Techno-economic analysis of the flexibility potential in Positive Energy Buildings

Camilla Neumann[1,1], Clemens Mayer [1], Andreas Türk [1], Hassam ur Rehman [2], Ilaria Marotta [1,3]

(1) JOANNEUM RESEARCH Forschungsgesellschaft mbH, Leonhardstraße 59, 8010 Graz, Austria, 0316/876 7657, camilla.neumann@joanneum.at, https://www.joanneum.at/en/

(2) VTT Technical Research Centre of Finland Ltd., P.O. Box 1000, FI-02044 Espoo, Finland, hassam.rehman@vtt.fi, https://www.vttresearch.com/en/about-us/contact-us

(3) National Research Council (CNR) of Italy, Institute for Advanced Energy Technologies (CNR-ITAE); 98126 Messina, Italy

Abstract:

Plus Energy Buildings (PEBs) have higher investment costs due to higher insulation standards, innovative heating systems, and integrated renewable energy solutions. These costs are only partially offset by energy savings or the sale of surplus photovoltaic (PV) electricity. However, PEBs offer the potential for additional revenues from using flexibilities due to their advanced energy management systems and flexible technologies, such as heat pumps or batteries. This study examines cost savings from flexibility optimization in four PEBs located in Austria, Finland, Spain, and Belgium, focusing on reducing electricity costs under fixed and flexible electricity tariffs. Results show that the optimal control of flexible demand reduces electricity costs, with savings varying by building characteristics, thermal storage capacity, and regional climate conditions.

Keywords: Positive Energy Building, Energy Flexibility, Economic analysis, Optimization Framework

1 Introduction

The European building sector is responsible for about 36% of the EU's carbon emissions [1]. To meet climate goals, all buildings will need to be highly energy-efficient and carbon-neutral by 2050 [2]. The updated Energy Performance of Buildings Directive (EPBD) sets clear targets: starting in 2030, all new buildings must meet a Zero Emission standard, with public buildings required to comply even earlier, by 2028.

Newly built positive energy buildings (PEBs) and the renovation of existing buildings to meet PEB standards could play a key role in reaching these targets, as they actively contribute to a climate-neutral built environment. The EU has embraced this concept, setting goals to establish 100 Positive Energy Districts (PEDs) by 2025 and decarbonize 100 cities by 2030 [3]. Despite these ambitious plans, progress has been slower than expected, and large-scale adoption of PEBs has yet to take off. One of the main hurdles is cost—both constructing new PEBs and upgrading existing buildings to meet PEB standards require higher upfront investment costs (up to 65%) compared to conventional building projects [4].

[1] Jungautorin

PEBs generally have higher investment costs compared to conventional buildings due to improved insulation standards, innovative heating systems, and integrated renewable energy and storage systems [4]. These higher costs can only be partially offset by energy savings or the sale of renewable electricity from photovoltaic (PV) systems [5]. PEBs, however, generally offer significant flexibility potential due to the installation of smart and flexible technologies and a high thermal mass, which could generate revenues through the utilization of flexibilities. The flexibility potential also depends on the climate zone. For instance, in colder regions, heating cannot be interrupted as long as in warmer climates, limiting the potential for flexibility [4].

In general, the use of flexibility can be divided into implicit and explicit optimization. Implicit optimization refers to the use of flexibilities for on-site optimization such as an increase in self-consumption or the shift of demand towards low tariff periods. Explicit flexibility means that flexibility is offered towards the grid on existing markets (e.g. auxiliary service markets). Market-based revenues are more developed at the TSO level, with incentives for flexibility procurement, while DSOs still lack such mechanisms and are mostly in the pilot phase [2]. Aggregating demand-side flexibility is crucial for households and small businesses to access these markets, but high entry barriers remain. The EU Clean Energy Package introduces key market reforms through the Electricity Market Directive [3] and Electricity Market Regulation [4] to offer explicit flexibility. The EMD enhances aggregator integration, ensures non-discriminatory demand response participation, and promotes local flexibility markets. The EMR mandates smaller trading products (500 kW or less) in day-ahead and intraday markets to support demand response, energy storage, and small-scale renewables, including direct customer participation. However, implementation in Member States is still in its early stages, and therefore estimations regarding financial benefits are lacking.

