Energy renovation of non-residential buildings in Sweden

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Lund University

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The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Building Design.

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Abstract

The recast Energy Performance of Buildings Directive introduces binding Minimum Energy Performance Standards for existing non-residential buildings, requiring Member States to identify and renovate the worst-performing segments of their building stock. This study develops and applies an integrated framework for evaluating energy renovation measures in office buildings, addressing building category selection, model fitting under data uncertainty, and techno-economic assessment of renovation packages.

Two office buildings of similar construction period in Stockholm, both connected to district heating, were selected as case studies. Building energy models were developed and fitted against measured heating energy data, based on the most impactful parameters, followed by a parametric simulation evaluated against the calibration criteria of ASHRAE Guideline 14. Three energy models were retained per building to preserve residual modelling uncertainty. Among the input parameters investigated, ventilation system parameters showed the strongest influence on simulated heating demand.

A systematically selected set of renovation combinations was evaluated through parametric simulation, assessed using energy savings and simple payback time for individual measures and a profitability framework for packages. Ventilation-related measures, specifically AHU replacement and conversion from constant to variable air volume operation, consistently delivered the highest energy savings combined with short payback times across both buildings and all energy models with average return on investment of 27 % and 40 %, respectively. At the package level, the replacement of the air handling unit together with LED lighting formed a high-return renovation package with a cumulative return on investment above 30 %. The further conversion of the ventilation system control from constant air volume to variable air volume increased the energy savings while keeping the package return on investment above 25 %. Adding roof insulation to the package consistently yielded moderate returns, with a cumulative return on investment of approximately 20 %. Window replacement provided a secondary contribution but highly sensitive to the precondition of the existing windows, at substantially higher investment cost. Lighting and pump replacement had marginal impact on total energy use despite relatively low investment.

The ranking of measures remained consistent across the three energy models selected per building, suggesting limited impact on the choice of interventions to modelling uncertainty for the building characteristics studied. The methodology supports structured identification of effective renovation pathways for office buildings sharing similar functional characteristics, providing a pathway to support energy improvement required by Minimum Energy Performance Standards under the recast Energy Performance of Buildings Directive.

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Note on AI and language tools: Grammarly was used for spelling and grammar checking. AI assistance supported translations and small coding tasks. All technical work, analysis, and conclusions are solely the authors' own.

Table of Contents

Abbreviations

AHU	Air Handling Unit
BBR	Boverkets Byggregler (Swedish Building Regulations)
CAV	Constant Air Volume
CV(RMSE)	Coefficient of Variation of the Root Mean Square Error
DCV	Demand-Controlled Ventilation
DHW	Domestic Hot Water
EEI	Energy Efficiency Index
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
EPG	Energy Performance Gap
EU	European Union
FTX	Från-/Tilluft med Värmeåtervinning (Mechanical Supply & Exhaust with Heat Recovery)
FT	Frånluft (Mechanical Exhaust Ventilation)
FX	Frånluftsventilation med värmeåtervinning (Mechanical Exhaust Ventilation with Heat Recovery)
GH	Grasshopper
HB	Honeybee
HR	Heat Recovery
IPMVP	International Performance Measurement and Verification Protocol
IRR	Internal Rate of Return
LCC	Life Cycle Cost
MEPS	Minimum Energy Performance Standards
NMBE	Normalized Mean Bias Error
NZEB	Nearly Zero-Energy Building
OFAT	One-Factor-At-a-Time
OVK	Obligatorisk Ventilationskontroll (Mandatory Ventilation Inspection)
PBL	Plan- och Bygglagen (Swedish Planning and Building Act)
ROI	Return On Investment

SFP	Specific Fan Power
STIL	STIL – Statistik i lokaler (Building Energy Use Statistics for Non-Residential Buildings, Sweden)
TMY	Typical Meteorological Year
VAV	Variable Air Volume
VFD	Variable Frequency Drive
VVC	Varmvattencirkulation (Hot Water Circulation loss)
WWR	Window to Wall Ratio

