate
7. CAPEX and OPEX

3.3.2 Case specific analysis and results

Heat consumption of space heating and domestic hot water heating

The heat consumption of space heating and domestic hot water heating has been monitored since 18.10.2024, analysed after the system was performing as planned during 19.11.2024-13.1.2025. The heat consumption was measured by cumulative energy measurement, and the instantaneous power has been calculated as difference between consecutive values (E_i-E_{i-1}). Figure 45 shows the measured consumption of the space heating (EM1.1) and Figure 46 the measured energy consumption of the domestic hot water system (EM3.1+EM1.02+EM1.04 + direct electricity for DHW). The thermal conductance for whole the building as function of outdoor temperature was then defined for the building heat losses (Figure 47). This was later used for the calculation of monthly and yearly heat consumption. The monthly and yearly heat consumption of domestic hot water was estimated based on short period measurements, which gave the average daily heat consumption. The consumption of the domestic hot water was not measured but can be estimated based on energy measurements. During the measured period the heat demand of domestic hot water was 449 kWh/day, which at 50 ^{o}C temperature difference (e.g. water heated from 8 to 58 ^{o}C) means 7,7 m^3/day at building level and average 148 dm^3/day per apartment. In the later analysis this amount was used in monthly calculations.

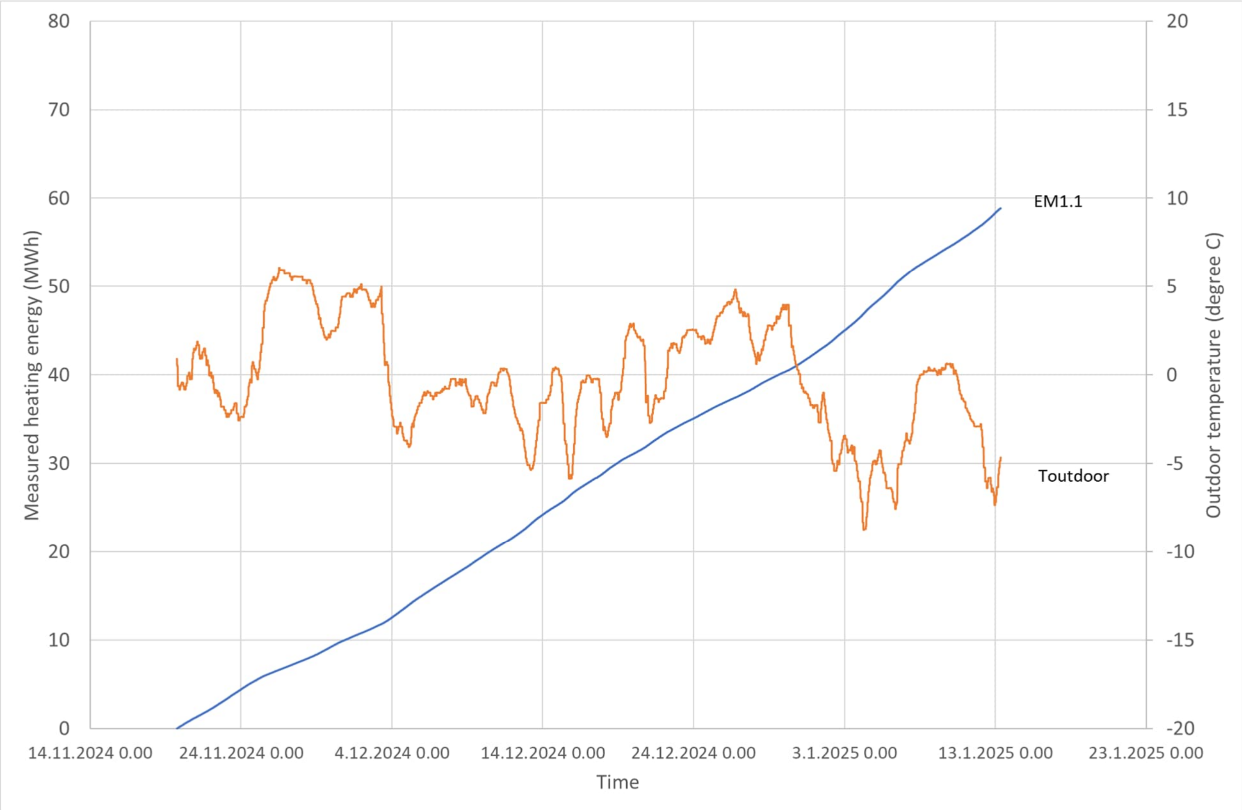

Figure 45: The measured consumption of the space heating (EM1.1) and outdoor temperature

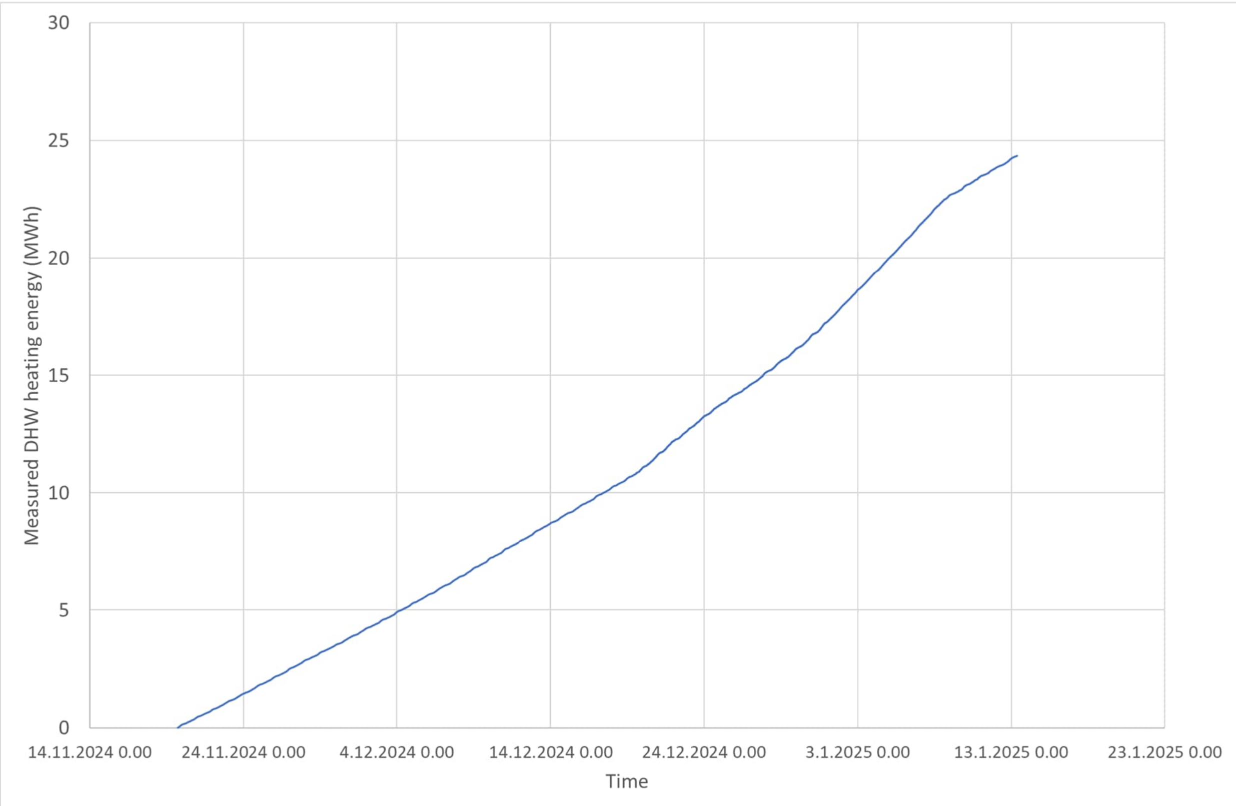

Figure 46: The measured energy consumption of the domestic hot water system (EM3.1+EM1.02+EM1.04+direct electricity for DHW)

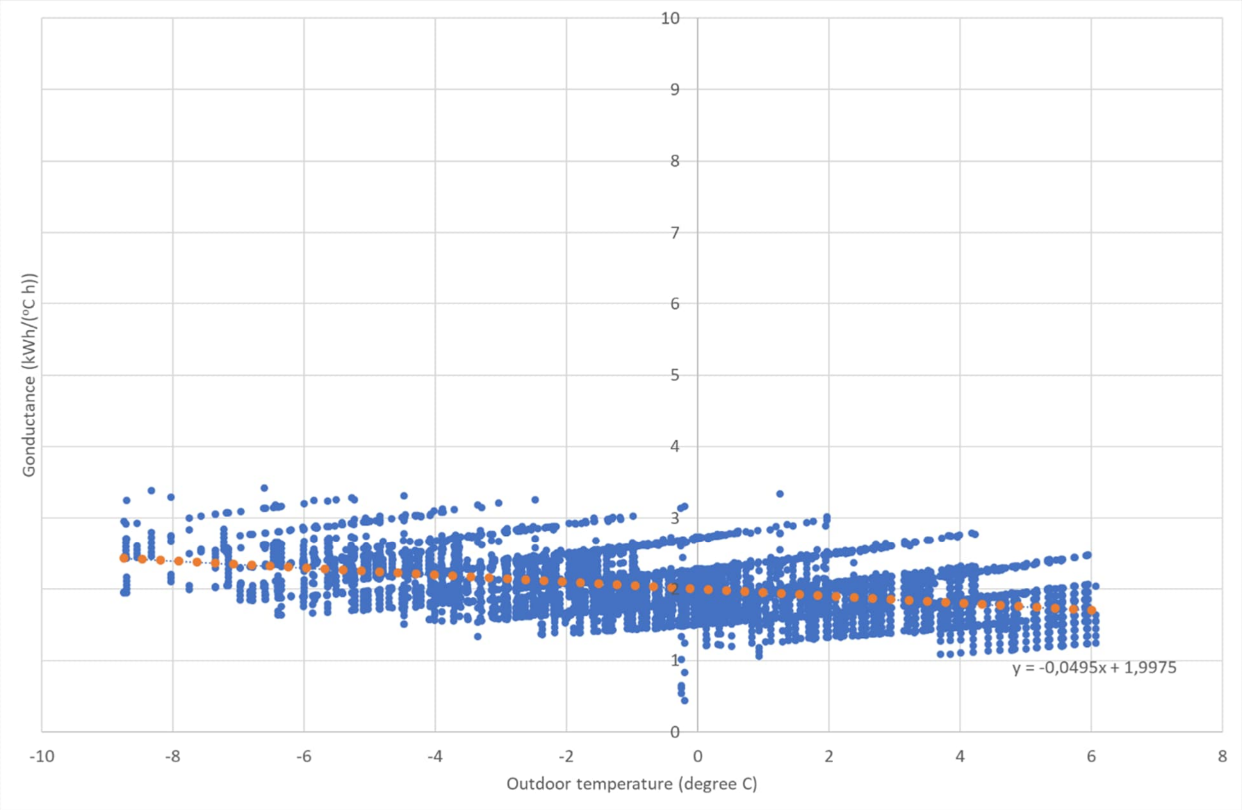

Figure 47: Thermal conductance for the heating of the building as function of outdoor temperature

The yearly and monthly heating energy consumption was estimated:

$$E = (1{,}9975 - 0{,}0495\ Toutdoor) * HDD$$

HDD is heating degree days of the location (unit W h/K d), and can be found for different locations and different years from web pages of Finnish Meteorological Institute.

Figure 48 presents the monthly heating energy demand in 2024. The total heat demand per heated floor area is 38,7 kWh/m^2. The electricity demand is presented later in Figure 53.

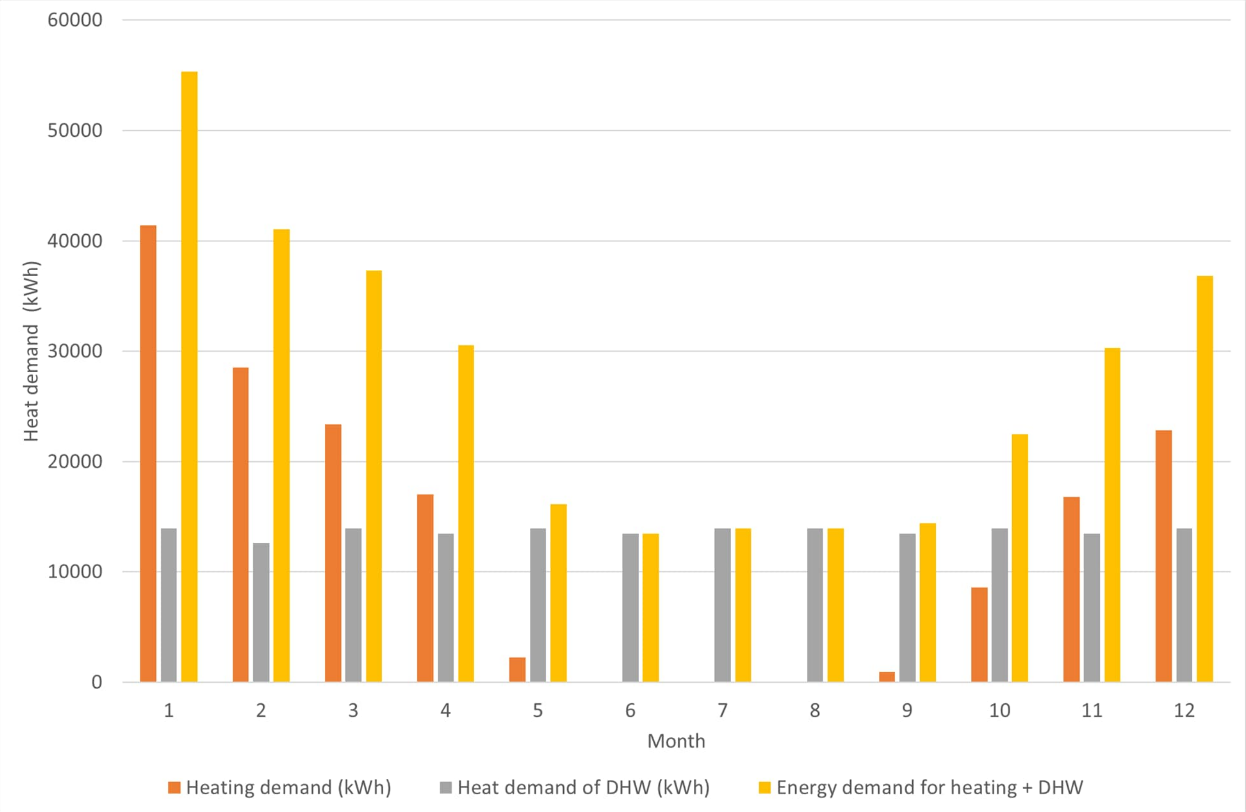

Figure 48: Monthly heating energy demand of EXCESS building in 2024 in normal operation mode.

Electricity consumption of heat pumps

The heat pump electricity use and detailed temperatures has been measured since August 2023. In 2024 the heat output metering has been added enabling the evaluation of coefficient of performance. Figure 49 presents the heat pump energy input (electricity) and output (heat) during 19.12.2024-13.1.2025, when the hybrid energy system was performing as planned. The energy figures are integrated energies in 6 hours periods, making the curves more readable.