Since revenues from explicit flexibility are either limited or still uncertain (e.g., local flexibility markets), this paper focuses on the potential of utilizing implicit flexibility to generate income and enhance the cost efficiency of PEBs. The research question, therefore, investigates to what extent optimized use of flexibilities in different climate zones can lead to cost savings, either through the optimization of fixed or variable electricity tariffs.

2 Methodology

2.1 Description of pilot sites

Austrian pilot site: The Austrian pilot site is located in a former industrial area in Graz. Graz benefits from a Mediterranean-influenced climate, characterized by a very sunny climate. The project involves transforming a former feed production silo, part of a complex with 19 buildings and a total area of about 31,000 m², into a positive energy office building. The building will achieve positive energy status by activating its existing thermal mass using prefabricated multifunctional facade elements with integrated PV panels to meet its heating, cooling, and electricity needs. The area’s energy supply will primarily come from PV systems and groundwater heat pumps. To maximize energy flexibility, the system incorporates advanced load shifting, energy storage, user integration, and smart predictive controls for interaction with the local electricity grid.

Spanish pilot site: The Spanish pilot site is located in the historic center of Valladolid, known for its cold winters and hot summers. The project involves renovating the building to create nine dwellings, including five duplexes, with a total floor area of 1089 m². Due to its heritage status, energy efficiency upgrades have to be made without altering the exterior façade, including window size and placement. High-performance heating, ventilation, and cooling systems and renewable energy solutions are implemented to enhance self-consumption. To achieve the PEB standard, an innovative smart energy system is deployed, featuring a centralized aerothermal heat pump, 51.4 kW of photovoltaic panels, 1.5 kW of PVT panels for domestic hot water, and a 60 kWh lithium-ion battery for energy storage. The PV system provides energy for collective self-consumption, storing surplus in the battery for daily use.

Belgian pilot site: The pilot site in Hasselt, Belgium includes four apartment buildings with 20 dwellings connected to a small district heating network powered by geothermal heat pumps, gas-fired geothermal heat pumps, and backup gas-fired boilers. Each unit has a substation for space heating and domestic hot water. The buildings are converted into PEBs by integrating innovative solutions such as PVT panels for renewable heat and electricity, multi-source direct-controlled heat pumps, and PV panels for renewable electricity.

Finnish pilot site: The Finnish pilot site is a PEB located in the Kalasatama district of Helsinki, an area with residential and commercial buildings. The building has eight floors and includes 51 apartments and commercial spaces with a total heated area of about 4000 m². The building uses a hybrid geothermal energy system, combining 600-meter-deep geothermal wells with integrated PV panels (87 kWp) and solar thermal PVT panels (79 kWp) to produce electricity and heat. A 67 kW multisource heat pump supports active heating and cooling, utilizing energy from the ground, PVT panels, and ventilation. The system also recharges the bedrock for long-term energy storage.

2.2 Definition of use cases

To assess the economic benefits of using flexibilities for reducing electricity costs in PEBs in the four pilot sites, two use cases (UC) are defined.

Use case 1: Optimization of electricity costs under fixed electricity tariffs

This use case examines shifting flexible electricity demand to align with PV generation. Comfort levels can vary depending on the control logic used as mentioned in [9]. However, according to [5], we can determine a specific shift for each pilot site while ensuring comfort is maintained. This is made possible by using PEBs with high thermal mass and effective insulation. Electricity prices for buying and selling from and to the grid remain fixed. Since electricity prices are typically higher than feed-in tariffs, increasing self-consumption lowers electricity costs.

Use case 2: Optimization of electricity costs under variable electricity tariffs

This use case shifts flexible demand to reduce costs, like UC1, but also considers a flexible electricity tariff based on the day-ahead spot market. Here, only the electricity price varies, while the feed-in price remains fixed. Flexible pricing offers an additional incentive for load shifting, with self-consumption generally prioritized over market-based optimization. Day-ahead market (DAM) price optimization becomes more relevant in winter when PV generation is low.