Terminology

Impactful parameters	Model inputs identified through sensitivity screening as having a high impact on simulation output and therefore selected as model fitting variables in the process.
Marginal ROI	The return on investment of an additional renovation measure when added to an existing package, used to order measures along the renovation path.
Model Fitting	A structured process in which uncertain input parameters are varied and evaluated against measured energy data to reduce discrepancies between simulated and measured heating demand. This process does not claim to produce a physically correct or unique representation of the building but rather identifies a set of plausible parameter combinations that satisfy accepted statistical criteria.
Non-observable parameters	Model inputs that cannot be determined from direct evidence (e.g., infiltration rate, internal gains, occupant behaviour, set-point deviations).
Observable Parameters	Model inputs supported by direct evidence from as-built drawings, technical documentation, site inspections, or verified geometric data.
Pareto Front	The set of renovation packages for which no alternative achieves both lower cost and lower energy use simultaneously; visualised as a trade-off boundary.
Sensitivity Screening	An initial analysis identifying which input parameters have a high impact on simulation output, used to select parameters for further calibration.

1 Introduction

The European Union aims to become the world's first climate-neutral continent by 2050, with Sweden targeting climate neutrality by 2045. Buildings represent approximately 40% of final energy use in the EU , and improving their energy performance is recognised as one of the most cost-effective pathways toward these targets (EPBD (Recast) 2024).

In line with the EU Renovation Wave (European Commission 2020), the recast Energy Performance of Buildings Directive (EPBD) introduces Minimum Energy Performance Standards (MEPS) for existing non-residential buildings, establishing binding renovation obligations for the worst-performing segments of the building stock. In Sweden, Boverket delivered the first interim report on MEPS in October 2024 (Boverket 2024), analysing the existing non-residential stock as of 2020 and proposing energy performance thresholds for two target years. Buildings representing the worst-performing 16 % of the stock are required to meet the first threshold by 2030, increasing to 26 % by 2033. These requirements must be transposed into Swedish law by May 2026 (Boverket 2025)

These standards create an urgent need to identify and implement effective renovation strategies, as building owners and policymakers must develop concrete pathways to meet compliance deadlines. However, determining effective renovation strategies is complex due to the variety of building functions, internal loads, and operational patterns across the non-residential sector. The frequent discrepancy between measured and simulated energy use, known as the Energy Performance Gap (EPG), adds further complexity, reducing confidence in predicted savings and hindering decision-making (Lassen et al. 2024).

This study addresses these challenges by developing and applying an integrated framework for evaluating energy renovation measures in non-residential buildings, selecting office buildings as the most appropriate category for analysis. The framework covers building category selection, energy model fitting under data uncertainty, and techno-economic assessment of renovation packages applied to two case study buildings in Stockholm.

1.1 Objectives

This thesis aims to investigate energy and cost-effective renovation strategies for existing non-residential buildings in Sweden, with a focus on office buildings as a representative category of the non-residential stock. Through a structured modelling and evaluation framework, the study develops a method for identifying renovation pathways to support energy improvement required by MEPS under the recast EPBD. The work addresses the challenge of evaluating renovation potential under data uncertainty, a common condition when working with existing building stock, by developing and applying a systematic model fitting process based on measured energy data. The study was carried out in collaboration with Zerotude AB, an innovative startup based in Lund specialising in large-scale energy renovation strategies.

The study aims to investigate the following:

- Identification of the most appropriate non-residential building category for analysis in the context of MEPS legislation and the Swedish building stock
- Determination of appropriate modelling assumptions and critical input parameters for energy performance simulation of the selected building category, addressing the performance gap between measured and simulated energy use
- Development and application of a model fitting framework that explicitly accounts for data uncertainty in existing buildings

- Evaluation of energy renovation measures and packages in terms of energy savings, cost of conserved energy, and economic return, identifying renovation pathways that balance technical performance with financial viability

2 Background and regulatory framework

This chapter establishes the regulatory context within which the present study is situated. Energy renovation of non-residential buildings in Sweden is currently shaped by a layered policy framework that originates at the European Union level and is progressively translated into national legislation, technical guidelines, and verification practices.