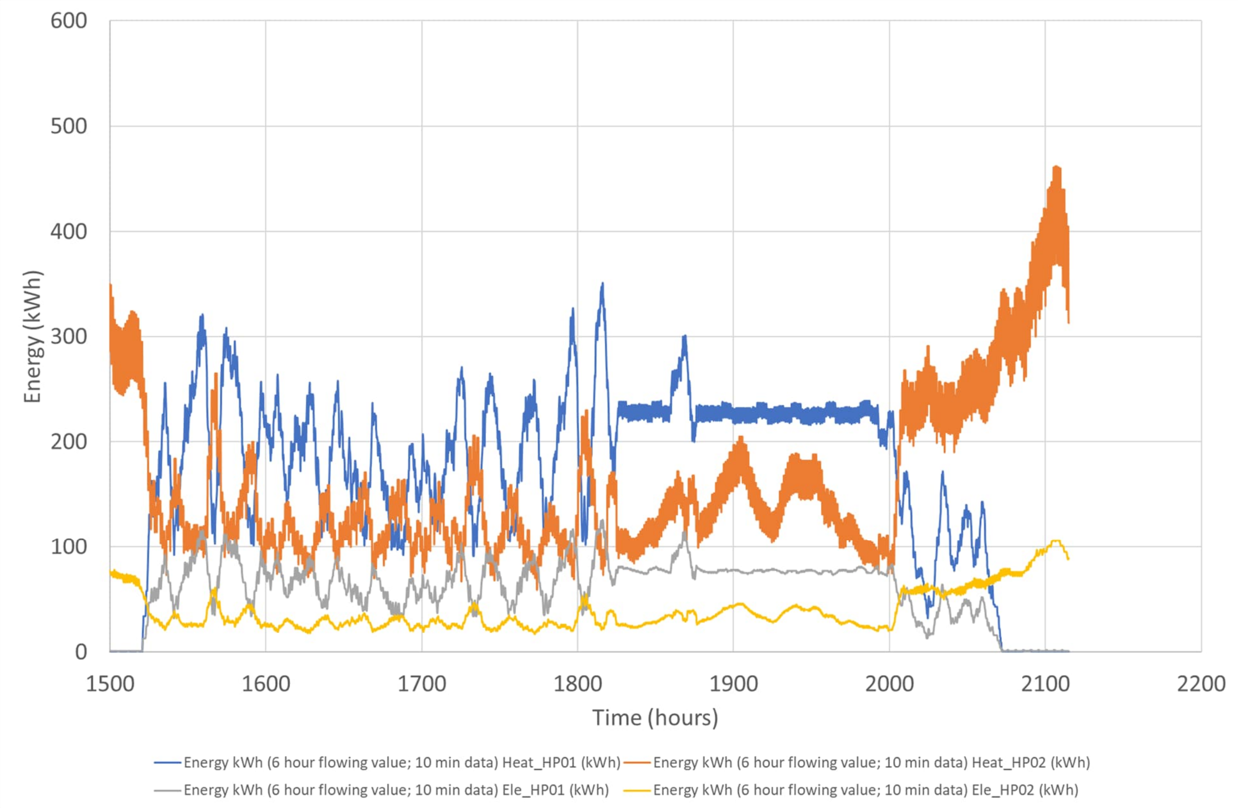

Figure 49: Heat pump energy input and output during 19.12.2024-13.1.2025

Performance evaluation of heat pumps

Figure 50 presents the heat pump energy flows and COPs during 19.12.2024-13.1.2025 and Figure 51 COPs during the same period calculated from energy measurements 6 hours backwards. During the monitored period the COP of heat pump #1 is 2,9 and heat pump #2 has a COP of 4,3. The overall COP_{HPs} for heat pumps is 3,4. In case the direct electricity is needed as extra power in heating or DHW system this decreases the system COP and in this period system COP_{sys} was 2,9. This happened during the measurement period in last 2 days, as seen in Figure 51.

The equations used for the COP calculations:

$$COP1 = \frac{\text{EM1.01} + \text{EM1.02}}{\text{BLP01}}$$

$$COP2 = \frac{\text{EM1.03} + \text{EM1.04}}{\text{BLP02}}$$

$$COP\_HPs = \frac{\text{EM1.01} + \text{EM1.02} + \text{EM1.03} + \text{EM1.04}}{\text{BLP01} + \text{BLP02}}$$

$$COP\_sys = \frac{\text{EM1.01} + \text{EM1.02} + \text{EM1.03} + \text{EM1.04} + \text{Direct electricity for DHW\&heating}}{\text{BLP01} + \text{BLP02} + \text{Direct electricity for DHW\&heating}}$$

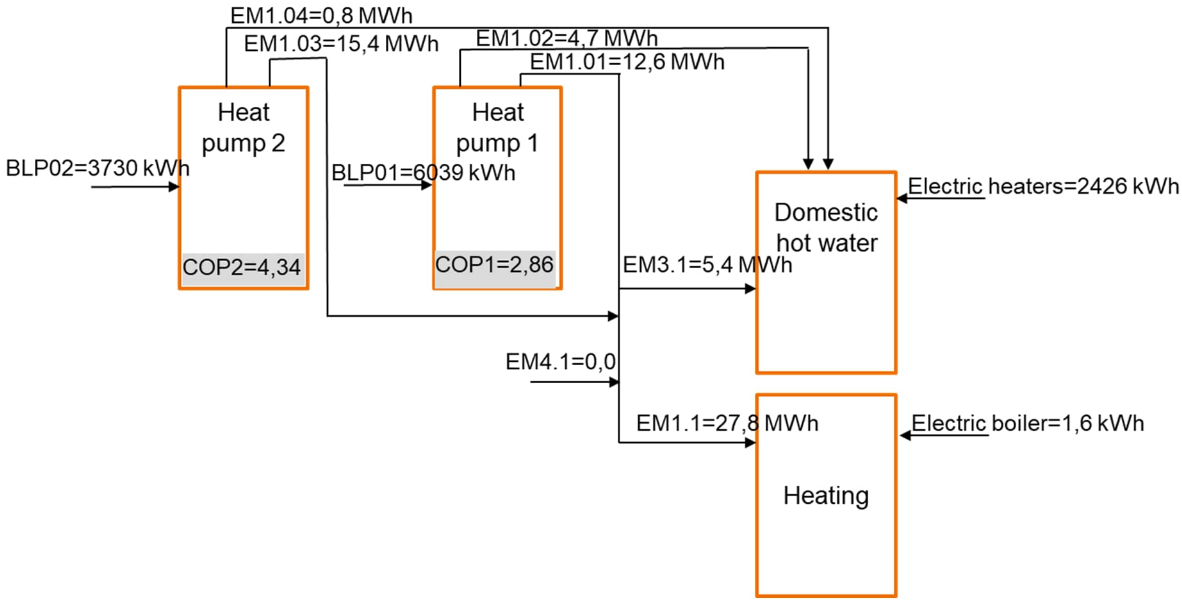

Figure 50: Heat pump energy flows during 19.12.2024-13.1.2025

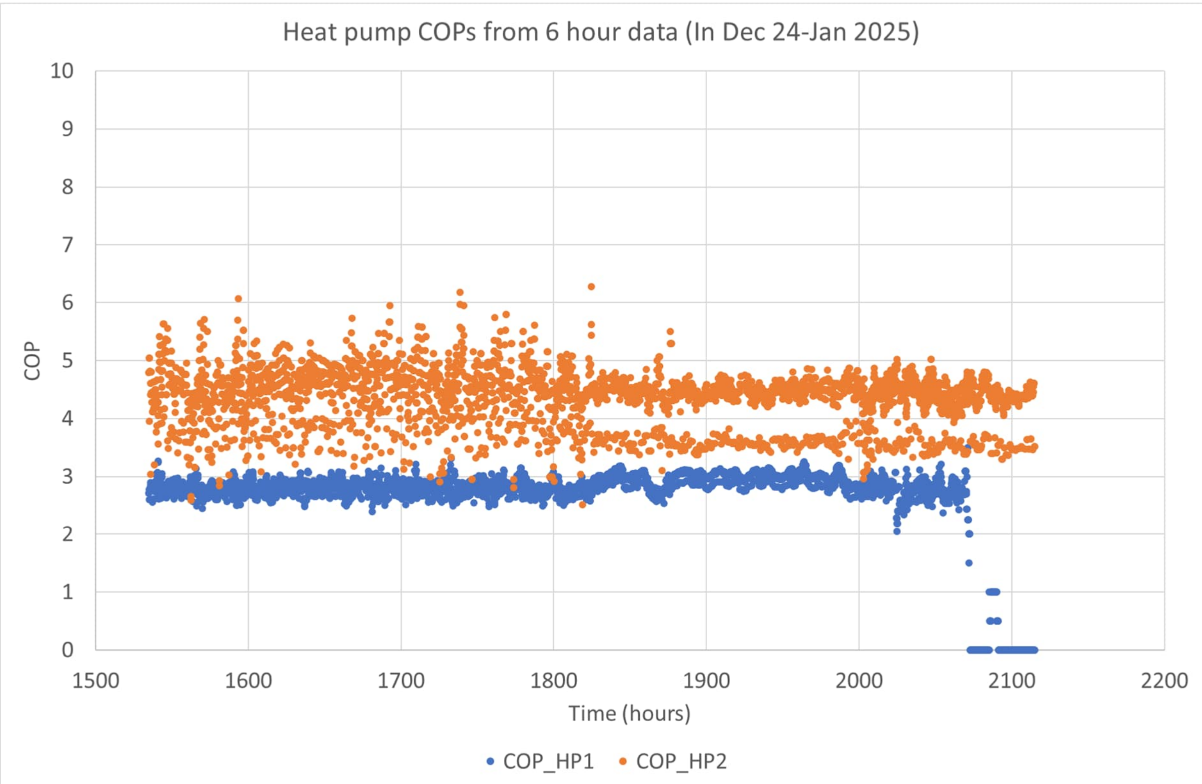

Figure 51: Heat pump COP during 19.12.2024-13.1.2025

Indoor air temperatures in 6 randomly selected apartments

Indoor air temperatures of 6 randomly selected apartments is presented in Figure 52. Table 19 is presenting average temperatures during the measured period. The average room air temperature in these six apartments was 22,2 °C. The apartment average temperatures were 21,0-23,3 °C. The minimum was 19,7 °C and maximum 24,5 °C.

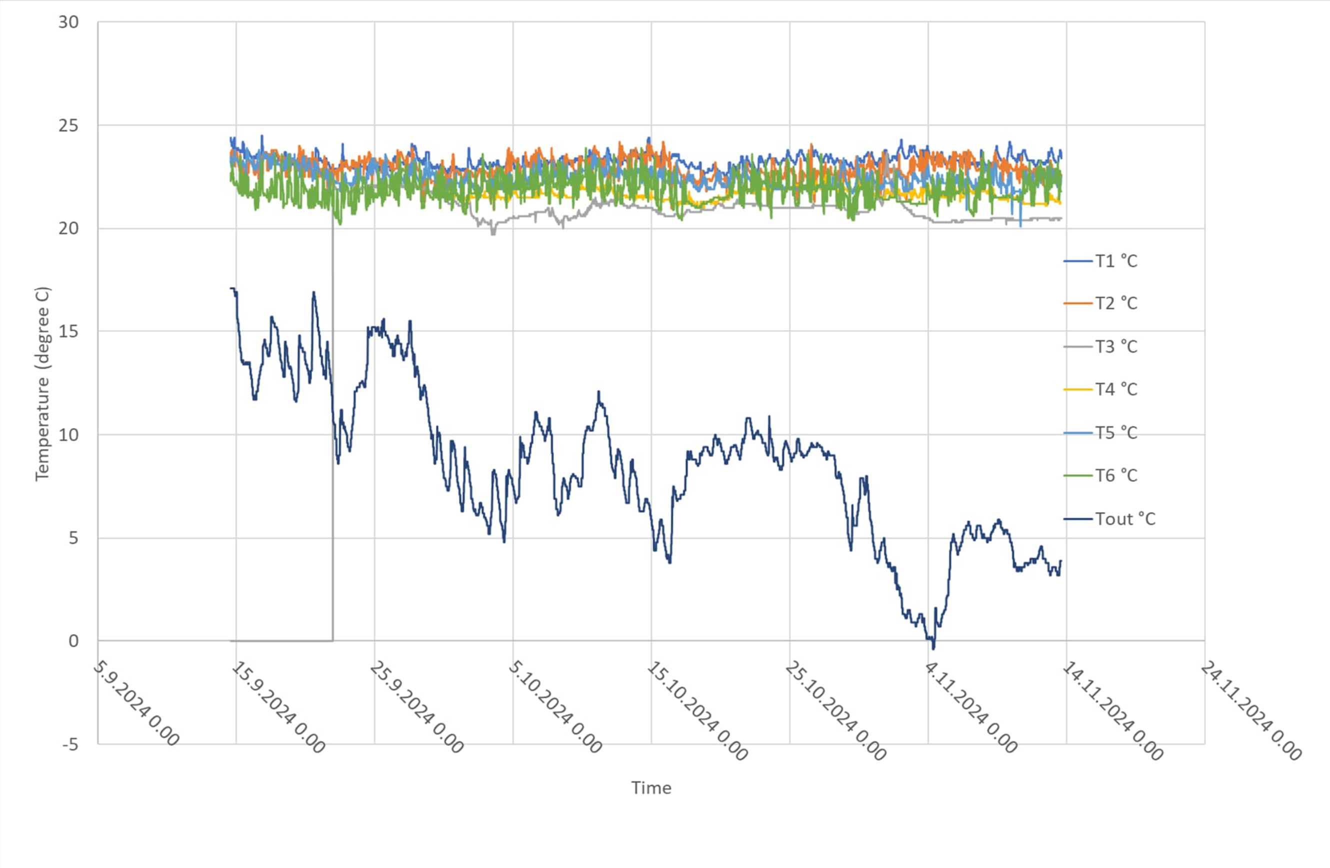

Figure 52: Room air temperatures in 6 apartments 14.9-13.11.2024

Table 19: Minimum, maximum and average room temperatures in 6 apartments 14.9-13.11.2024.

	T1	T2	T3	T4	T5	T6	Tout
Min	22,1	20,9	19,7	21,0	20,1	20,2	-0,4
Max	24,5	24,2	23,7	22,6	23,9	23,9	17,1
Average	23,3	22,9	21,0	21,7	22,4	21,8	8,4

Yearly and monthly electricity demand of heat pumps in normal operation mode

Figure 53 shows the yearly estimate of electricity demand of heating and DHW heat pumps. The yearly total electricity consumption for heating and domestic hot water is 94578 kWh, which is 22,6 kWh/floor-m^2.

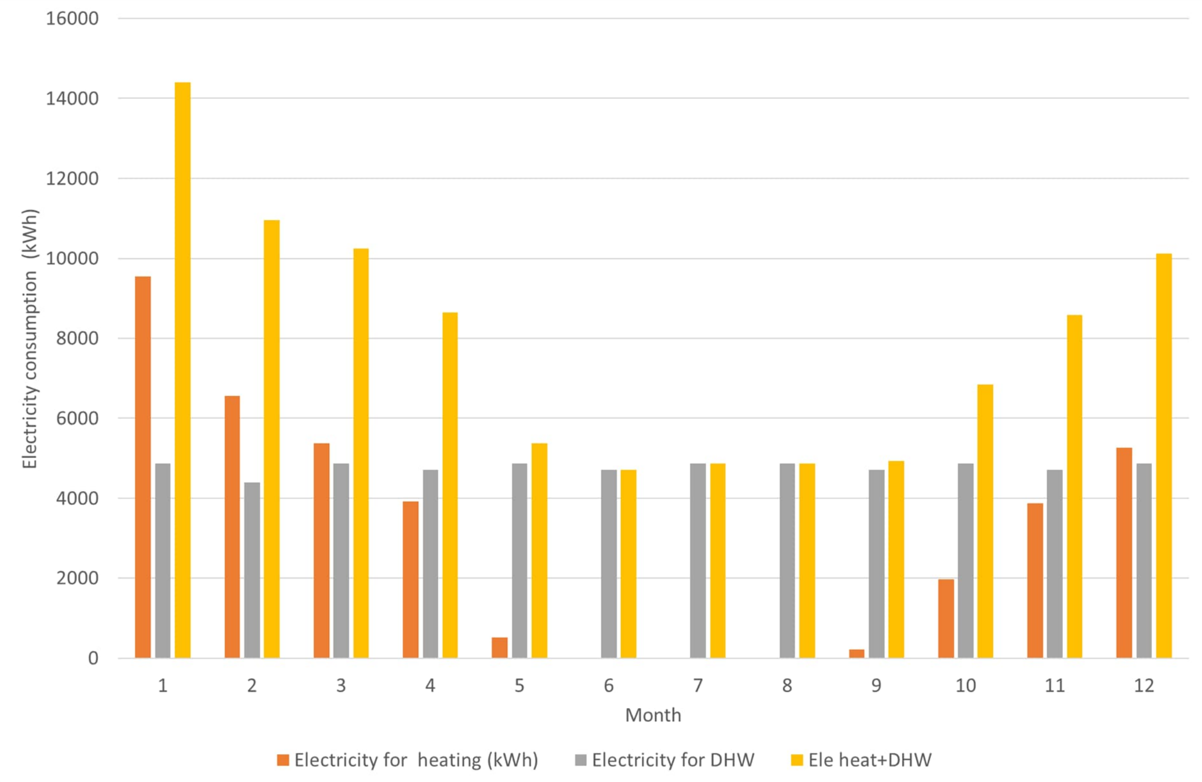

Figure 53: The yearly estimate of electricity demand of heating and DHW heat pumps

Yearly and monthly PV and PVT electricity production

Yearly PV and PVT system electricity production has been analysed using PVGIS-5 tool. Figure 54 shows the monthly production at south and west PV facades and roof 45° tilted PVT panels. South wall PV area is 100,2 m^2 and installed power 18,5 kW$_p$, West wall PV area is 247,5 m^2 and installed power 45,8 kW$_p$, roof tilted PVT area is 315 m2 and installed power 67,1 kW$_p$. The total calculated yearly production is 99724 kWh (South 12574 kWh, West 21900 kWh and roof 65249 kWh), per heated floor area total production is 23,8 kWh/m^2, a. The production per PV panel area in South façade is 125,5 kWh/m^2,a, West façade 88,5 kWh/m^2,a and roof tilted PVTs 207,1 kWh/m^2,a. The monthly production per installed kWp is presented in Figure 55. The roof PVT panel production in practice depend on the snow situation. In case there will be snow, the panels have to be cleaned regularly to guarantee the electricity output from the panels.