These two use cases are applied to four pilot sites of PEBs in different climate zones (Austria, Finland, Spain, and Belgium), and the cost savings were quantified using the DESIM optimization model from Joanneum Research [10]. The model enables the shifting of flexible loads within defined boundaries and objective functions while preserving the overall energy consumption. First, the PV production in relation to the overall demand as well as the flexible demand are analysed. Secondly, the model was used to shift the building's flexible electricity demand with fixed tariffs (UC1) or flexible electricity tariffs (UC2).

2.3 Input/Output data of the analysis

Table 1 presents the input data for the techno-economic analysis, which stems from building simulations from the Horizon 2020 project EXCESS [3]:

Table 1: Input parameters for the techno-economic analysis.

Non-flexible electricity demand	Yearly profile of non-flexible electricity demand, such as plug loads
Flexible electricity demand	Yearly profile of flexible electricity demand before optimization (heating, cooling, domestic hot water)
Timeframe to shift the heat pump	Potential shift of heat pump without unreasonable loss in comfort
Maximum power of heat pump, storage	Maximum power of the heat pump exhibits a limit to the load-shifting capacity

Table 2 presents the techno-economic parameters of the four different pilot sites. In Belgium and Finland, PV as well as a heat pump (HP) are in place, while in Austria and Spain, an electric battery storage is also installed. The electric batteries are characterized by a dis/charging efficiency of 95%. In UC2 the battery is charged when the price drops below 0.14€/kWh and is discharged when the price exceeds 0.18€/kWh. The feasibility of shifting energy consumption depends on the thermal storage capacity of the building envelope, which varies in the four case studies between 3 hours in Belgium and 12 hours in Austria [5]. A fixed electricity price was used for UC1 across all countries, whereas the flexible electricity price accounts for national market rates. Additional assumed costs for the flexible electricity price include a €0.015/kWh service fee, €0.09/kWh grid charges, and a 20% value-added tax (VAT).

Table 2: Overview of the techno-economic parameters of the case studies.

<table>
<tr><th></th><th>Technologies</th><th>Shift of heat pump</th><th>Fixed electricity price</th><th>Flexible electricity price</th><th>Revenues for excess electricity</th></tr>
<tr><td>Belgium</td><td>HP, PV</td><td>3 Hours</td><td rowspan="2">0.25 €/kWh</td><td>EPEX spot market 2023</td><td rowspan="2">0.05 €/kWh</td></tr>
<tr><td>Finland</td><td>HP, PV</td><td>6 Hours</td><td>Nordpool market 2023</td></tr>
</table>

Austria	HP, PV, Battery (60 kWh/60kW)	12 Hours		EPEX spot 2023	
Spain	HP, PV, Battery (60 kWh/60kW)	3h in winter, 10h in summer, warm water 4h		OMIE spot 2023	

Based on these input parameters the yearly energy balance, the self-consumption rate (SCR), the self-sufficiency rate (SSR) [9] as well as the yearly savings for the two use cases are calculated for the four pilot sites.

$$Yearly\ energy\ balance = \frac{Yearly\ PV\ generation}{Yearly\ consumption}$$

$$SCR = \frac{(Yearly\ PV\ generation - electricity\ to\ grid)}{Yearly\ PV\ generation}$$

$$SSR = \frac{(Yearly\ consumption - electricity\ from\ grid)}{Yearly\ consumption}$$

Finally, this study relies on the following assumptions:

- As previously mentioned, the aim of this research is to develop a techno-economic optimization framework for exploiting the flexibility potential of PEBs and quantifying the economic benefits of flexibilities. In this regard, the detailed study of the thermophysical behavior of buildings is out of the scope of the research. On this line, we assume that shifting the operation of the heat pump neither increases nor decreases overall electricity demand nor affects the average room temperature.
- Additionally, the heat pump's efficiency remains unchanged regardless of supply temperatures or temperature set points.
- Moreover, technological investment costs are not considered in this study, which focuses on the quantification of the electricity cost savings due to flexible control.

