Economic and Environmental Optimization of Retrofitting Options for a Community Building: A Case Study from Förslöv-Grevie Parish, Sweden

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Abstract

The research evaluated retrofitting options for a three-story church community building in Grevie, Sweden, assessing the impacts on energy efficiency, life cycle cost, and environmental concerns. An energy model was generated in IDA ICE to simulate the building performance. Various improvements were tested in two separate retrofit package scenarios. They had the following measures in common: the addition of insulation to the walls and roof, the addition of sealant and secondary glazing, the installation of a heat pump with a better seasonal coefficient of performance (SCOP) on the ground floor, and the installation of a photovoltaic (PV) system. In the first scenario, modifying the controllers of electric radiators was considered while leaving other pre-existing systems untouched. In the second scenario, all systems were replaced by two heat pumps, one for the ground floor and the second for the first floor, with improved SCOP. In the study, 1,620 different energy improvement cases with simultaneous 3,000 simulation combinations of PV systems were examined, using scripted and parametric optimization. Results suggest that adjusting controllers and adding PVs could yield significant energy savings and cost reductions. Notably, cases with an additional air-to-air heat pump on the first floor showed the best energy consumption reduction, though not the highest profitability. The research highlights the importance of combining passive and active measures and their impact on energy efficiency, life cycle costs, and environmental factors. It also shows that the most energy-efficient options may not always be the most cost-effective or environmentally friendly during a building's lifetime.

1. Introduction

Aligned with the EU's and Sweden's shared energy reduction goals for 2050, there is a focus on improving existing building energy efficiency. Targets include a 20% reduction by 2020 and 50% by 2050. The growing building sector emphasizes the need to upgrade older structures (Communication from the Commission to the European Parliament, 2023). Heat pump systems play a crucial role in boosting efficiency and cutting emissions. EU heat pump sales data show a steady annual market growth of over 10% in recent years (Monica & Fredrik, 2005). There is also rising interest in combining heat pumps with solar systems for both single-family and multi-family buildings. This aims to increase the renewable portion of the system's heat source by enhancing PV power self-consumption and reducing grid-supplied energy (Isoleringsskiva Lambda 37 Isover, 2023). The study explores retrofitting active and passive measures for economic viability, energy savings, and environmental impact reduction.

2. Methodology

2.1 Overview

The study comprised four stages. Initially, the current building condition was evaluated through a site visit and energy usage data provided by the owners. Building geometry was then created in Revit and exported to IDA ICE 4.8for energy simulation, validated against actual energy use. In the second stage, two scenario groups were suggested

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to involve active and passive measures. In scenario one, all combinations of the passive parameters combine with two active parameters: adjustment of the controller type on the electrical radiators (PI and thermostat) and whether to keep the current ground floor air-to-air heat pump (A2A HP) or replace it with a more efficient one (seasonal coefficient of performance (SCOP) of 4.5, 5.0), resulting in 684 cases. In two, the same set of passive parameters was taken into account while also adding two active parameters: keeping the current ground floor A2A HP or replacing it with a more efficient one (SCOP of 4.5, 5.0), and adding a second A2A HP on the first floor (SCOP of 3.9, 4.5, and 5.0) to replace the hydronic radiators, resulting in 972 cases. Parametric simulation was performed for all 1,620 cases (annual energy, a software limitation in parametric study). The life cycle cost (LCC) analysis for the 1,620 cases was performed using Visual Basic Application (VBA) in two economic situations (see LCC section), considering each case's net present value (NPV). In the third stage, hourly energy simulation results were used to assess the PV system's performance combined with the 42 improved cases, accounting for the variation in production and consumption. Conducting hourly energy simulations was considered too time-consuming for 1,620 cases. To avoid bias and data loss during the selection process of retrofitting cases, a semi-random selection was introduced to cover a wider distribution of parametric input rather than only using the four identified cases. If only the cases with the most significant energy savings were kept for further analysis, there would have been a risk of excluding less optimized cases with a different energy use pattern than those with the most significant energy savings. This method includes one of the passive or active represented measures to a fixed value, while other parameters were chosen randomly. For example, a wall's insulation thickness of 45 mm could be a fixed control element, and other variables (e.g., glazing *U*-value, SCOP of heat pump, etc.) were chosen randomly by VBA script from the parameter mentioned above in each scenario the selection process scripted the way to avoid the repetition of the 37 cases. The 4 cases with the most significant energy savings and 37 semi-random cases were selected for integration with photovoltaic (PV) systems on an hourly energy basis. These less optimized cases could potentially better match the PV electricity production. Finally, the optimal cases and PVs were chosen for LCA evaluation and post-processing.