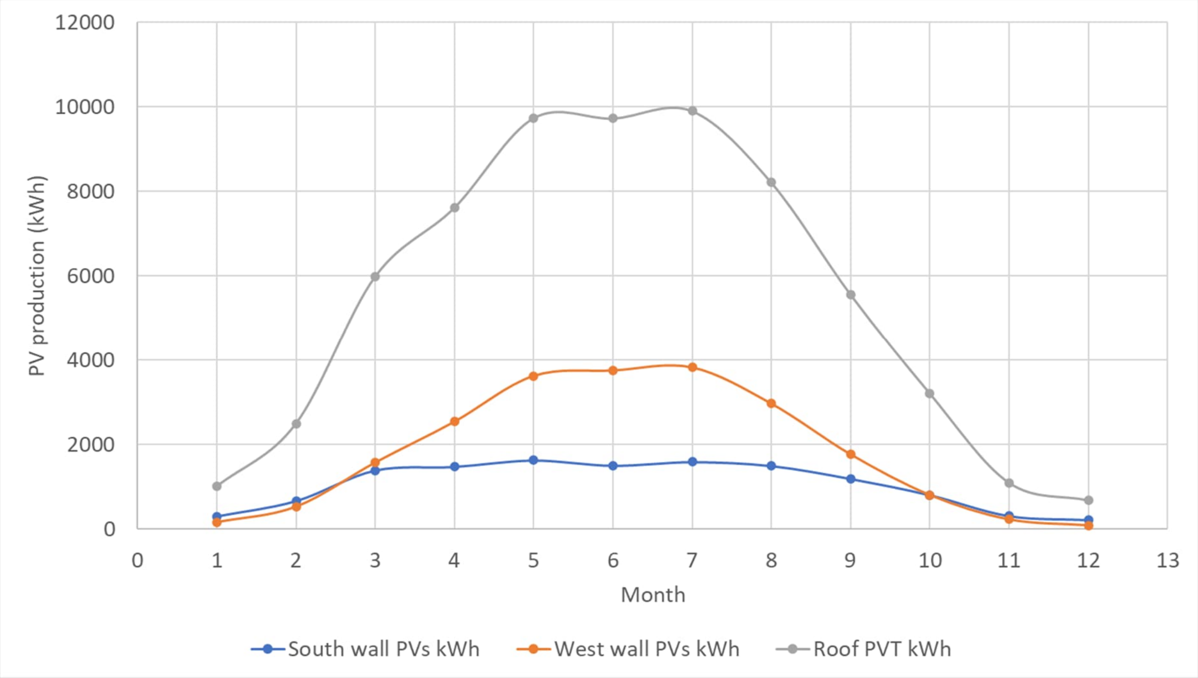

Figure 54: The monthly production at South and West PV facades and roof South 45° tilted PVT panels

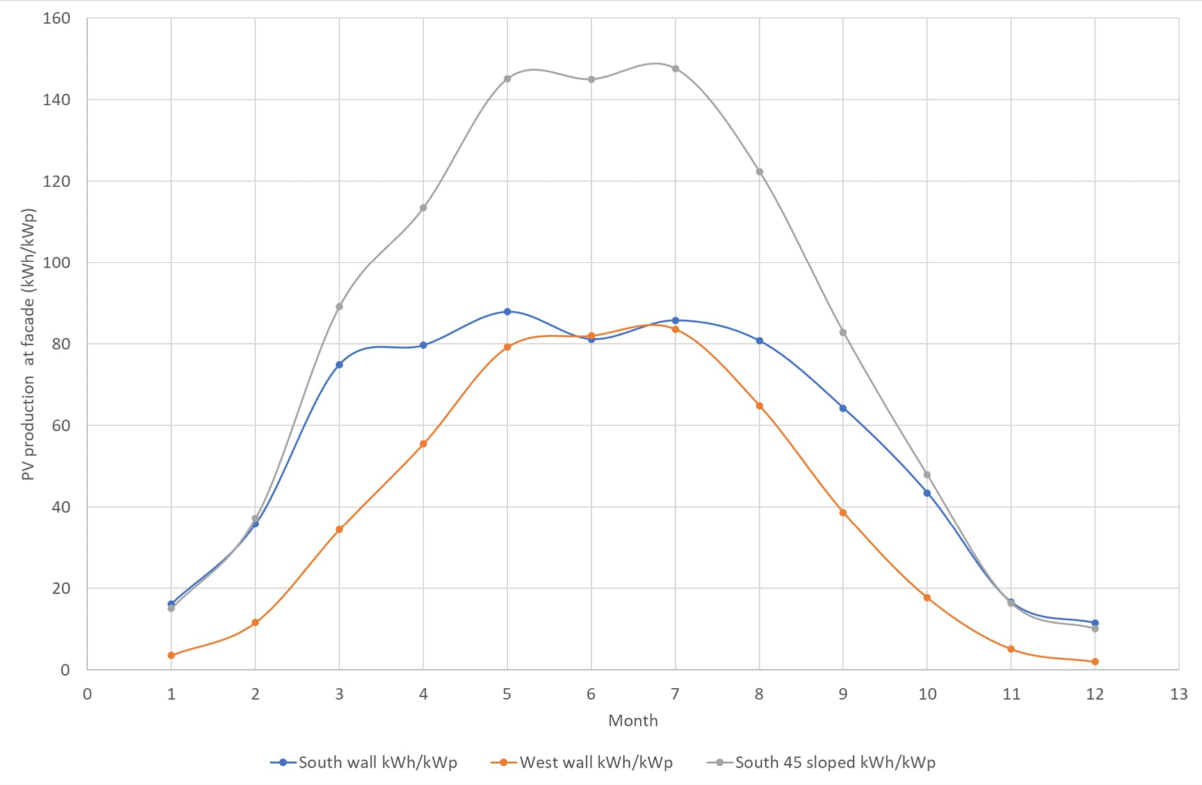

Figure 55: The monthly production per installed kW_p at South and West PV facades and roof South 45o tilted PVT panels

Estimation of the yearly and monthly net electricity consumption vs. production and utilisation rate

Based on monthly level analysis of electricity demand of heating and domestic hot water, and calculated electricity local production by PV and PVT, the net electricity demand or surplus is presented in Figure 56. The total yearly electricity production was 99724 kWh and consumption 94578 kWh. The self-consumption based on monthly balances is presented in Figure 57. The solar PVs and PVTs produce for 4 months summer period about 3 times the consumption. In March-April and September-October the production fits well with the consumption. In January, November and December the solar production is very small, and in roof tilted surfaces in practise almost negligible. At yearly level the self-utilisation rate is 55 % and share of sold-out is 45 %.

The electricity demand of HVAC fans was not included in the analysis, because this information was not available during the reporting. The HVAC fan energy consumption would increase the electricity demand and would improve the utilisation of own PV production. The monthly estimate of energy consumption was based on heating degree days (HDD), where the set temperature is 17 ºC. In practise the room air temperatures are at least 20-21 ºC, and as notice in Figure 52 earlier, even 21-23 ºC.

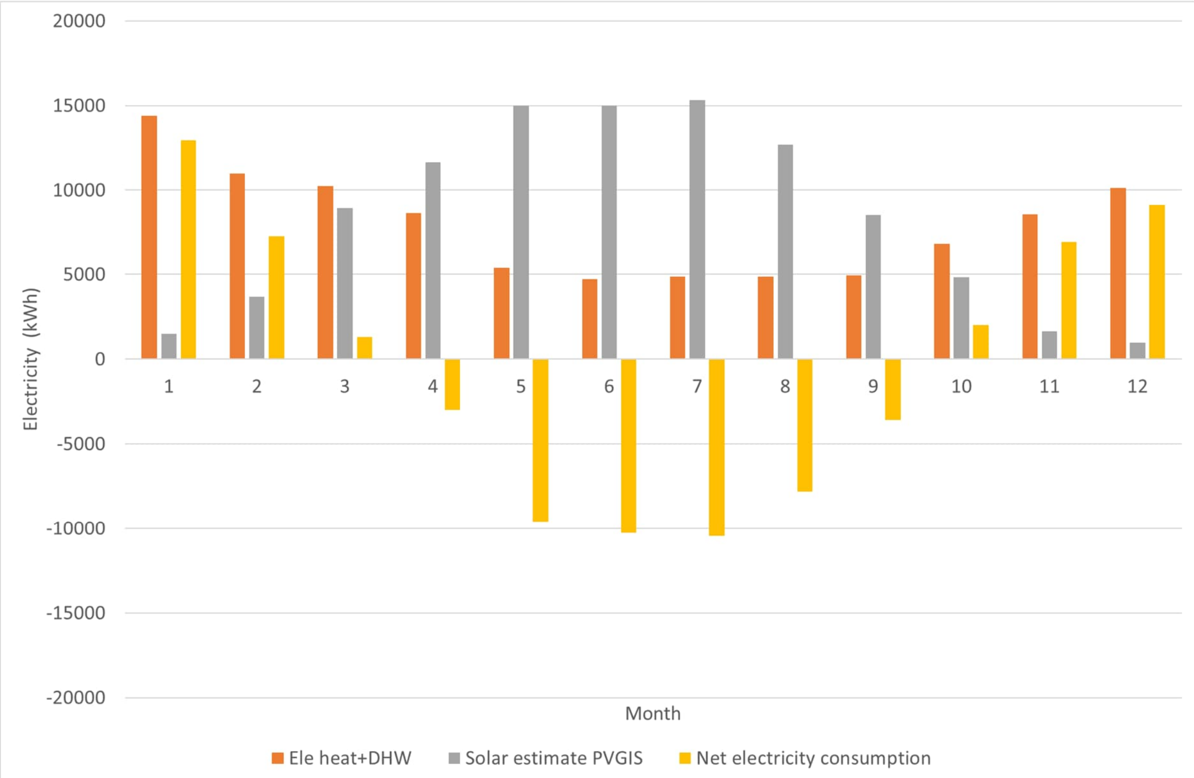

Figure 56: The yearly estimate of electricity demand of heating and DHW heat pumps, local electricity production by PVs and PVTs, and monthly net consumption

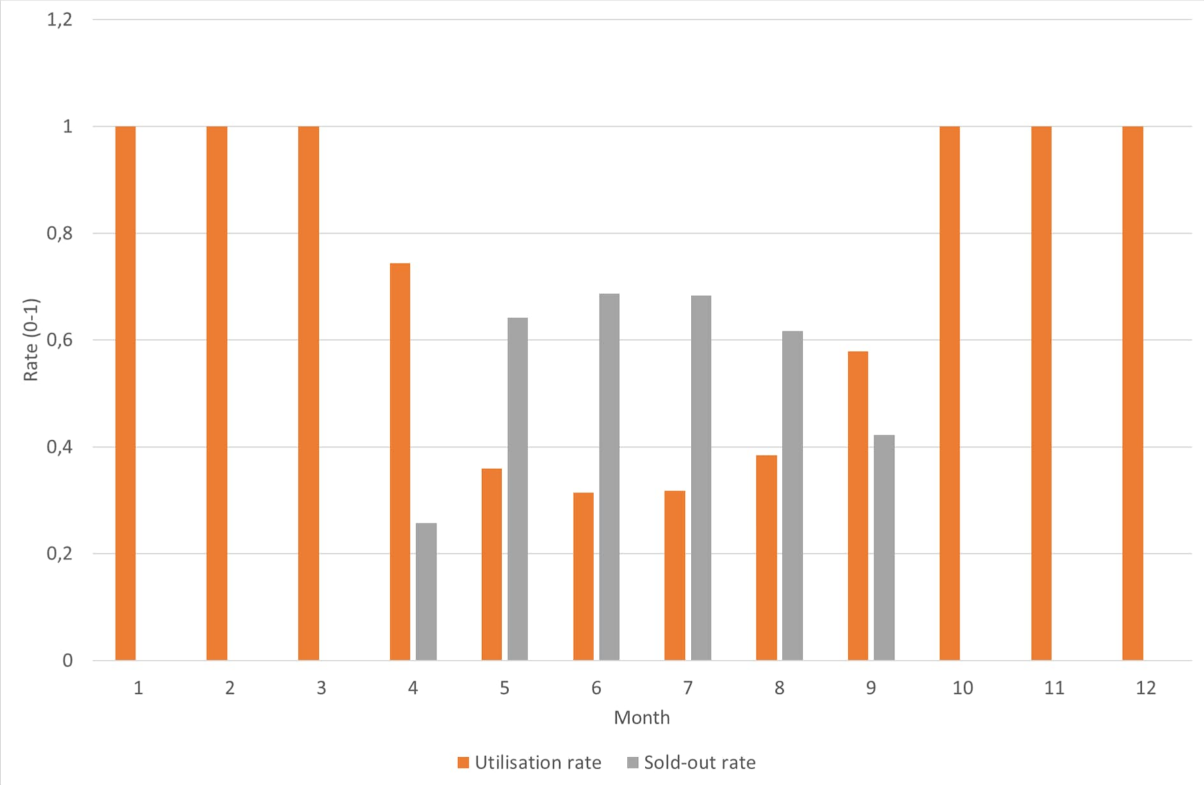

Figure 57: The monthly estimate of utilisation and sold-out rate based on monthly balances of PV production and heating (space heating + DHW) electricity consumption

3.3.3 Cost analysis

The detailed CAPEX and OPEX costs of the Finnish demo building are outlined in Table 20.

The Finnish demonstration focused on new multi-storey apartment building, having energy efficient envelope and HVAC with heat recovery, semi-deep boreholes (13 x 400-600 m deep) combined with heat pumps serving heat for space heating and domestic how water systems, PVs (64 kW_p) and PVTs (67 $kW_{p,el}$) used for local electricity production, and PVTs thermal part charging the boreholes with solar heat. These elements were interconnected and controlled with smart BMS. The detailed CAPEX, OPEX and energy costs are outlined in table 1. Total net energy costs are calculated as the difference between electricity consumption costs and revenues from grid feed-in.