3 Results

3.1 Flexibility potential across climate zones

This section presents the flexibility potential of the pilot sites in the four different climate zones.

Austrian pilot

The Austrian pilot site has a high potential for flexibility, primarily due to the activation of a significant thermal mass via a multifunctional facade that heats/cools the building and produces PV. Flexibility can be offered year-round, with heating needs in winter and cooling needs in summer, which are both covered by the ground-source heat pump. In the Austrian pilot site, the yearly energy balance is 99.8%, which means that the building is almost PEB standard.

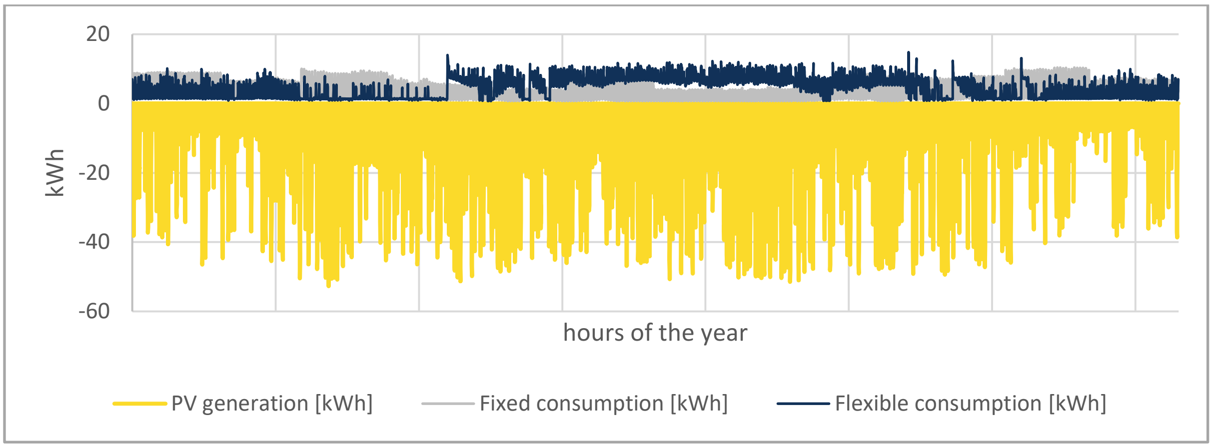

Figure 1: Flexible, non-flexible demand and PV generation for the Austrian pilot site.

Spanish pilot

In the Spanish pilot site higher flexibility can be offered in autumn and spring due to lower heating needs, as well as in summer due to cooling needs, lower flexibility is available in winter due to constant heating demand, which does not allow to shift electricity demand over several hours. The reason for this is that the Spanish pilot site comes with a low thermal mass and small domestic hot water (DHW) tanks resulting in limited flexibility. The yearly energy balance is 116%, which means that the yearly PV production is higher than the yearly demand of the building.