2.2 Energy Measures

In this study, passive and active measures were applied to comply with Swedish building regulations (BBR 29 by the Swedish National Board of Housing, Building, and Planning – Boverket). In Table 1 and Table 2, the inputs used for the base case are listed.

Table 1– Base case simulation inputs

	Basement	Floor 0	Floor 1
Area/ m^2	134.3	144.9	102.0
Lighting load/ W/m^2	0.1	2.291	0.163
Equipment load / W/m^2	4.4	6.694	–
Domestic hot water	0.5	0.5	0.5
Infiltration rate / ACH_{50}	1.3	1.3	1.3
Heating set point/ °C	17	23	17
Cooling set point / °C	–	–	–

Table 2– Base case *U*-values of various building elements

	Roof	Ext. wall	Window	Ground slab
U-value / W/(m²·K)	0.250	0.202	0.950	3.170

2.2.1 Passive measures

On-site measurements revealed CO_2 concentrations exceeding 1,000 ppm during occupancy. Therefore, natural ventilation was implemented in all improved cases by opening up to eight ground-floor windows from 12:00 to 13:30, and from 14:30 to 15:00 (at the beginning and the end of the occupancy schedule), reducing CO_2 levels to 800 ppm during operational hours. Thermal insulation was added to the exterior side of the wall to mitigate heat loss, with options of 45 mm and 95 mm thickness of Isover glass wool (λ = 0.037 W/(m·K)), guaranteed to contain at least 70% recycled glass (Isoleringsskiva Lambda 37 Isover, 2023). Retrofit measures can reduce infiltration rates by up to 77%, contributing to decreased energy demand and costs (Johnston et al., 2023). By enhancing the building's air-tightness, the infiltration rate can be lowered from 1.3 ACH at 50 Pa to the proposed values of 1.1, 0.9, and 0.7 ACH at 50 Pa. Windows contribute to heat transmission five times more than the other envelope components (Bülow-Hübe, 2001). However, secondary glazing can reduce this effect by enhancing the thermal performance of existing single/double-glazed windows, without removing the original glazing. It is achieved by adding a second glass pane, low emissivity coating, or plastic film, thereby reducing the *U*-value by up to 50% (Madushika et al., 2023; Harjunowibowo et al., 2019). The current window with a *U*-value of 0.95 W/(m²·K) and two new windows with *U*-values of 0.85 and 0.65 W/(m²·K) were used in the parametric simulation.

2.2.2 Active measures

The proposed retrofit involves adding a new A2A HP, either as a replacement on the ground floor or adding a new A2A HP with a different SCOP while removing the current hydronic radiators on the first floor. Three sizes of A2A HPs with SCOP values of 3.9, 4.5, and 5.0 were considered. Two different temperature control systems were assessed: the existing PI controller and an improved thermostat. Mechanical ventilation was excluded due to the perceived inefficiency of ducting in low-ceilinged floors and infrequent building occupancy. Passive and active measure parameters created two scenarios aimed at reducing energy demand and electricity consumption (see Table 3 and Table 4). The scenarios were then simulated in IDA ICE, resulting in 648 cases for scenario one and 972 cases for scenario two.