Table 20: Cost of Demo Finland

Investment costs (CAPEX)	High Efficient Envelope	500 k€
	Hybrid Thermal System (Geothermal heatpump, BTES, tanks, boreholes	450 k€
	BiPV (347m2)	200 k€
	PVT (315 m2)	300 k€
Operation costs (OPEX)	Maintenance of Hybrid Thermal System	9 000 €/year
	Maintenance of PV	2 000 €/year
	Maintenance of PVT	5 000 €/year
Energy costs	Net primary energy demand	1 kWh/m2a
	Net energy costs	2,04 €/m2a
Overall life time costs (global costs)		473 €/m2a

It can be seen that the main part of the investment cost comes from the envelope and the geothermal energy system with deep boreholes. The hybrid geothermal energy system costs are twice the costs for the conventional geothermal energy system. The PVT panels lead to higher costs compared to PV, as it is more complicated to install them (additional heat circuit). However, it has to be mentioned that the EXCESS heat of the PVT panels is used to recharge the bedrock. Therefore, the PVT is an enabling technology that ensures the long-term functioning of the whole energy system.

It is not possible to calculate a payback time for the Finnish pilot case, as it is a new building. Payback times could be only calculated for building renovations or for technologies that lead to a reduction in energy consumption or additional revenues (e.g. PV).

For more details on the calculation method and calculation parameters of the life cycle cost calculation, see D5.1. This deliverable also shows a comparison of the Finnish demo technology package with other technology packages.

3.4 Belgium

3.4.1 Methodology

The energy system was fully commissioned in May 2024, therefore the measurement data set includes the period May 2024 – December 2024. Measurement data from 2023 is used as a reference to compare the system performance. In addition, a simulation model is used to benchmark PVT output for normalized weather conditions.

3.4.2 Case specific analysis and results

The main non-KPI related results for the Belgian case study are described per technology.

PVT – electricity production

The monthly total electricity production from the PVT panels is presented in Figure 58. The output is compared to the expected output for a normalized reference climate year (Meteonorm[2]). The spring and summer months of 2024 were slightly cooler with less sunshine compared to the meteorological average. During the winter months less hours of sunshine were measured compared to the normal values (e.g. in December only 35% of the normal hours of sunshine[3] was measured). The electrical output of the PVT panels is in line with the expectations, however, the total electricity produced by the PVT was lower in 2024 due to curtailment of the inverter and meteorological conditions. The DSO had to reinforce the capacity of the central electricity connection of the demo building and this was only realised on December 13th. The electrical output of the PVT is expected to be higher in 2025. In total 24,6MWh$_e$ was produced in the measured period while for a normalized reference climate year we would expect 30MWh$_e$.

[2] https://meteonorm.com/en/

[3] https://www.meteo.be/resources/climatology/pdf/klimatologisch_maandoverzicht_202412.pdf

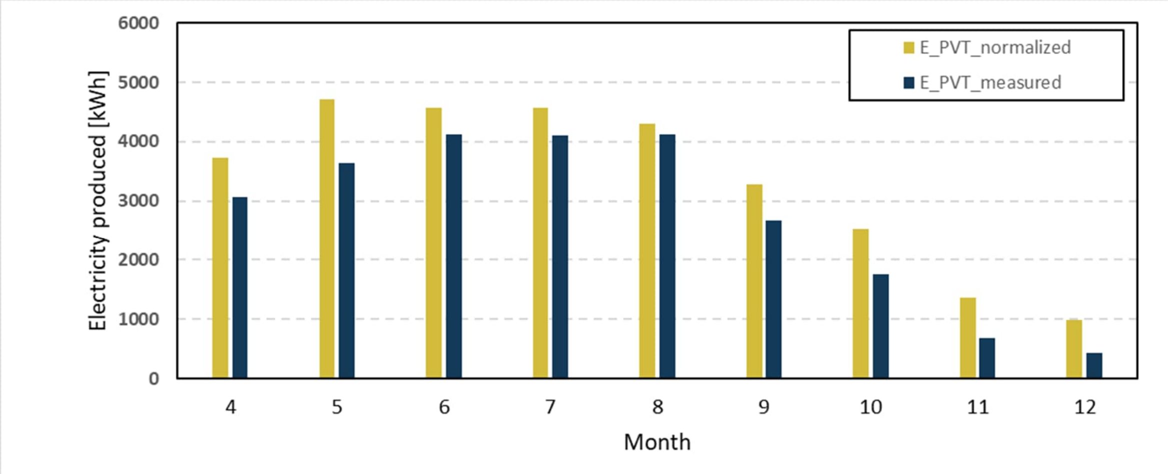

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Figure 58: PVT electricity output - monthly totals

Low temperature heat production (PVT + BTES)

The low-temperature heat output of the PVT and Borehole Thermal Energy Storage is given in Figure 59. The BTES cooling output (red) represents the solar heat share that is transferred to the BTES. The BTES heat output (orange) indicates how much heat was recovered from the BTES to be used by the heat pump. As can be concluded from the chart, a majority of the heat pump's evaporator heat is delivered directly by the PVT. In total, 51% of the heat pump's evaporator heat comes directly from the PVT while 49% is delivered by the BTES. The PVT panels delivered 27MWh of heat to the BTES and the same amount of heat was extracted again by the heat pump.

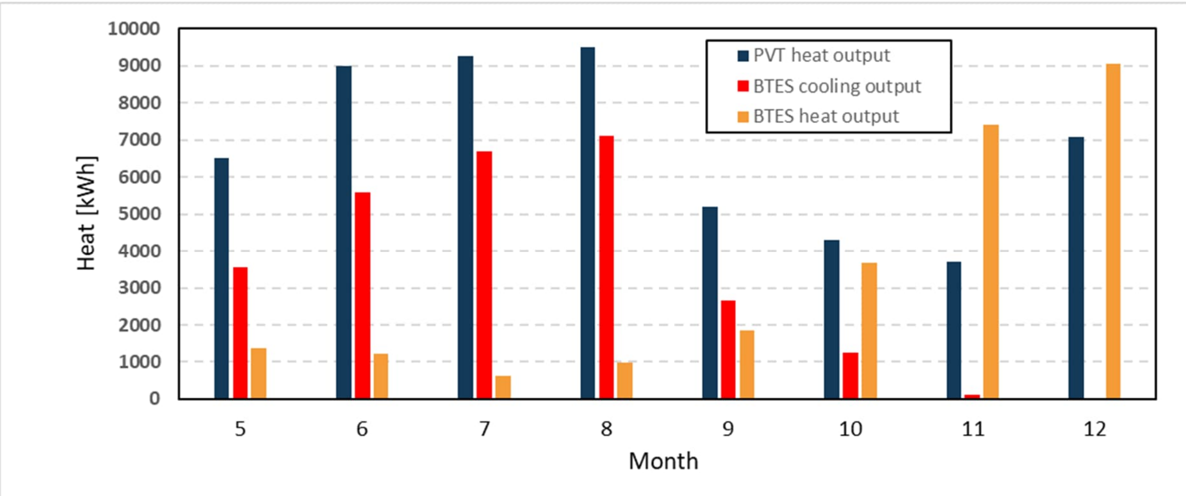

Figure 59: Low temperature heat output - monthly totals

Heating temperature regimes

The temperature regime for heating is compared to the values of 2023, before the EXCESS setup was activate. The average temperature regime in 2023 was 57,2/52,2°C. With the EXCESS setup, the average supply temperature regime was reduced to 52,4/50,1. Therefore, the supply temperature reduction was 4,8°C (Figure 60) and the return temperature was reduced with 2,1°C. By reducing the operational temperature regime, the overall heat losses of the heating network were reduced by 9,5%.

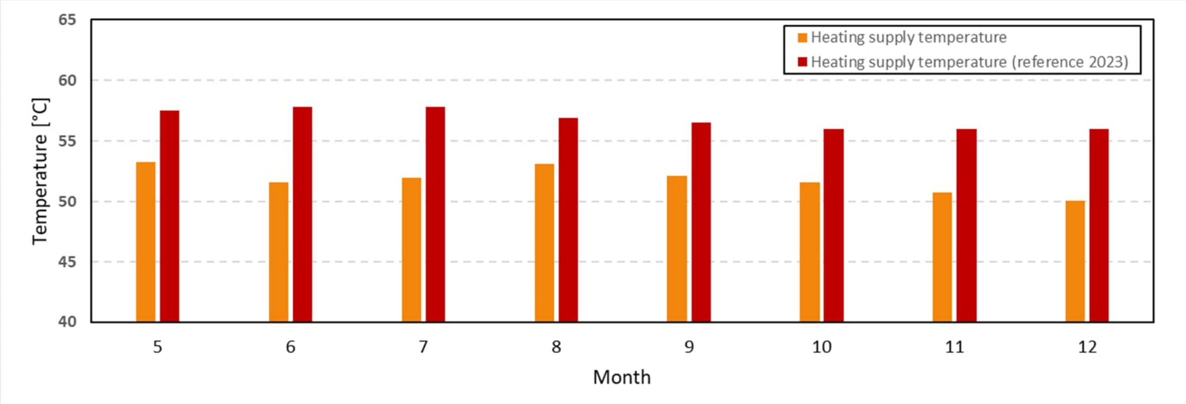

Figure 60: Supply temperature - monthly average

Heat pump

The heat pump COP is presented in Figure 61. A comparison was made with the existing heat pump and without BEMS control based on 2023 measurement data. The COP increased significantly in the summer months as a result of higher evaporator temperatures. In the winter months, the heat pump efficiency reduces due to lower evaporator temperatures since the ratio of heat pump capacity / BTES capacity is relatively low. The BTES is dimensioned for a 20kW$_{th}$ heat pump while the EXCESS heat pump has a rated capacity of 40kW$_{th}$. The PVT panels cannot compensate fully for the lack of low-temperature heat in cold winter conditions. Some gas-fired back up is needed to cover peak heat demand from the buildings (+/- 4% of the heat is delivered by gas-fired back-up).

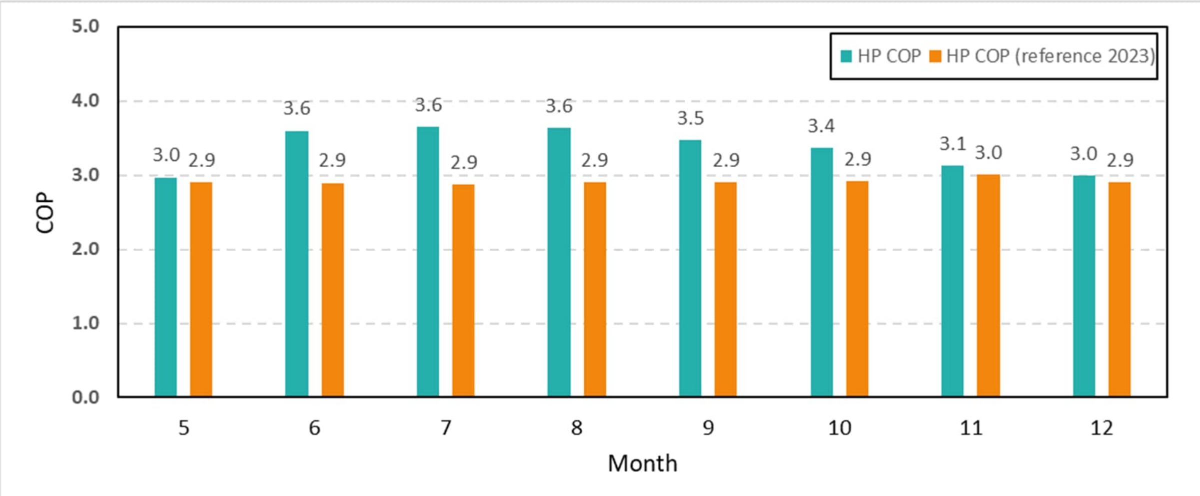

Figure 61: Heat pump COP – monthly average

The overall heat pump efficiency increased from 2.9 in 2023 to 3.2 for the EXCESS setup (+10%). There are several aspects which contributed to this:

- The condenser temperature decreased due to the reduction of the overall heating supply temperature.
- The evaporator temperature increased due to the PVT installation.
- The inverter compressor allows for longer operational runs and less start/stops.

- The heat pump is controlled by BEMS which determines the optimal control setpoint of the heat pump considering energy production from the PVT panels. The heat pump is operated at a higher load when the conditions are more favourable.

Self-consumption

The self-consumption of PVT electricity is calculated and compared with a reference system with normal control (based on 2023 measurement data with HP with the same thermal power). The spring and summer period is the period with typically the lowest self-consumption rates due to the high share of renewable electricity production and the low thermal demand and vice versa for the winter period (where self-consumption of PVT energy can reach 100%). Based on the measurement data presented in Figure 62 we can conclude that the self-consumption rate increased from 50% to 58%.

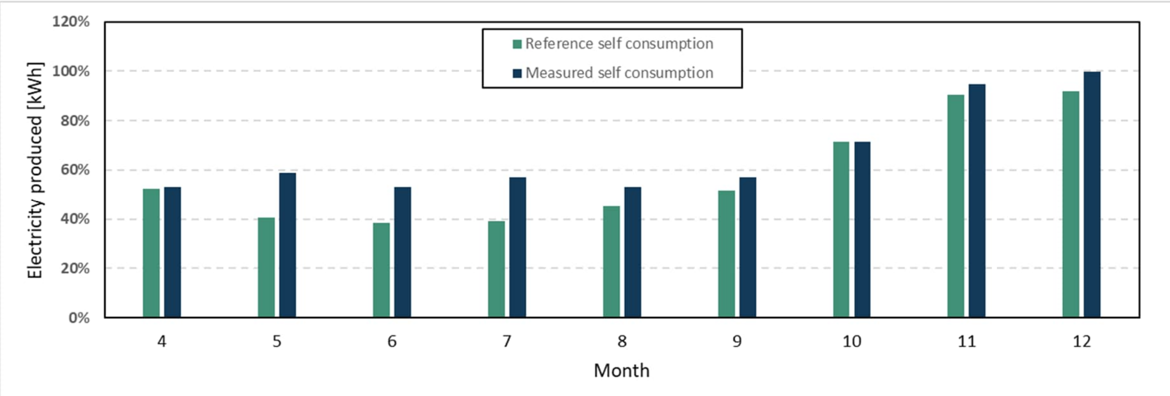

Figure 62: Self-consumption rate – monthly totals

Other results and KPI's

3.4.3 Cost analysis

The detailed CAPEX and OPEX costs of the Belgian demo building are outlined in Table 21. In the cost analysis two technology packages are considered:

- EXCESS_concept_PVT: the energy system that was developed, implemented and tested during the EXCESS project.
- EXCESS_concept_PV: the EXCESS energy system with PV and additional BTES instead of PVT.

Two reference cases were used in order to evaluate the total costs for the PEB technology packages. One reference case includes individual air-source heat pumps. This reference can be used to evaluate the feasibility of the PEB concept for new-built projects. The second reference case uses a central gas-fired heating system as a reference. This allows to evaluate the feasibility of the PEB concept for retrofitting.

- Reference_concept_Air_HP: individual air-source heat pumps per dwelling with PV
- Reference_concept_gas: the heating system with natural gas (current system). There are no investments considered in this case. A central gas-fired boiler with heating network is already in place.

The following financial parameters were used as input in the analysis:

Table 21: Cost of demo Belgium

Investment costs (CAPEX)	PVT (35kW$_p$)	70 k€
	PV (35kW$_p$)	35 k€
	Heat pump (40kW$_{th}$)	40 k€
	BTES (20kW$_{th}$)	25 k€
	PVT installation costs (hydraulic, piping, E&I)	100 k€
	Installation costs HP (hydraulics, piping, E&I)	25 k€
	Building management software upgrades	10 k€
	Reference technology (Air/water HP system)	8 k€/apartment
	DHN satellite	2500 €/apartment
Operation costs (OPEX)	Maintenance of PVT	1500 €/year
	Maintenance of central heat pump	1000 €/year
	Maintenance of individual heat pump	250 €/year
	Maintenance of gas-fired boiler	500 €/year
Energy costs	Electricity	250 €/MWh
	Electricity feed-in tariff	0 €/MWh
	Natural gas	85 €/MWh
	Natural gas (incl. ETS2, long term)	105 €/MWh
Overall life time costs (global costs)		300 €/m2a

The total cost of ownership is presented in Figure 63. The following conclusions can be drawn:

- The EXCESS technology package with PVT is slightly more expensive than the reference case with individual air source heat pumps (+10k€).
- The EXCESS technology package with PVT is 145k€ more expensive than with only PV altough both technology packages have similar primary energy consumptions.
- For the conversion of existing central gas-fired heating systems to PEB, the EXCESS technology package with PV is cost effective.
- Also for new-built installations the EXCESS technology package with PV is more cost effective than individual heat pumps for the considered building typology.