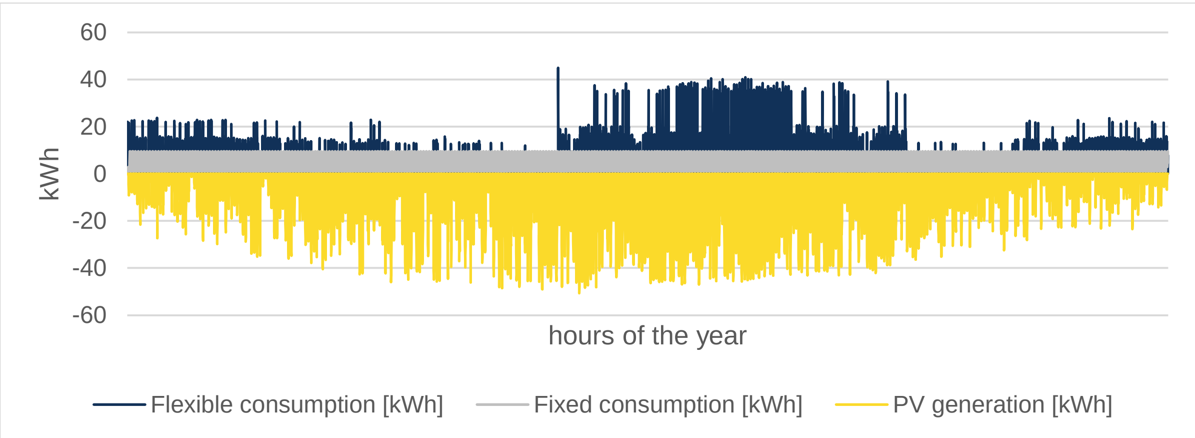

Figure 2: Flexible, non-flexible demand and PV generation for the Spanish pilot site.

Belgian pilot

In the Belgian pilot site, flexibility can be offered in winter due to the geothermal heat pump. However, in summer, there is minimal flexible demand, as the heat pump is not used for cooling. The yearly energy balance is 100%, which means the building reaches PEB standard.

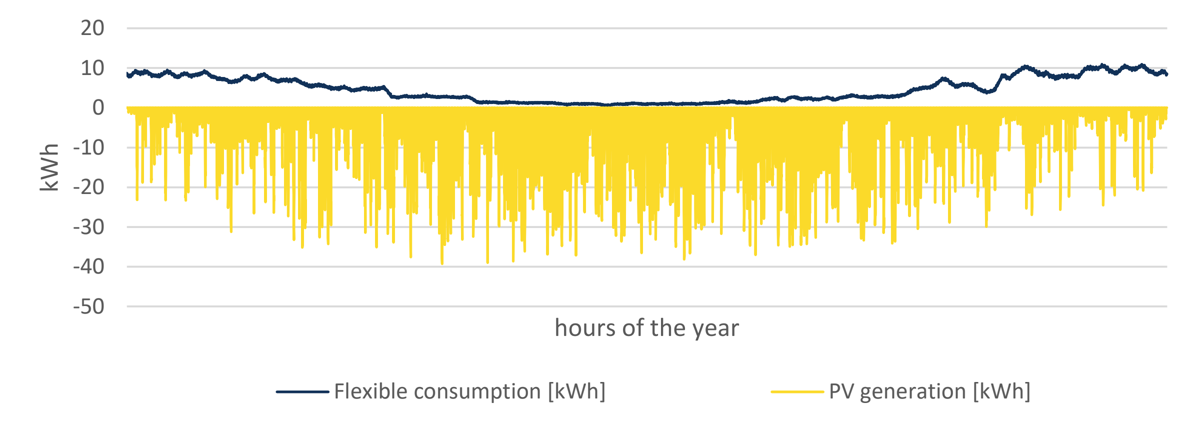

Figure 3: Flexible, non-flexible demand and PV generation for the Belgian pilot site.

Finnish pilot

The Finnish pilot site does not meet PEB standards, as the building's shape (high building with many floors) restricts PV installation, making it difficult to compensate for the high heating demand, which is shown in the yearly energy balance of 87%. The cold climate limits flexibility, as heating requirements are consistent, and the small DHW tanks with high circulation losses prevent effective shifting. Consequently, the overall flexibility potential remains low.