Table 3 – Parameters of passive retrofitting measures

Measure	Scenarios 1 and 2
Wall and Roof insulation / mm	0, 45, 95
Infiltration / $ACH_{50\,Pa}$	0.7, 0.9, 1.1, 1.3
Window *U*-value / W/(m²·K)	0.65, 0.85, 0.95
Natural ventilation	Scheduled in all cases

Table 4 – Parameters of active retrofitting measures

Measure	Scenario 1	Scenario 2
Controller type	PI, thermostat	–
SCOP Floor 0	3.9, 4.5, 5.0	3.9, 4.5, 5.0
SCOPFloor 1	–	3.9, 4.5, 5.0

2.2.3 PV system

In the System Advisor Model software (v. 2022.11.21), 3,000 annual simulations were performed parametrically, with variations in modules per string (5–16), number of parallel strings (1–10), tilt (25°–45° in steps of 5°), and number of inverters (1–5). The azimuth was fixed at 180°. Uniform module (Molin, n.d.) and inverter ("Sunny Tripower Mit SMA Smart Connected 8.0 / 10.0," n.d.) types commonly available in the Swedish market were used: a monocrystalline module with 48 cells, maximum power of around 550 W_P, and a nominal efficiency of 22.1%; the inverter of maximum DC power of around 12,200 W_P. The linear decline in energy output capacity over the module's 30-year lifespan was disregarded for simplicity. No shading or self-shading was considered in the analysis, supported by the analysis of the site geometry and neighboring objects. Typical irradiance losses, and DC and AC losses were also assumed.

2.3 Life Cycle Cost

The life cycle cost for all 1,620 cases in scenarios one and two were calculated using the VBA script to seek profitability for each case. Two scripts were developed to calculate LCC for each scenario. These scripts identify the parameters used in each case, allocating each parameter's initial cost, labor cost, operation cost, and all costs for replacement and repair during the study lifespan (Wikells, 2023; Svensson 2017). A 50-year building occupancy period was examined, and an NPV geometric gradient equation (Eq. 1) was used for cost calculation. The windows and ground floor A2A HP repairs were excluded from the calculation due to the consistency of these costs in the base case and improvement cases. For the sensitivity analysis, an interest rate of 3.5% (Statistics, 2023), an inflation rate of 2% (The Inflation Target, 2023), and 7.5% (The Inflation Rate According to the CPI, 2023) were used. This resulted in economic scenarios one and two, respectively. The life span of the thermostat is 15 years so three replacements were considered at years 15, 30, and 45. For the A2A HP, the yearly maintenance over 50 years was applied in the calculation.

$$\mathrm{NPV}_{\mathrm{energy}} = A_1 \cdot [(1-(1+g)^{N} \cdot (1+i)^{-N})/(i-g)] \quad (1)$$

A_1 annual savings in the first year
g nominal rate of price change
i nominal interest rate
N number of years

Building consumption and PV production vary at each time of day, so to analyze the performance of PV systems with improved cases, hourly energy results of improved cases were compared with the PV production on an hourly basis. Considering the hourly price of the electricity for buying to and selling from the grid, the NPV was calculated, evaluating the profitability of each case. As described below, a limited number of diverse cases were selected for this evaluation. Based on the highest NPV and the highest reduction in energy demand (the Pareto optimum), four optimal cases were selected among all improved cases. Additionally, by semi-random selection, 37 cases were selected, aiming to encompass more results from the entire parametric field and, consequently, minimize the likelihood of focusing solely on a local maximum. A VBA script was devised for this selection. As depicted in Fig.1, the selection principle is configured to ensure the inclusion of each variable at least once, with other parameters being assigned randomly. In scenario one, 18 cases were selected, whereas in scenario two, 19 such cases were chosen.

Case	Controller	Insulation wall	Insulation roof	Window	Infiltration	A2A HP SCOP
1	**PI**	random	random	random	random	random
2	**Thermostat**	random	random	random	random	random
3	random	**00**	random	random	random	random
4	random	**45**	random	random	random	random
5	random	**95**	random	random	random	random
6	random	random	**00**	random	random	random
7	random	random	**45**	random	random	random
8	random	random	**95**	random	random	random
9	random	random	random	**0.95**	random	random
10	random	random	random	**0.80**	random	random
11	random	random	random	**0.65**	random	random
12	random	random	random	random	**0.7**	random
13	random	random	random	random	**0.9**	random
14	random	random	random	random	**1.1**	random
15	random	random	random	random	**1.3**	random
16	random	random	random	random	random	**3.9**
17	random	random	random	random	random	**4.5**
18	random	random	random	random	random	**5.0**

Fig.1 – Schematic representation of the semi-random selection principle for the first scenario

Additionally, to assess the PV system's performance with improved cases, the hourly energy simulation results were used, accounting for the variation of production and consumption throughout the day. Considering hourly electricity price for grid transactions (Day-Ahead Prices on SE4 - Malmö, 2023), with economic situation 1 (real interest rate at 3.5%, inflation rate at 2%, and price growth of 4%) the NPV uses the same equation mentioned above, evaluating the profitability of each case. In PV systems, replacement of the inverters was also assumed every 15 years, thereby considerably increasing the PV system costs, as seen in Table 5.