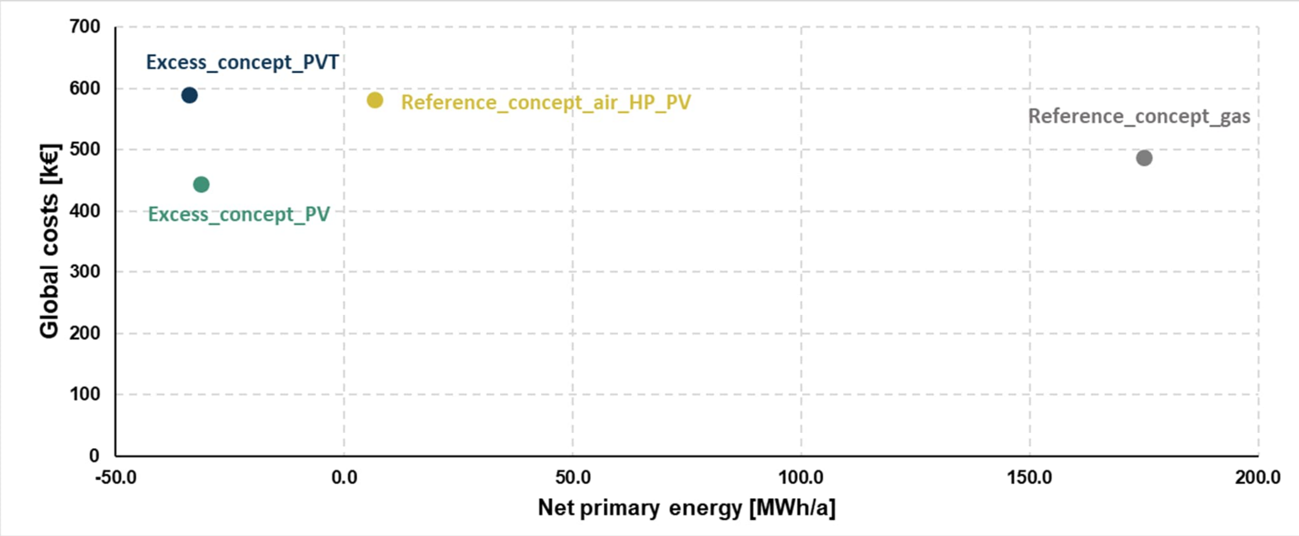

Figure 63: Total cost of ownership for the different cases as function of the annual primary energy consumption

From the perspective of the social housing company as heat supplier, the cost effectiveness of the technologies not only depends on the global costs, but also on the heat tariff. If we consider the financial gap (the surplus of CAPEX that needs to be invested for PEB technology compared to the reference) we can determine the effect on the heat tariff at which the total cost of ownership for WIL is the same. Compared to the existing gas-fired system – the installation of the EXCESS_concept_PVT package would lead to an increase in the heat tariff of 3.7 c€/kWh for the end consumer. The EXCESS_concept_PV package would result in a cost reduction of 1.5 c€/kWh. We assume that the cost for CO_2 in the upcoming ETS2 system would remain stable at 45 €/ton. It is clear that a higher CO_2 price would reduce the heat tariffs compared to gas further.

3.5 KPI analysis

An overview of the KPI framework is presented in Table 22. The results are further discussed per demo case.

Table 22: Overview of the KPI's defined in work package 4 for all demo sites

Domain		Unit	FIN	BEL	SP	AUT
Energy	Energy consumption - heat	kWh/a	325.000	160.000	14.560	27.738
	Energy consumption - electricity	kWh/a	94.000	50.000	58.125	39.635
	Local renewable energy production	kWh/a	99.700	35.000	67.644	62.006
	Renewable share	%				
	Self-consumption rate	%	55	58	55	37
	Self sufficiency ratio (or load cover factor)	%	58	32	67	58
	Cooling energy consumption	kWh/a				31.010
	Domestic hot water consumption	kWh/a	164.000			15.601
	Electrical peak load	kW			25	
	Energy flexibility			✓	✓	
	Grid energy consumption (balance)	kWh/a	-5.100	34.000	-9.520	16708
	Primary energy	kWh/a			-2.1900	
	CO2 emissions	ton CO_2		1,6		
	Heating degree days HDD	Kd/a			2,07	
	Cooling degree days CDD	Kd/a			0,243	
Economy	CAPEX – capital expenditures	k€	1.450	245	684	903
	OPEX – operational expenditures	k€/year	16	2,5	3,3	8,8
	Levelized cost of energy	€/MWh				✓
	Revenue	€		✓		
	Net present value	€		✓		
	Pay back period	years			30	
	Economic balance (costs vs revenue)	€				
Technology	SCOP – seasonal coefficient of performance	number	✓	3,2	3,7	
	State-of-charge of storages	%		✓		
	Forecasting accuracy (for MPC, control)			✓	✓	
Social	People reached	%		95%		
	User acceptance	Likert		✓	✓	
	Comfort	Likert	✓	✓	✓	

3.5.1 Spain

An overview of energy related KPI's and metrics is provided in Table 22. The values correspond to the annual simulated performance of the building during the year 2024.

For the economic KPIs, the CAPEX costs were evaluated directly with the actual invested value to do the building renovation. The OPEX was estimated with the annualized maintenance cost and the simulated annual energy cost with a standard energy price of 0.15€/kWh from the available commercialization companies in 2024. The payback period of 30 years correspond to the extra investment compared with a BAU renovation.

Regarding the technology KPIs, the SCOP of the heat pumps was estimated from the annual energy simulation, obtaining a value of 3.7. The forecasting accuracy has not been evaluated due to the delays in the commissioning of facilities and obtention of feed-in permit.

Likewise, user acceptance and confort has not been evaluated as there are still no inhabitants living in the building.

3.5.2 Austria

The results for the Austrian demo case are presented in section 3.2.2.

3.5.3 Finland

An overview of the KPI's for the Finnish case are presented in Table 23.

The following remarks should be considered:

- Overall analysis is combining measurements and simulations; the yearly energy and electricity consumption was evaluated based on the model tuned with a short period of measurements.
- Electricity consumption of HVAC fans was not included in the analysis because this information was not available during the analysis.
- Yearly PV and PVT system electricity production has been analysed using PVGIS-5 tool, because the PVs and PVTs were not operational during the analysis.

Table 23: KPIs for Finnish demo

Domain			Unit		Unit
Energy	Energy consumption – heat - not including DHW & DHW circulation - including DHW &DHW circulation	161 325	MWh/a	38,7 77,9	kWh/m²a
	Energy consumption – electricity - not including HVAC, DHW, DHW circulation & cooling - including HVAC, DHW, DHW circulation & cooling	37 94	MWh/a	8.9 22,6	kWh/m²a
	Local renewable energy production	99,7	MWh/a	23,9	kWh/m²a
	Self-consumption rate	55 [1)]	%	[1)] from monthly balance	
	Self-sufficiency ratio (or load cover factor)	58 [1)]	%		
	Domestic hot water consumption (incl circulation)	164	MWh/a	39,2	kWh/m²a
	Grid energy consumption (balance)	-5,1 [1)]	MWh/a	-1,2*	kWh/m²a
	Heating degree days HDD	3400	Kd/a	in 2024	
	Cooling degree days CDD	N.A.	Kd/a		
Economy	CAPEX – capital expenditures	1 450	k€		
	OPEX – operational expenditures	16 [2)]	k€	[2)] not incl energy costs	
Technology	SCOP – seasonal coefficient of performance Heat pump COP 2,7-5,0	N.A 2,8...5,0	number		
	PV efficiency - nominal/design values - seasonal	18,5 [3)] N.A.	%	[3)] manufacturer data	
	Share of local electricity	105	%		
Social	Comfort	N.A.	Likert		
	Thermal/indoor temperature	19,7...24,5[4)]	ºC	[4)]heating season	

3.5.4 Belgium

Energy

An overview of energy related KPI's and metrics is provided in Table 24.

The total electricity consumption includes all electricity consumption on the public domain of the demo site (e.g. HVAC, pumps, control, lights, building management system, …). The measured electricity consumption was significantly higher than expected, the heat pump only consumed half of the total electricity consumption. Therefore, if we consider the total electricity consumption, the building cannot be considered a PEB at this moment. In addition, there is still a small fraction of heat delivered by the gas-fired back-up systems (+/- 4%). This also has an impact on the self-sufficiency (32%).

WIL has an energy contract with 100% renewable electricity, therefore, the remaining share of natural gas consumption brings the renewable share of energy to 96%. The total CO_2 emission was 1,6 tons where it was still 19,3 tons in 2023. For the conventional gas-fired system, the CO_2 emission would be 32,2 tons.

In the near future it is expected that the building will become a PEB as soon as the remaining available roof surface will be equipped with PV panels as part of the Aster project[4].

Table 24: Energy related KPI's for Belgian demo

Energy	Total heat produced	71 MWh
	Total electricity consumption	44 MWh
	HP electricity consumption	22 MWh
	PVT electricity produced[5]	25 MWh
	Grid energy consumption (import)	29,9 MWh
	Renewable share of energy[6]	96,3%
	Self-consumption rate	58%
	Self-sufficiency	32%
	CO_2 – emission reduction	92%
	CO_2 - emissions	1,6 ton

Economy

The total operational costs of the EXCESS setup in 2024 were 53% lower compared to 2023. The total energy costs[7] were 6.600€ compared to 14.300€ in 2023. A CO_2 tax (ETS2) of 45€/ton was taken into account. More details on the economical aspects can be found in the cost analysis (section 3.4.3).

Technology

The forecaster accuracy is monitored continuously, the Mean Absolute Scale Error (MASE) is calculated for a 24h moving horizon. A screenshot of the forecaster monitoring system is presented in Figure 64.

[4] https://aster.vlaanderen/nl/wat-is-aster
[5] Production with curtailment, next year the output is expected to be 30MWh
[6] WIL has an electricity contract with 100% renewable energy
[7] Calculated with the latest energy tariffs on 10/01/2025

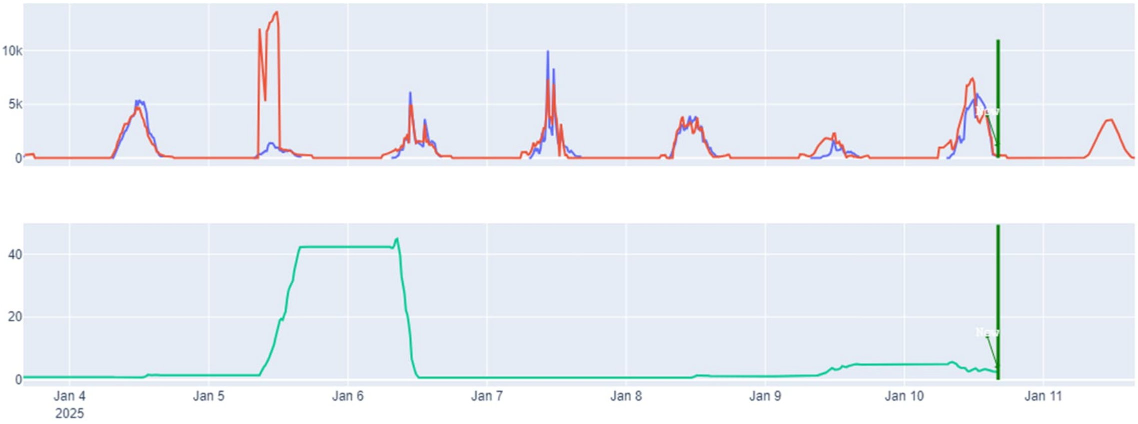

Figure 64: Snapshot of the PV forecaster and the accuracy over moving time horizon of 7 days (Red = predicted PV output, blue = measured PV output, green = MASE over 24h period)

The state of charge calculation for the domestic hot water tanks was implemented and tested. The temperature in each storage tank is monitored and additional temperature sensors were added to the side of the tanks at different heights to analyse temperature distributions and the relation with the default sensor readings (see Figure 65).

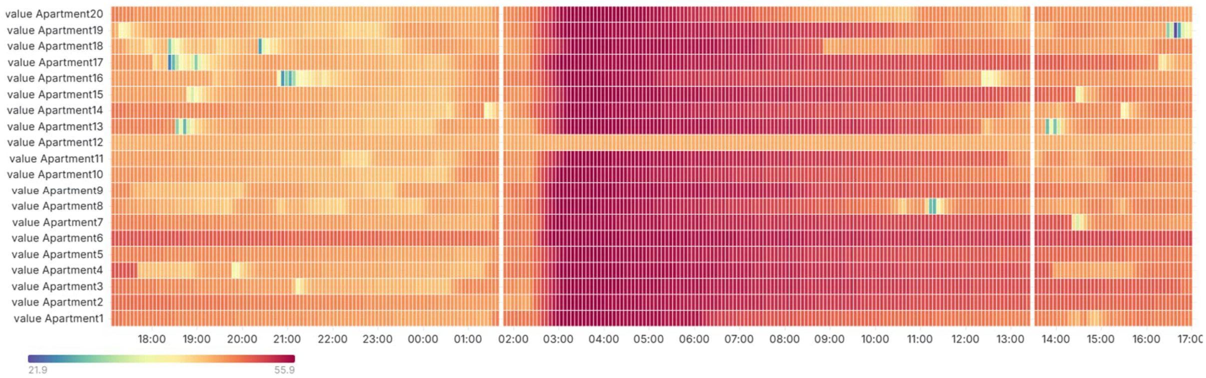

Figure 65: Storage tank temperatures to determine SOC

Social

A survey on thermal comfort was organised among the tenants of the Belgian demo case. The results were gathered in the beginning of December 2024 covering an operational period of approximately 7 months. In total 18 out of 19 users were questioned (1 apartment was empty) resulting in a response rate of 95%. The results of the survey are summarized in the graphs below.

In terms of warm water availability, the majority of people (78%) finds it to be sufficient. 6% disagrees and encounters problems when multiple people shower shortly after each other. Logically, this problem occurs in apartments where multiple people live together (3 person households). A general conclusion is that domestic hot water storage volume should be aligned with the number of users or tenants (e.g. linked to the number of bedrooms).

Only 6% of the users find the domestic hot water not warm enough during certain periods. This confirms that the use of thermal flexibility from the warm water buffers does not affect thermal comfort. Before the EXCESS project, the temperature of the warm water was constant (variation of 3°C on setpoint). In the new energy management system the temperature varies with 10 °C.

28% of the users find it difficult to manage the indoor temperature of the apartment. Although the room thermostat is very simple (no display, only + and – turn knob available), many users use the radiator valves to manage the temperature in the apartment. The open staircase allows warm air to flow easily to the first floor making it more difficult to maintain comfortable temperature levels in the living room and bedrooms (lower room temperature required).

54% of the users finds thermal comfort good all year round and 28% of users do not have an opinion on this. 45% of the users experiences problems with thermal comfort and most of the complaints (6 responses) deal with overheating in the summer period. Although the heating system uses geothermal energy, it is not possible to apply passive cooling in the current setup (radiators inside apartments).