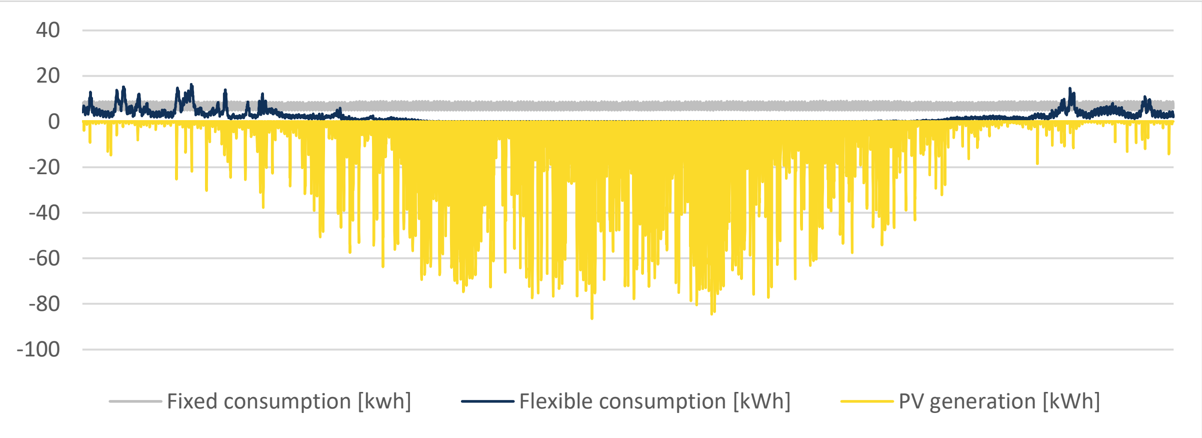

Figure 4: Flexible, non-flexible demand and PV generation for the Finish pilot site.

3.2 Techno-economic analysis

This section presents the results for UC1 – self-consumption optimization and UC2 - Optimization of electricity costs under variable electricity tariffs due to the use of flexibilities in PEBs for the four pilot sites.

UC1 – Optimization of electricity costs under fixed electricity tariffs due to the use of flexibilities in PEBs

Table 3 presents the results for UC1. It is shown that without any flexibility measures the self-consumption rate is between 26% and 42% for the pilot sites. For the Austrian and Spanish pilot sites, the SCR increases by 14%-19% when the HP is optimally controlled. For the Belgium and Finnish pilot sites the increase in the SCR is lower (1%-8%), due to a lack of flexibility in summer months, where PV production is highest. Installing an electricity storage battery further increases the SCR in the Spanish and Austrian pilot sites to 64% and 80% respectively. A similar development can be observed regarding the self-sufficiency rate.

In the Finnish pilot site, the savings are modest, adding up to €218 per year or a 1.5% reduction in electricity costs. One reason is the limited thermal flexibility of the Finnish pilot building, with only a 6-hour shift possible, due to the cold climate and as mentioned above the lack of cooling in the summer months. As this also holds true for the Belgian pilot site, savings are also limited to 518€/year or 10% electricity cost savings. For the Spanish and Austrian pilot sites, electricity costs can be approximately reduced by 30% with the optimization of the heat pump only, and by 60% with an additional battery.

Table 3: Results UC1 for each pilot site.

		Self-consumption ratio [%]	Self-sufficiency ratio [%]	Savings [€/year]	Electricity cost savings [%]
Austrian pilot site	Reference	42%	42%	-	-
	HP	61%	61%	2 425	32%
	HP, battery	80%	80%	4 495	60%
Spanish pilot site	Reference	27%	31%	-	-
	HP	41%	47%	1 538	26%
	HP, battery	64%	74%	3 741	63%
Belgian pilot site	Reference	26%	26%	-	-
	HP	34%	34%	518	10%
Finnish pilot site	Reference	34%	29%	-	
	HP	35%	30%	172	1.5%

UC2 - Optimization of electricity costs under variable electricity tariffs due to the use of flexibilities in PEBs

Table 4 presents the results for UC2. It is visible that there are only minor changes to the SCR and the SSR in comparison to UC1, as usually, the shift towards self-consumption is the cost-optimal solution. Savings are between 218€/year in the Finnish pilot site and 4 785€/year in the Austrian set-up with a battery. The electricity cost savings for the Austrian pilot site do not increase significantly in comparison to UC1, while for the other pilot sites higher savings can be achieved. This is because in the Austrian pilot, the majority of the demand has already been shifted to optimize self-consumption, taking advantage of the long shifting window of 12 hours. As a result, a limited flexible load remains available for further adjustment based on day-ahead market prices. In absolute numbers savings from the two scenarios are not comparable, as a flexible electricity price was used in UC2 in comparison to the fixed one in UC1.

Table 4: Results UC2 for each pilot site.