Table 5 – Costs of PV systems

PV system	Inverter replacement
10.9SEK/W_P	228,596SEK/inverter

2.4 PV System Selection

To come up with a manageable number of hourly simulations to run manually in SAM, some of the 3,000 results had to be filtered out, as graphically depicted below Fig. 2, firstly based on the high AC and DC inverter clipping losses. After, due to simulation-proved inferior energy output, all cases with the oversized inverters were eliminated. In the following step, options characterized by an excessive number of inverters, which result in energy production achievable with a smaller number of inverters, were also disregarded. From the remaining options, suboptimal tilt options were excluded (45° is in the vast majority of cases the best). Additionally, suboptimal combinations of parallel strings and the number of modules per string were filtered, (e. g. 8 × 3 or 12 × 2 would have the same amount of PV panels, but different energy production). In the end, 81 cases remained, from which only 16 representative cases were selected in steps of approximately 5,000 kWh of energy production to ensure diverse output options were investigated, but also that the too-similar results would not be redundantly analyzed.

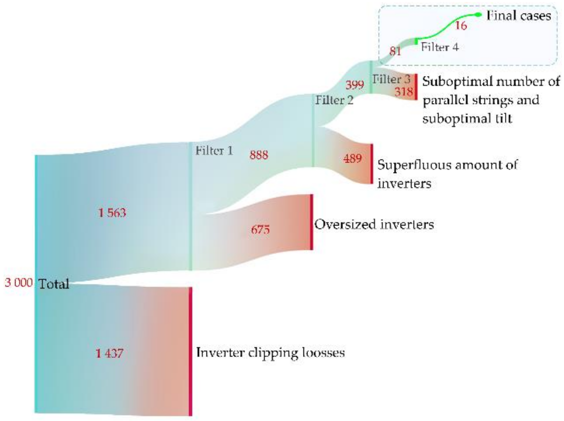

Fig. 2 – Visual representation of the filtering process for the PV cases selection

2.5 Life Cycle Assessment

LCA is performed in two parts: firstly, calculating the environmental impact of the building's operational energy using Open LCA 2.0. In the second part, the focus is on evaluating the environmental impact of the newly introduced materials in each case. These evaluations were done using EPDs ("EPD International," n.d.) and VBA scripts. For normalization and weighting, the shadow cost method (Javed, 2023) was used. The LCA included cases with the best performance with the PV system (five cases–all with the thermostat as the controller), the four best cases (with the highest NPV and the highest reduction in energy), and the base case. Additionally, the LCA of a random PV system (production of 55 500 kWh annually) is calculated. In the next step, LCA results were integrated with the LCC results. The integration sensitivity analysis was calculated considering 30%–70%, 50%–50%, and 70%–30% of environmental and economic impact ratios, respectively. In the assessment, a period of 50 years, and cycle stages A1–A3 and B6 were taken into consideration, with a unit of the heated floor area with sustained thermal comfort (m^2) as the functional unit. When looking at typical impact categories applied to the buildings' LCA, the most frequently examined ones included global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), and eutrophication potential (EP), as these factors were consistently addressed (Scheuer, Keoleian, and Reppe, 2003; Buyle, Braet, and Audenaert, 2013). Therefore, these four categories were chosen to evaluate the environmental effects of the presented cases.

3. Results and Discussion

3.1 Energy Measures

The building energy consumption during occupied six hours per week (base case) is 28,981 kWh. In scenario 1, the energy reduction with only passive measures ranges from 0.05% to 17.3%. By changing the controllers of electric radiators, higher energy reduction is achieved, ranging from 46.5% to 60.2%. After proposing a second A2A HP for the first floor in scenario 2, energy consumption is significantly reduced, and the reduction of energy ranges from 69% to 77%. The best cases have passive measures and thermostat controllers and a reduction range of 57% to 62.2%, and random cases have various reductions and are distributed among all cases.