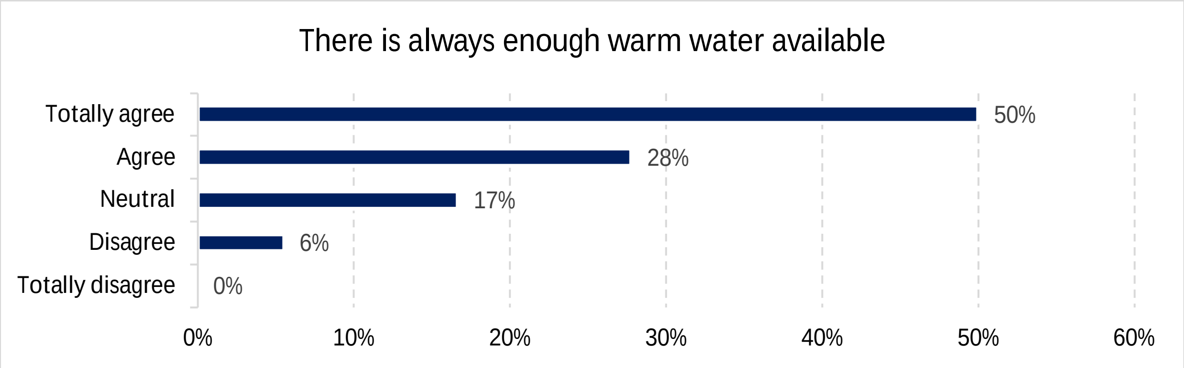

Figure 66: Availability of warm water

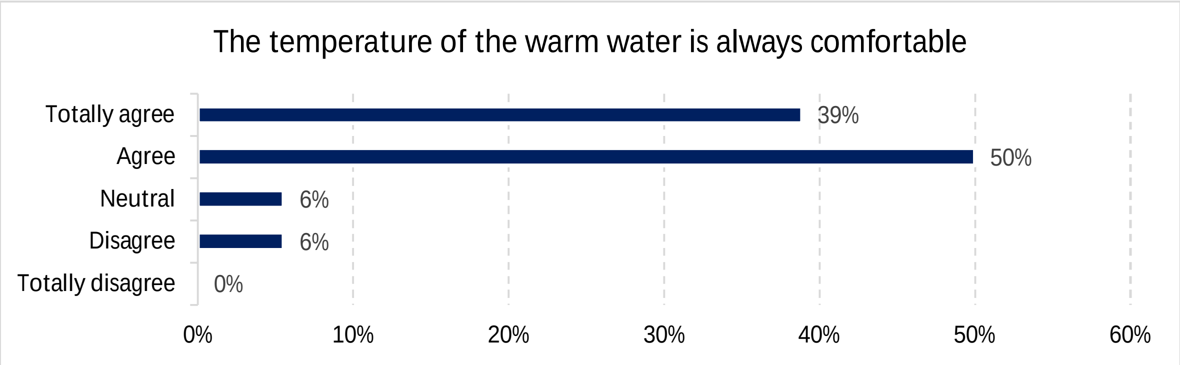

Figure 67: Temperature of warm water

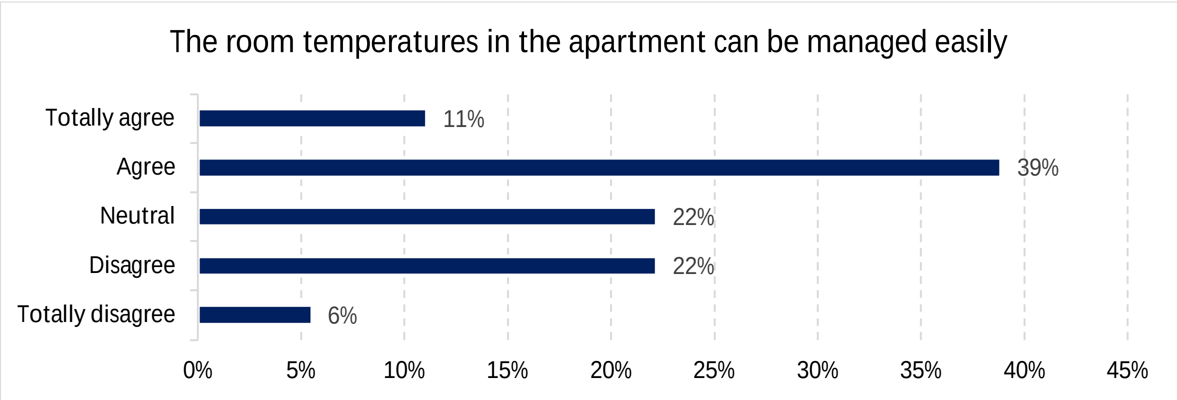

Figure 68: Room temperature management

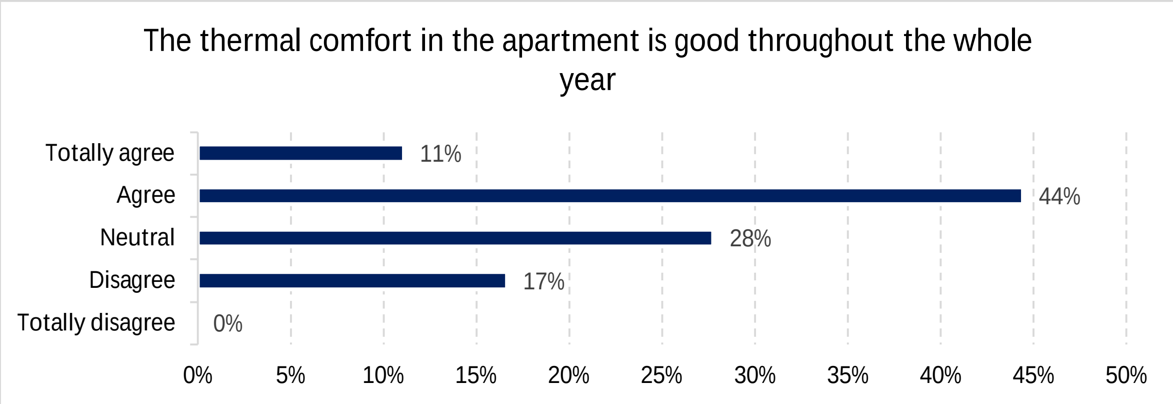

Figure 69: Overall thermal comfort

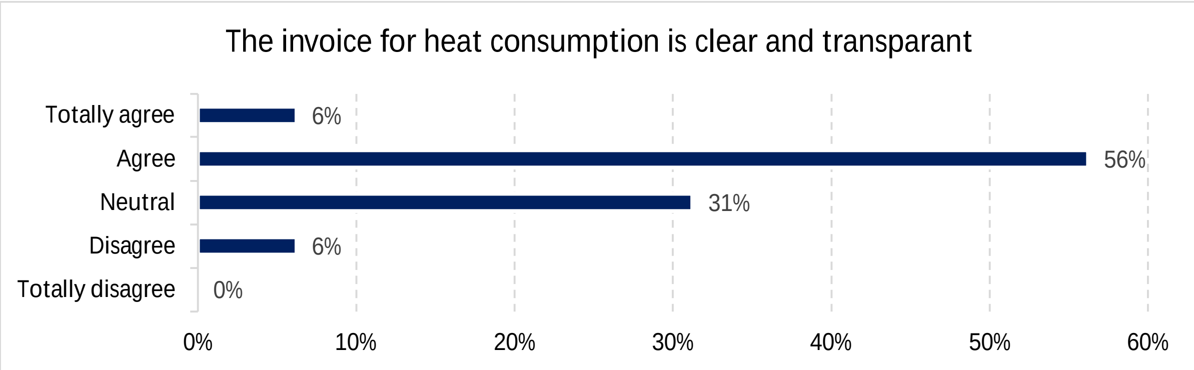

Figure 70: Heat invoice transparency

3.6 Greenhouse gas emissions

Greenhouse gas emissions for different technology packages for the demos in Belgium and Austria were assessed using the method of life cycle assessment (LCA). A detailed description of this assessment is found in the additional report: “Life Cycle Assessment of Technology Options for Plus Energy Buildings“. Here the main points are summarized:

The LCA addresses the environmental impacts (here GHG emissions) throughout a product’s life cycle from raw material acquisition through production, use and end-of-life treatment, recycling and final disposal (from cradle-to grave) [1]. In the assessment we also followed the calculation rules for the environmental performance of new and existing buildings from EN 15978-1:2021 (draft version), and included the following life cycle stage for the investigated technologies [2]:

- Product stage: Raw material supply, Transport, Manufacturing (A1-A3)
- Construction stage: Transport to site (A4)
- Use stage: Use (B1), Maintenance (B2), Replacement of building components (B4), Operational energy use (B6)
- End of life stage: Transport to waste processing or disposal (C2), Waste processing for reuse, recovery and/or recycling, Disposal of waste (C4)
- Benefits and loads beyond the system boundaries: Potential net benefits from reuse, recycling, energy recovery (D1), Potential benefits and loads from exported utilities (D2)

As in both investigated case studies the building already existed, the building itself was not included in the assessment.

3.6.1 Belgium

The goal of the LCA of the Belgian demo was to investigate the GHG emissions of different technology packages. In total 18 combinations of different technology combination for the thermal system of the building (natural gas boiler or heat pump) and on-site electricity generation (PV, PVT and natural gas fired co-generation unit) were investigated. All of the investigated technology packages provide the same energy service to the building (Figure 71). They cover the heating energy demand of 77 kWh per square metre and year and provide the needed electricity for lighting, domestic hot water and plug loads.

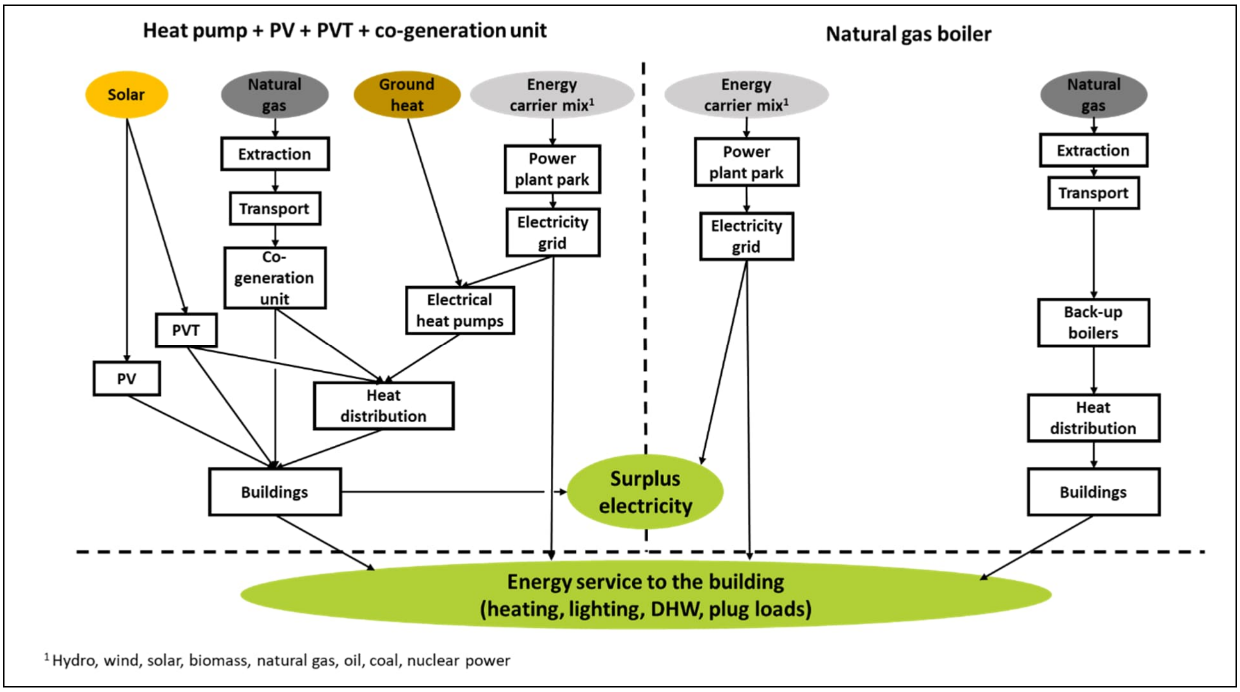

Figure 71: Simplified scheme for the LCA calculation of technology packages with heat pump, PV, PVT and co-generation unit in comparison to a system with natural gas boiler

In the technology packages with PV, PVT and/or a co-generation unit electricity is fed into the grid as not all of the produced electricity is consumed on site. In the LCA this surplus electricity was included in the calculation in two different ways:

(1) Credits for replaced electricity generation: surplus electricity injected into the grid influences the electricity generation in the network and electricity generation by other power plants might be replaced. To include this effect of surplus electricity on the electricity generation mix of the system two options for replaced electricity were investigated:
   a. For the replaced electricity generation mix a European electricity mix was assumed.
   b. For surplus electricity it is assumed that the electricity generation in a natural gas power plant is replaced, since natural gas power plants, as flexible electricity generation units, are high on the merit order curve of the day-ahead electricity market.

(2) Allocation: Another possibility to assess the effect of surplus electricity generation in buildings is allocating the investigated impacts (GHG emissions) between the energy used to provide heat and electricity to the building and surplus electricity fed into the grid.

Important foreground data for the LCA are the yearly energy balances of the investigated technology packages (Table 25), which were calculated based on simulation data. Simulation data was used as (1) monitoring data was not available for the technology package representing the demo site ("Heat pump + PV 44 kWp + PVT 44 kWp") when the LCA was conducted, and (2) to have data for the technology packages, which are not implemented in the demonstration.

Table 25: Yearly energy balance of the investigated technology packages in MWh/year

	Total natural gas demand	Total electricity demand	Total electricity production	*Electricity production from PV/PVT*	*Electricity production from Co-generation unit*	Grid feed-in	Self-produced electricity consumed on site	Grid electricity demand (incl. plug loads)
	[MWh/a]							
Gas boiler only	173	35	0	*0*	*0*	0	0	35
Heat pump only	0	75	0	*0*	*0*	0	0	75
Gas boiler + PV 44 kWp	173	35	40	*40*	*0*	36	4	31
Heat pump + PV 44 kWp	0	75	40	*40*	*0*	28	12	63
Gas boiler + PVT 44 kWp	173	35	40	*40*	*0*	36	4	31
Heat pump + PVT 44 kWp	0	70	40	*40*	*0*	28	12	58
Gas boiler + PV 44 kWp + PVT 44 kWp	173	35	79	*79*	*0*	75	4	31
Heat pump + PV 44 kWp + PVT 44 kWp[1]	0	70	79	*79*	*0*	63	17	53
Gas boiler + co-generation unit	198	35	28	*0*	*28*	20	8	27
Heat pump + co-generation unit	100	57	28	*0*	*28*	11	17	41
Gas boiler + PV 44 kWp + co-generation unit	198	35	67	*40*	*28*	60	8	27
Heat pump + PV 44 kWp + co-generation unit	100	57	67	*40*	*28*	46	21	36
Gas boiler + PVT 44 kWp + co-generation unit	198	35	67	*40*	*28*	60	8	27
Heat pump + PVT 44 kWp + co-generation unit	100	55	67	*40*	*28*	48	19	35
Gas boiler + PV 44 kWp + PVT 44 kWp + co-generation unit	198	35	107	*79*	*28*	99	8	27
Heat pump + PV 44 kWp + PVT 44 kWp + co-generation unit	100	55	107	*79*	*28*	87	19	35
Heat pump + PV 88 kWp[1]	0	75	79	*79*	*0*	61	18	56
Heat pump + PV 88 kWp + co-generation unit	100	57	107	*79*	*28*	86	21	36

[1] *Technology packages meeting the EXCESS PEB definition*

Figure 72 shows show the development of GHG emissions over their complete life cycle, starting with the GHG emissions arising in the product stage for the production of the technologies, going on with their development within 20 years of use and ending with the GHG emissions arising at the end of their life. In the use stage benefits of replaced electricity generation with a natural gas CC power plants are included. In the end of life stage credits for the replacement of primary materials are included. The lowest life cycle GHG emissions have the technology packages transforming the demo site to a PEB: “Heat pump + PV 88 kWp” and “Heat pump + PV 44 kWp + PVT 44 kWp”. In the case, where surplus electricity replaces a natural gas CC power plant, the life cycle GHG emissions of the PEB technology options turn negative. When the replacement of the European electricity mix is assumed life cycle GHG emissions of the PEB technology packages are very low to zero but do not turn negative.