		Self-consumption ratio [%]	Self-sufficiency ratio [%]	Savings [€/year]	Electricity cost savings [%]

Austria pilot site	Reference	42%	42%	-	-
	HP	61%	61%	2 579	33%
	HP, battery	79%	79%	4 785	61%
Spanish pilot site	Reference	27%	31%	-	-
	HP	41%	48%	1 798	37%
	HP, battery	64%	74%	4 095	70%
Belgian pilot site	Reference	26%	26%	-	-
	HP	34%	34%	990	20%
Finnish pilot site	Reference	34%	29%	-	
	HP	35%	30%	218	3%

4 Discussion

The results indicate that cost savings are highest for the Austrian pilot site. This is primarily because the parameters for shifting the heating system are significantly higher compared to other pilot sites, due to the building's high thermal mass and the relatively warmer climate—unlike the Finnish pilot site, where cost savings were minimal. Additionally, both the Austrian and Spanish pilots experience high flexible loads in summer due to increased cooling demands. This leads to greater overall cost savings in these countries, as higher PV generation during summer enhances cost reductions through load shifting.

In general, it can be said that the level of savings strongly depends on building-specific parameters such as thermal mass, energy consumption profile, or PV system size. Moreover, regional factors such as heating and cooling demand or PV yield in winter influence savings potential as shown by the pilot sites situated in four different climate zones.

As for the limitations, the study assumes that shifting heat pump operations does not alter overall electricity demand, average room temperature, or the heat pump's efficiency. These simplifications limit the approach compared to detailed building simulation models. Additionally, investment costs, including those for batteries, are not considered. To calculate the profitability of the battery, electricity cost savings should be compared with investment costs and yearly depreciation of the battery.

5 Conclusions

The techno-economic analysis highlights that the use of flexibilities reduces electricity costs in the analyzed PEBs. The integration of a battery leads to significantly higher savings of up to 70%. It is also shown that considering the variable electricity tariffs can further increase electricity cost savings such as in the Spanish pilot site where savings are increased from 26%-37% without a battery and 63%-70% with a battery respectively.

The analysis also showed that due to high electricity grid fees, maximizing self-consumption of generated electricity is more cost-effective than optimizing for DAM prices. Substantial cost savings due to the shift to low-tariff periods are only possible when there are large differences in day-ahead market prices within a day as shown in UC2.

Even, PEBs are energy efficient and therefore have a low overall energy demand, a greater flexibility potential than conventional buildings is available due to higher insulation standards and innovative energy management systems, which enables significant cost savings.

In future scenarios, revenues from the external use of flexibilities, (e.g. on local flexibility markets) could further increase the economic profitability of PEBs.

6 Acronyms

DAM	Day-ahead market
HP	Heat pump
PEBs	Positive energy buildings
PV	Photovoltaic
SCR	Self-consumption rate
SSR	Self-sufficiency rate
UC	Use case

7 References

[1] European Commission - Press release, „Renovation Wave: doubling the renovation rate to cut emissions. boost recovery and reduce energy poverty,“ 2020.

[2] EC, „Directive (EU) 2024/1275 of the European Parliament and of the Council on the energy performance of buildings (recast),“ European Commission, 2024.

[3] E. C. EC, „Directorate-General for Research and Innovation, EU missions - 100 climate neutral and smart cities,“ Publications Office of the European Union, 2024.

[4] C. Mayer, A. Tuerk, C. Neumann, K. Allerts, J. Villar, R. Aylagas, H. ur Rehman, M. Ala-Juusela und M. Cantalapiedra, „EXCESS D5.3: Business models for PEBs,“ 2024.

[5] C. Mayer, A. Tuerk, M. Cantalapiedra and R. Ciria Aylagas, „EXCESS D5.1 Report on cost optimal technological solutions for PEBs,“ 2023.

[6] smartEN, „The implementation of the electricity market design to drive demand-side flexibility,“ 2020.

[7] European Parliament, „Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU,“ 2019.

[8] European Parliament, „REGULATION (EU) 2019/943 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 5 June 2019 of the internal market for electricity (recast),“ 2019.

[9] V. Lara, „EXCESS D2.6 Report on simulation based energy performance assessment of PEBs,“ 2020.