3.2 Life Cycle Cost

NPV results for all 1,620 cases on an annual energy basis and electricity price indicate that only cases with passive measures and thermostat controllers in economic scenario one is profitable, as shown in Fig. 3. The savings from energy reduction surpass the investment in thermostat controllers, rendering these cases profitable.

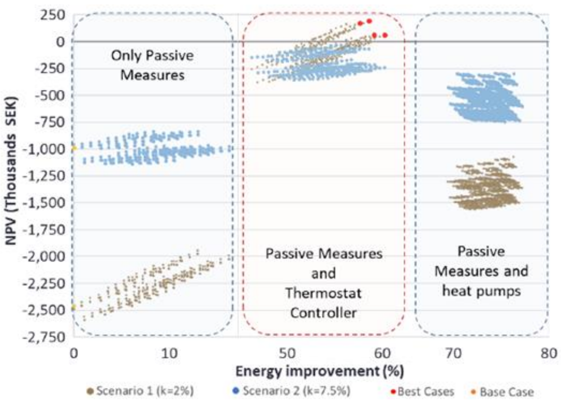

Fig. 3 – The net present value of all cases with the energy savings relative to the base case

The remaining cases are not profitable in either economic scenario. Introducing a new A2A HP yields diminishing returns, with increased energy savings failing to justify high initial and maintenance costs. Among the 16 PV systems evaluated, only six are profitable, ranging from around 40 kWp to 90 kWp, or 50,000 kWh to around 100,000 kWh annual production, as seen in Fig. 4. Cases with thermostats demonstrate the highest NPV when combined with PVs. Only five cases out of 42 selected ones are profitable (red dots in Fig. 4) with all six PV systems starting from PV11 to PV16. These cases share existing windows and thermostat controllers, while other parameter values vary. It is worth noting that the study's limitation lies in not simulating all potential cases hourly, as the semi-random selection method does not guarantee identifying the ultimate best solution.

3.3 PV Systems

For PVs, the energy production of the final 16 PV cases is directly correlated with the size of the system or the total module area. This shows that there is no option that is inherently more energy-efficient, and therefore the determination of which case merits investment should be based on an economic or environmental standpoint.

3.4 Life Cycle Assessment

The results depicted in Fig. 5 show that the lowest LCA belongs to cases "best 1" and "best 4", which have the existing windows, leakage of 0.7 $ACH_{50\ Pa}$, a new A2A HP with SCOP of 5, and additional wall and roof insulation thickness of 95 mm. Random case 16 has the highest environmental impact, including existing windows, leakage of 0.7 $ACH_{50\ Pa}$, A2A HP with SCOP of 4.5, and additional wall and roof insulation thickness of 95 mm. The majority of cases have a higher environmental impact than the base case. Most of the difference between the cases is seen in the GWP, which stems from the more efficient A2A HP for the ground floor and additional insulation thickness implemented in the wall and roof, and the airtightness of the building in random cases 7 and 16, "best 2", and "best 3".