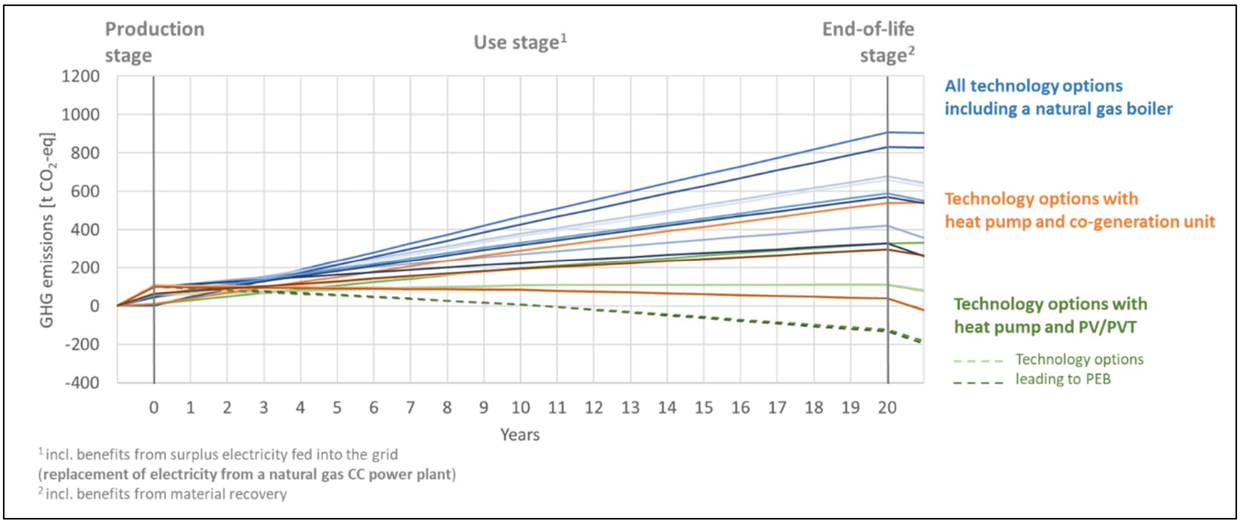

Figure 72: Life cycle GHG emissions of technology packages including credits for surplus electricity fed into the grid assuming the replacement of natural gas CC power plants

The methodological approach for crediting surplus electricity by replacing electricity generation has limitations: Total GHG emissions and the comparative ranking of technology packages heavily depend on the energy source being replaced. Future electricity generation mixes, which are uncertain, must be considered. While replacing natural gas CC power plants is reasonable for the current situation, this assumption may not hold for buildings and energy technologies with longer lifespans, as conditions could change in the next years.

Therefore, for all technology packages including heat pump, PV and PVT the GHG emissions were allocated between (1) the energy used to provide heat and electricity to the apartments (operational energy) and (2) surplus electricity fed into the grid. Figure 73 compares the GHG emissions for the operational energy of the building. The highest GHG emissions for the operational energy has the system with the heat pump only, although the GHG emission in the production phase are the lowest. After approximately 6 years of operation the GHG emissions of the heat pump only system exceed the GHG emissions of all other system with PV or PVT. The lowest GHG emissions for operation have the systems reaching PEB status. GHG emissions factor for the surplus PV electricity fed into the grid ranges between 18 and 22 g CO_2-eq/kWh. Based on the results of the LCA it is not possible to draw a conclusion on the GHG impact of PVT compared to PV. The difference in GHG emissions of the corresponding systems (PV 44 kWp and PVT 44 kWp, PV 88 kWp and PVT 88 kWp) is too small and lays within the uncertainties of the LCA.

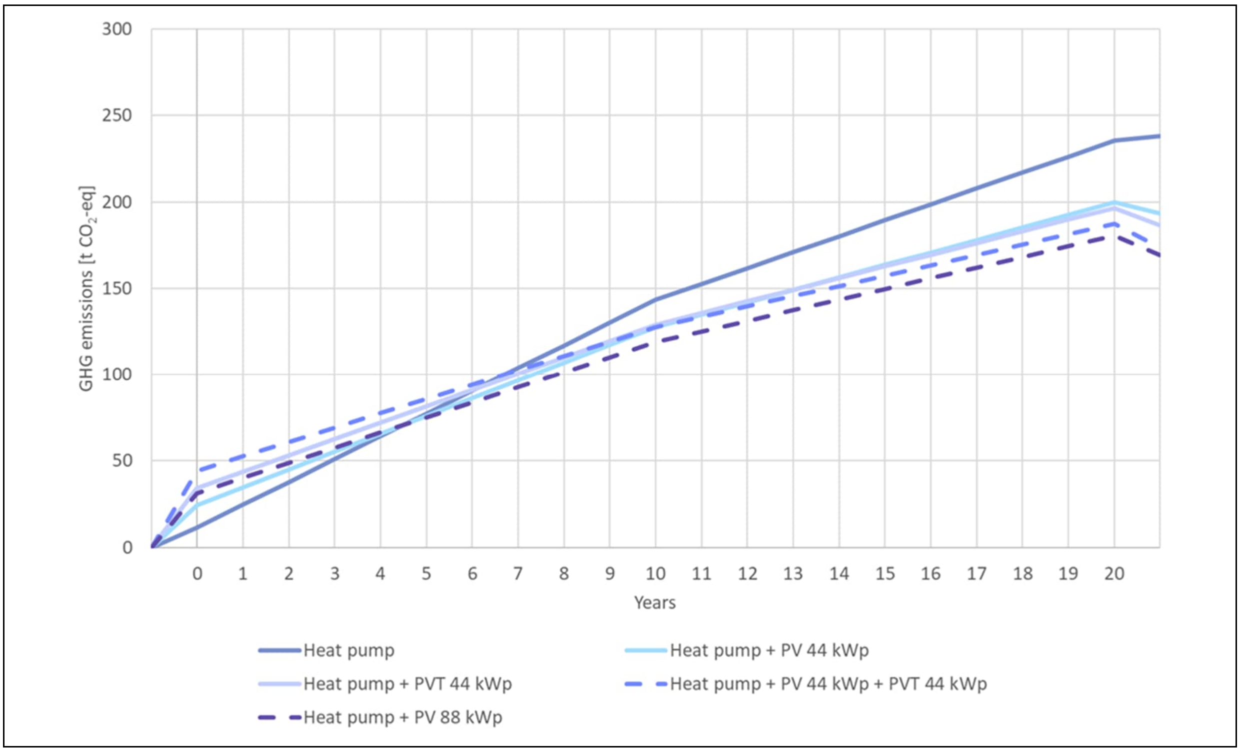

Figure 73: Life cycle GHG emissions for operational energy of technology packages with heat pump, PV and PVT

3.6.2 Austria

For the Austrian demo GHG emissions of the multifunctional façade element were compared to GHG emissions of a traditional façade renovation including different heat generation systems and BiPV. Therefore, 9 technology packages were investigated combining different scenarios for the envelope renovation, the thermal system and BiPV (Table 26).

Table 26: Scenario description for the envelope, thermal system and BiPV

	Scenario	Description	Expected technology lifetime
Envelope	D0	Standard renovation of envelope according Austrian legislation requirements; Interpolated average U-value of envelope: 0.39 W/(m^2 K)	25 years
	D1	Multifunctional façade element (incl. thermal circuit for wall heating, insulation, fixture for BiPV); Interpolated average U-value of envelope: 0.27 W/(m^2 K) (walls 0.15, roof 0.17, floor 0.51, windows 0.85) – EXCESS scenario	40 years
Thermal system	TS0	Gas heating system with floor heating	25 years
	TS1	Ground water heat pump with floor heating	25 years
	TS2	Ground water heat pump with only partial floor heating system – EXCESS scenario	25 years
Building integrated PV (BiPV)	BiPV0	no PV	0 years
	BiPV1	44kWp building integrated PV	20 years
	BiPV2	88kWp building integrated PV	20 years

Figure 74 shows in a simplified scheme the main processes considered in the LCA calculation for the EXCESS renovation case with the multifunctional façade element in comparison to the reference renovation with a heat pump and a standard facade renovation. Both systems provide the same energy service to the building: a defined indoor climate (heating, cooling), domestic hot water and electricity for lighting and plug loads. Depending on the technology packages electricity is also needed for heating and cooling (heat pumps). Therefore, the electricity demand of the technology packages differ. In addition, the amount of thermal energy needed for heating differs as the multifunctional façade element and the standard renovation have different U-Values (Table 26).

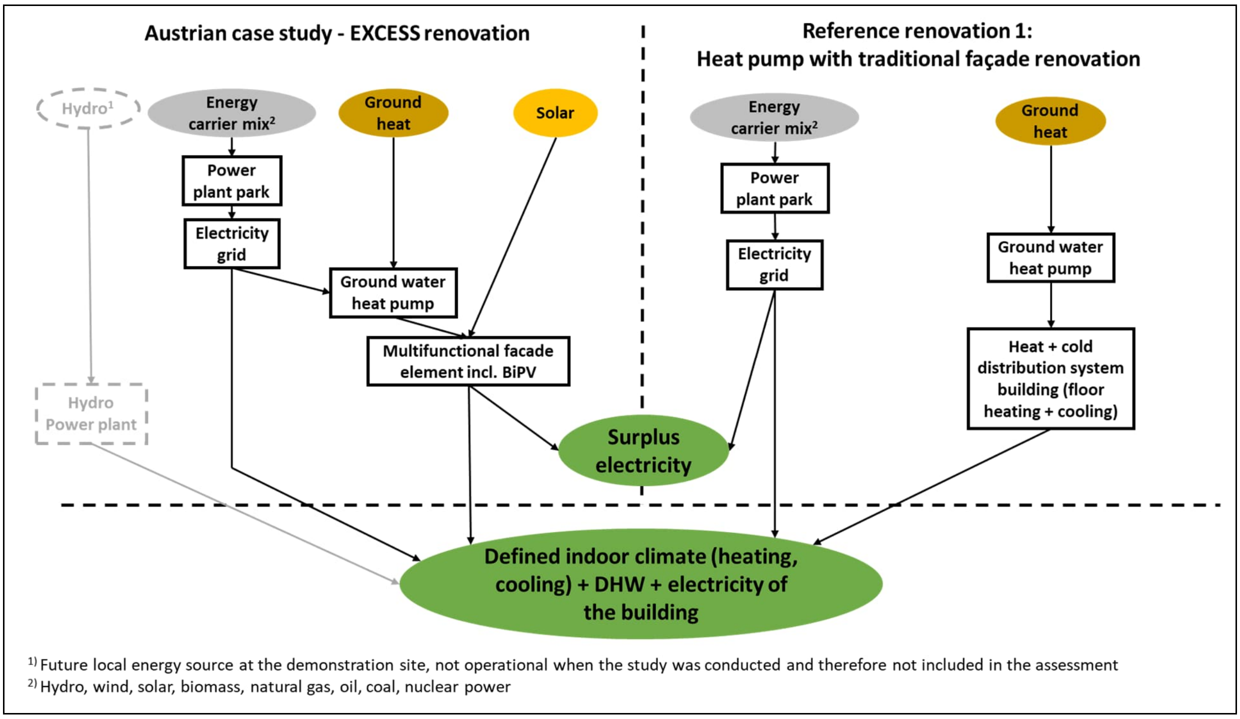

Figure 74: Simplified scheme for the LCA calculation of the EXCESS renovation case with a multifunctional façade element compared to the reference renovation with a heat pump in combination with traditional façade renovation

In the technology packages with PV not all of the PV electricity is consumed on site. Some electricity is fed into the grid. In the LCA this surplus electricity was included in the calculation in the following way:

Credits for replaced electricity generation: surplus electricity injected into the grid influences the electricity generation in the network and electricity generation by other power plants might be replaced. To include this effect of surplus electricity on the electricity generation mix of the system two options for replaced electricity were investigated:

a) For the replaced electricity generation mix a European electricity mix was assumed.
b) For surplus electricity it is assumed that the electricity generation in a natural gas power plant is replaced, since natural gas power plants, as flexible electricity generation units, are high on the merit order curve of the day-ahead electricity market.

The technology packages "Multifunctional facade element + heat pump + PV 88 kWp" and "Standard renovation of envelope + heat pump + PV 88 kWp" turn the tower to a PEB, as the locally used energy sources are renewable and more electricity is produced than consumed during the time span of a year.

Important foreground data for the LCA are the yearly energy balances of the investigated technology packages (Table 27), which were calculated based on simulation data. Simulation data was used as (1) monitoring data was not available when the LCA was conducted, and (2) to have data for the technology packages, which are not implemented in the demonstration.

Table 27: Yearly building energy consumption and electricity production

	Overall building energy consumption [MWh/a]		Electricity production	Grid electricity consumption	Grid feed-in
	Gas	Electricity (incl plug loads)	[MWh/a]	[MWh/a]	[MWh/a]
Standard renovation of envelope + gas boiler	57	18	0	18	0
Standard renovation of envelope + gas boiler + PV 44 kWp	57	18	26	7	15
Standard renovation of envelope + gas boiler + PV 88 kWp	57	18	52	5	39
Multifunctional facade element + heat pump	0	35	0	35	0
Multifunctional facade element + heat pump + PV 44 kWp	0	35	26	21	12
Multifunctional facade element + heat pump + PV 88 kWp[1]	0	35	52	18	35
Standard renovation of envelope + heat pump	0	38	0	38	0
Standard renovation of envelope + heat pump + PV 44 kWp	0	38	26	25	13
Standard renovation of envelope + heat pump + PV 88 kWp[1]	0	38	52	22	36

[1] *Technology packages meeting the EXCESS PEB definition*

First the GHG emissions for the production of the multifunctional façade element were calculated and compared to the product stage GHG emissions of the standard renovation of the tower envelope (Figure 75). The assessment showed that, the product stage GHG emissions the multifunctional façade element without PV are approximately three times higher than those of the standard façade renovation without PV. For the standard façade renovation, the main impact on the product stage GHG emissions is the production of mineral wool. For the multifunctional façade element without PV mineral wool contributes to 32% of the total production GHG emissions. The metals (chromium steel, cooper and aluminium) contribute to 60%. As the multifunctional façade element originally was developed with a wooden frame, also this version was investigated and compared to the façade element with a steel frame, which was developed for the demo site due to fire safety regulations for high-rise buildings. The wooden frame reduces the GHG emission for the production of the multifunctional façade element by 37 kg CO_2-eq/m² or 25% (for the version without PV panel).

Including PV to increases the GHG emissions from 33 to 328 kg CO_2-eq/m² for the standard renovation and from 144 to 458 kg CO_2-eq/m² for the multifunctional façade element with steel. However, it needs to be pointed out that in this comparison the function of the systems is not the same. Where the standard renovation system only contributes to the renovation of the envelope and its insulation, the multifunctional façade element already includes a part of the heat distribution system.

Therefore, Figure 76 presents the GHG emissions for the production of the complete technology packages providing the same energy service to the tower (defined indoor climate, lighting and plug loads) and surplus electricity fed into the grid (which varies deepening on the size of the installed PV in the respective technology package). In the case of the standard renovation the tower needs a floor heating in all floors. In the case of the multifunctional façade element a floor heating is only included for the ground floor (partial floor heating), where a commercial use was planned, when the systems for this study were defined. For the other floors the heat distribution happens via the walls with multifunctional façade element. Still the technology packages with the multifunctional façade element have higher GHG emissions than the corresponding technology packages with standard renovation (e.g. "Standard renovation of envelope + heat pump" with 130 t CO_2-eq compared to "Multifunctional façade element + heat pump" with 248 t CO_2-eq). PV increases the product stage GHG emissions of the technology packages in all cases substantially.

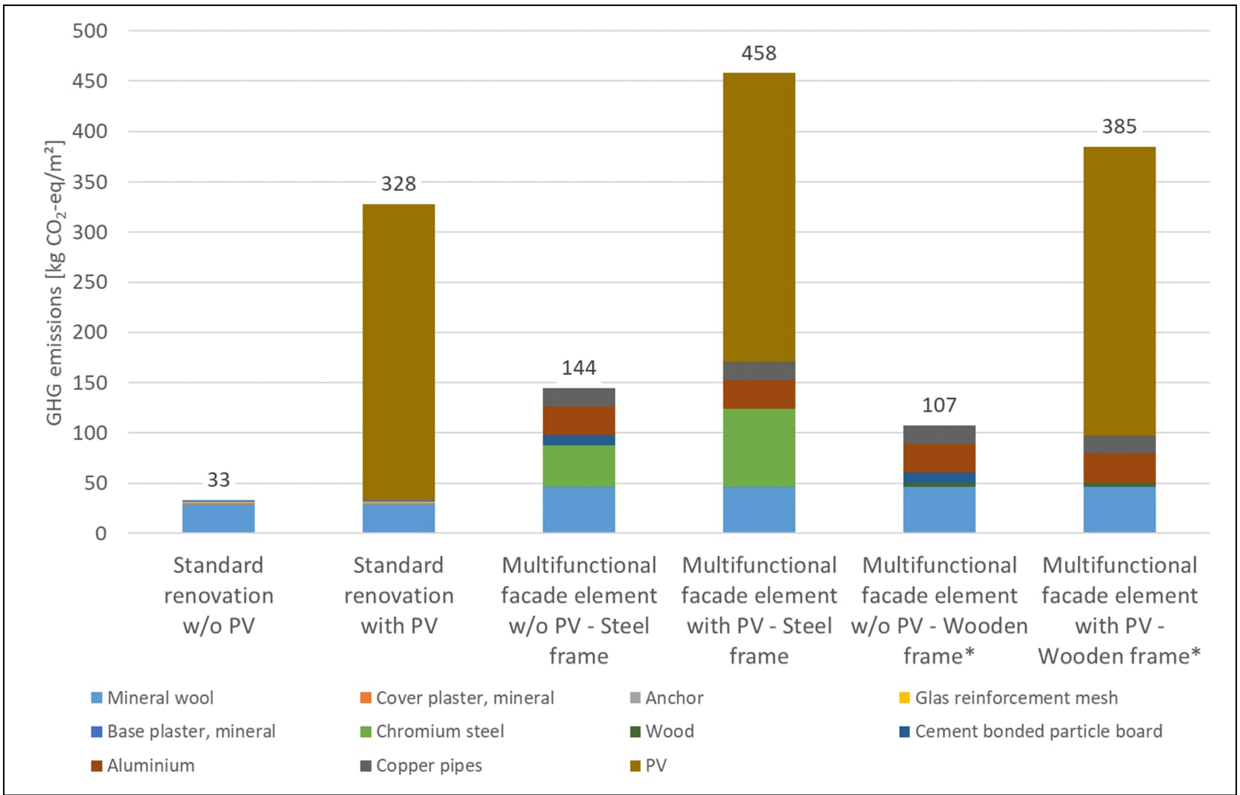

Figure 75: Life cycle GHG emissions of the multifunctional façade element with steel frame and wooden frame in comparison the standard renovation

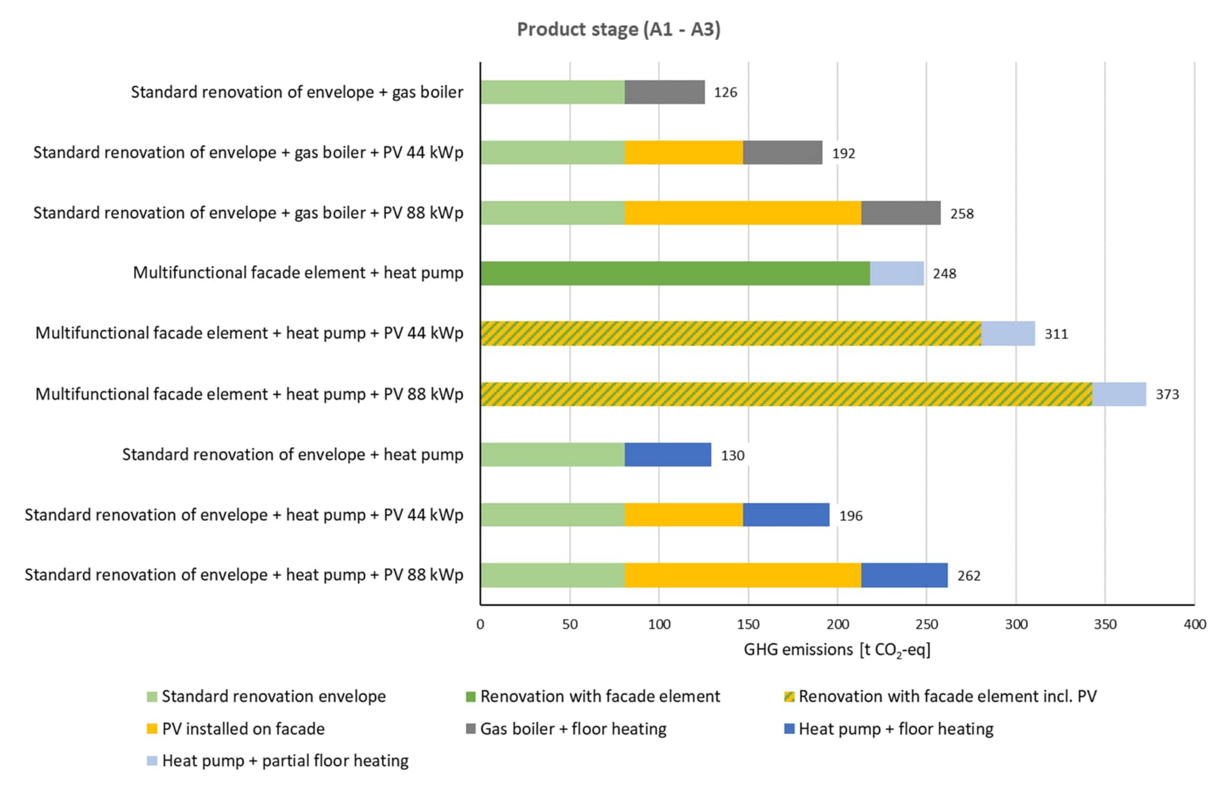

Figure 76: GHG emission for the production of the investigated technology packages

The results on the complete life cycle of the technology packages are shown in Figure 77, considering the benefits from grid feed-in by assuming the replacement of electricity generation with a natural gas CC power plant. Here, the PEB technology packages have the lowest life cycle GHG emissions. Total GHG emissions are even negative, as the benefits are higher than the GHG emissions from the operation of the systems. Comparing the multifunctional façade element to the standard renovation the higher GHG emissions in the product stage cannot be compensated completely in the use stage. At the end-of-life stage the benefits from replaced primary material are higher for the multifunctional façade element as the metals used in the system reach higher recycling ratios (90-95% according to [3]) compared to the materials used for the standard renovation. However, uncertainties in the calculation of the end-of-life phase are high due to long study period of 40 years and the replacement of primary products with today's GHG emissions factors might overestimated the benefits. Also it was assumed that mineral wool is landfilled, which is going to change as mineral wool is subject to the landfilling ban under Europeans Union's circular economy package. Considering these uncertainties in the end-of-life phase and the small differences in total GHG emissions for comparable technology packages with standard renovation and multifunctional façade element no robust conclusion can be drawn, which system is more beneficial in terms of GHG emissions.

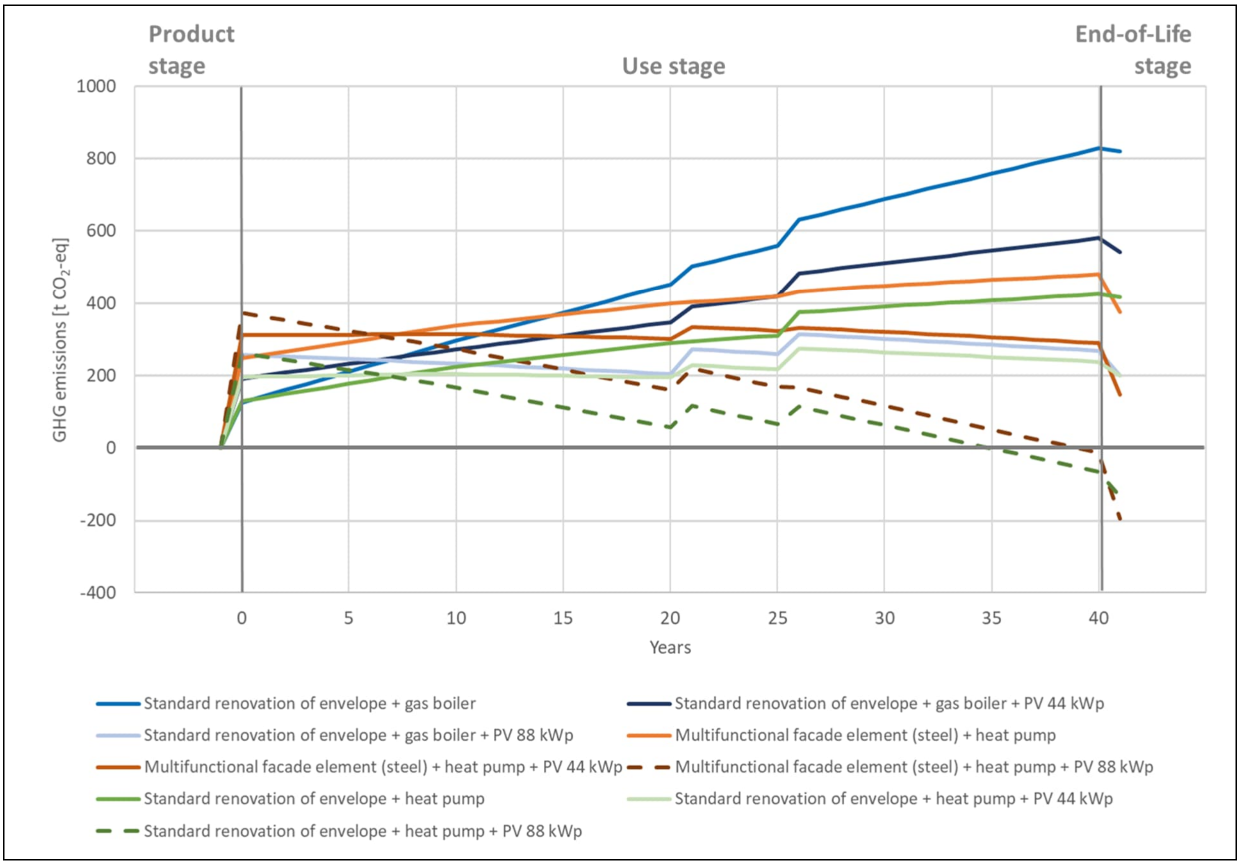

Figure 77: Life Cycle GHG emission for the investigated technology packages including benefits of surplus electricity (replacement of natural gas CC power plant)

4 Conclusions

This report presents the results from the four EXCESS demonstration sites, highlighting the most important aspects and lessons learned from PEB implementation. While all demo sites are now operational, their commissioning occurred later than initially planned. Measurement data collected from each site is presented, providing insights into the performance of the EXCESS technology packages and solutions, both on short and long-term. Each demonstration site offers unique insights, allowing for more detailed, site-specific conclusions to be drawn:

Spain

The Spanish Demo demonstrates PEB refurbishment in heritage buildings. Despite the many challenges associated with heritage building renovation, the EXCESS technologies manage to enhance the energy balance and reduce the energy cost of the building. The smart energy management system reduces energy consumption by 5% by operating the HVAC system more efficiently while maintaining user comfort preferences in the dwellings and reduces energy cost by 20% with the activation of battery storage flexibility. However, the system was not tested during a full year, so more time is needed to observe if it adapts as designed to the diverse climate and user conditions that normally occur in the building lifecycle. Forecasting accuracy has to be extensively monitored, as this is a key factor for the whole system performance. Additionally, with the arrival of inhabitants to the dwellings, this will reveal the acceptance level of the user with the smart control functionalities.

Austria

The refurbishment project for the demonstration site began with the ambitious goal of transforming a former industrial silo structure into a Positive Energy Building (PEB) while showcasing innovative renovation techniques. Despite delays in construction and the limitation to a scaled-down demo setup, significant progress was achieved like the proof-of-concept and validation for critical technologies such as the active facade system, advanced IoT devices, and user-centric control applications.

Testing of the innovative facade included the mounting procedure for the prefabricated facade elements which was successfully demonstrated. Challenges like material inconsistencies such as the difference between brick and concrete sections were identified. Temperature, heat flux and thermographic measurements confirmed effective heat transfer and integration of the energy-active facade layer. Additionally, the implemented IOT devices together with the OBS app played a vital role in enabling detailed monitoring, data analysis, and user participation, further enhancing energy system integration.

The dynamic building and energy system simulations, which incorporated a supervisory Model Predictive Control (MPC) algorithm, demonstrated significant performance improvements over conventional energy management strategies. By leveraging the large thermal storage capacity of the activated building mass, the MPC optimized load shifting to align with renewable energy availability, achieving nearly 60% renewable energy coverage for heating and domestic hot water. Furthermore, it also reduced peak grid loads by 12.3% during high-demand periods, demonstrating its ability to balance energy efficiency, grid stability, and occupant comfort.

Despite construction challenges, the EXCESS demonstration building in Graz successfully met its research objectives, proving the feasibility of key technologies and validating the effectiveness of combining advanced facade solutions, IoT technologies, and predictive control strategies.

Finland

The hybrid semi-deep geothermal heat pump system at the Finnish demo site is operational since August 2023. Initial monitoring shows satisfactory indoor temperatures and heat pump performance with a coefficient of performance (COP) ranging from 2.8 to 5.0. However, full seasonal COP evaluation could not be performed due to the limited measurement period. The evaluation of the performance was done by using monitoring data to tune the model for yearly analysis. Once the PV and PVT systems are operational in 2025, their integration is expected to significantly enhance system efficiency by providing electricity for heating and low-temperature heat for recharging the geothermal wells. While the current analysis indicates a self-consumption rate of 55%, future refinements will likely optimize energy usage.

Due to the bankruptcy of the construction company, the PV and PVT could not be commissioned during the EXCESS project. The bankruptcy estate oversees the completion of the installations. The remaining activities are funded through a deposit established at the beginning of the project, ensuring that the installation process will be finalized in 2025.

Belgium

In the Belgian demo, the implementation of the EXCESS technology concept resulted in significant savings in terms of operational costs and CO_2 – emissions. The self-consumption of locally produced electricity was increased by 8% due to activation of thermal flexibility within the decentralised domestic hot water tanks. The efficiency of the heat pump increased with 10% compared to a standard geothermal heat pump system. The total annual operational costs were reduced with 53%. The intention of removing the gas-fired system completely proved to be difficult and very much depended on the weather conditions. On cold winter days, it is not possible to source enough energy from the BTES and PVT system and some gas-fired back-up is needed.

A complex design and potential budget overrun caused significant delays in the implementation process. The design had to be reevaluated in order to reduce installation costs and to keep within the timing of the project. There were also challenges in finding experienced installers of PVT panels. The technology developments on the Collindi heat interface units (SOC, P2H and control) were tested and implemented successfully. In addition, the data management platform developed within EXCESS proved to be successful. It was further developed and updated after implementation in 2022 and today it is also used in other projects.

A user survey on thermal comfort was conducted with a response rate of 95%. In general, the users are satisfied with the thermal comfort in their houses while a few aspects and considerations should be taken into account when designing new systems. For example, the risk of overheating should be considered more carefully and the size of the domestic hot water tank should be adapted to the needs and size of the dwelling.

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