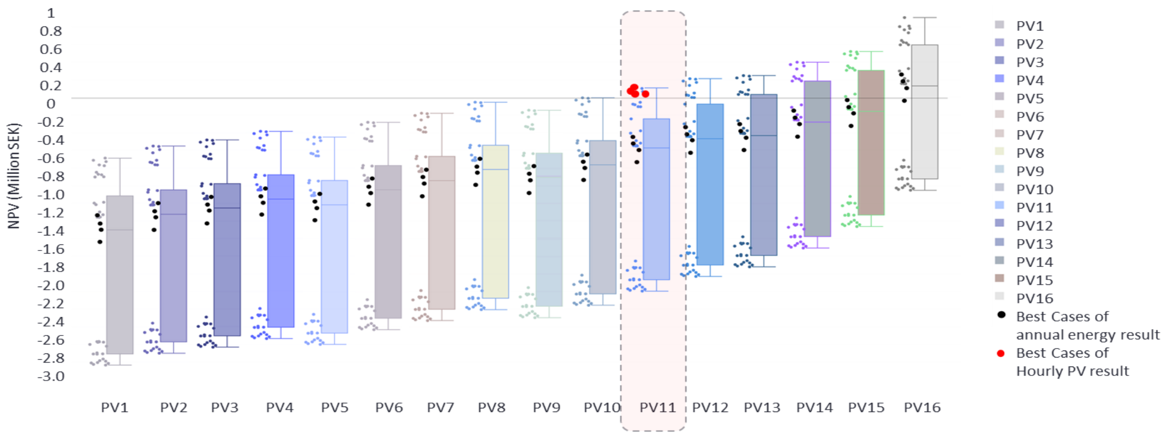

Fig. 4 – NPV of the integrated PV systems and selected energy cases. PV11 is the PV system selected for further life cycle analysis

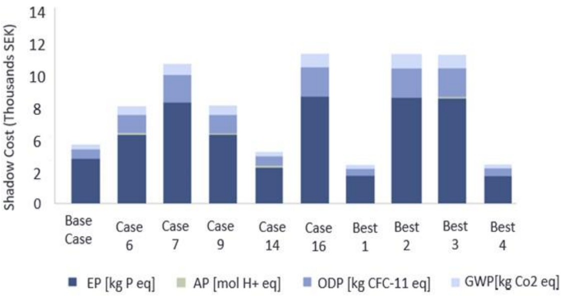

Fig. 5 – Integrated LCA of the base case and 9 selected cases

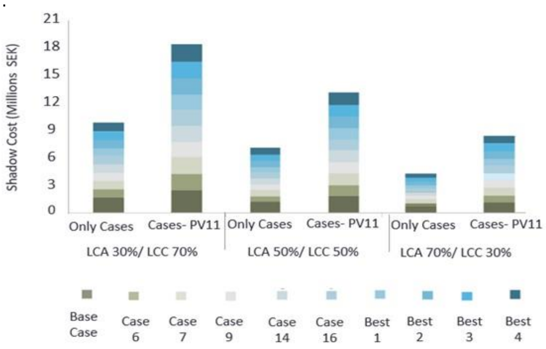

Fig. 6 – Sensitivity analysis weighting LCA and LCC

The significant difference between LCA and LCC resulted in the same trend in the three integrated weighting scenarios. As shown in Fig. 6, when LCA has more weight, the shadow cost of cases and cases including the PV goes down, due to the reduction of the energy impact. Three cases show more promising results in all three domains. One of these cases originated from the initially best cases that were chosen from a pool of 1,620 cases, while two others were selected from random cases that have the lowest LCA. This highlights the fact that the most economical scenarios may not necessarily be the most favorable ones when it comes to either LCA or integration with PVs.

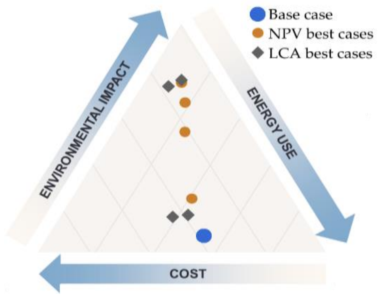

Fig. 7 – Relationship between LCA, energy use, and LCC of the base case and 9 selected cases

4. Conclusion

The study assessed energy improvements and life cycle costs across various scenarios. Passive measures alone resulted in modest energy consumption reductions (0.05% to 17.3%). However, adding thermostat controllers for electric radiators substantially increased energy reduction (46.5% to 60.2%). Introducing a second heat pump on the first floor led to significant energy consumption reductions (69% to 77%). Profitability analysis indicated that only cases with passive measures and thermostat controllers were profitable. While an additional A2A HP saved more energy, higher initial and maintenance costs offset the savings. Among PV systems, only six cases showed profitability, with annual production ranging from 50,000 to 100,000 kWh. However, combining a second heat pump with PV systems was not profitable in any scenario. Assessing energy consumption, life cycle cost, and PV system evaluations identified only five profitable retrofit cases when combined with selected PV systems. These cases differed from the initially selected four best cases based solely on NPV and energy reduction. GWP was the highest environmental impact category, mainly from the new heat pump and increased wall insulation thickness. Integrated LCA underscored the need for balanced decision-making in energy systems, as achieving lower costs, reduced energy use and lower environmental impact simultaneously may be challenging or unattainable.

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