The chapter is organised into two parts. First, it introduces the European Union Energy Performance of Buildings Directive (EPBD), outlining its overall objectives, the role of the Renovation Wave initiative within its most recent recast, and the introduction of Minimum Energy Performance Standards (MEPS) for non-residential buildings. Second, it addresses the implementation of the EPBD in Sweden, covering its transposition into national law, the structure of the Swedish energy performance certification and regulatory framework.

2.1 European Union EPBD

2.1.1 Overview and objectives of the EPBD

The building sector represents one of the largest sources of energy usage and greenhouse gas emissions in the European Union (EU), accounting for approximately 40 % of final energy use and around 36 % of energy-related greenhouse gas emissions, while a substantial proportion (75 %) of EU buildings are still energy-inefficient. As a result, improving the energy performance of buildings is recognised by the EU as a critical and cost-effective measure to reduce emissions and support the transition towards climate neutrality (EPBD (Recast) 2024).

The EPBD was first adopted in 2002 with the objective of establishing a common framework for improving the energy performance of buildings across Member States (DIRECTIVE 2002/91/EC). The initial focus of the Directive was on harmonising calculation methodologies, introducing minimum energy performance requirements for new buildings, and providing transparency through Energy Performance Certificates (EPCs) (EPBD 2002).

Subsequent revisions of the EPBD in 2010 and 2018 progressively expanded the scope and ambition of the Directive. The 2010 revision (DIRECTIVE 2010/31/EU) introduced the concept of Nearly Zero-Energy Buildings (NZEBs), strengthened requirements for technical building systems (EPBD (Recast) 2010; Kalaycioglu and Yilmaz 2018).

The 2018 act (DIRECTIVE (EU) 2018/844) amends the 2010 EPBD. Its main shift is from "design of new buildings" to "deep renovation, digitalisation and smart readiness of the existing stock". As stated in Article 2a each EU nation must develop a comprehensive strategy to decarbonize its entire building sector by 2050. This involved creating a roadmap to cost-effectively renovate all private and public buildings, with the aim of turning them into energy-efficient, nearly zero-energy structures (EPBD Amendment 2018). Despite these advances, EU policy for the existing building stock continued to rely primarily on financial incentives, information instruments and long-term renovation strategies, while binding obligations remained largely limited to major renovations and the replacement of building elements or systems (Economidou et al. 2020).

The 2024 recast of the EPBD (DIRECTIVE (EU) 2024/1275) marks a fundamental shift in regulatory approach by explicitly addressing the energy performance of existing buildings and introducing binding renovation requirements, by the recognition that voluntary renovation rates are insufficient to meet climate targets within the required timeframe. A central objective of the recast EPBD is the introduction of MEPS, which require Member States to identify the worst-performing buildings within their national building stock and ensure that these buildings are renovated to meet defined energy performance thresholds by specified target years. Article 9 of the directive establishes a progressive compliance pathway for non-residential buildings, targeting the worst-performing segments of the stock rather than imposing uniform requirements across all buildings (EPBD (Recast) 2024).

2.1.2 The renovation wave initiatives and its role in the EPBD recast

The Renovation Wave initiative (COM (2020) 662 final) was launched by the European Commission in 2020 as part of the European Green Deal, as a strategic response to persistently low renovation rates across the EU. At the time of its adoption, annual renovation rates were estimated at approximately 1 % of the building stock, with the majority of interventions classified as shallow renovations delivering limited energy savings (European Commission 2020).

The Renovation Wave established ambitious targets that MEPS operationalize reducing building sector greenhouse gas emissions by 60 % and final energy use by 14 % by 2030 compared to 2015 levels. Therefore, the objective of Renovation Wave was aiming to renovate 35 million buildings by 2030, at least doubling the annual rate of energy renovations in the EU. The Renovation Wave directly drove the creation and implementation of MEPS as a core mechanism to accelerate building renovations across Europe (European Commission 2020).

The revised EPBD, finalized in May 2024 (DIRECTIVE (EU) 2024/1275), embedded MEPS as the primary policy instrument to deliver on these goals by creating legally binding renovation obligations rather than relying on general encouragement.

2.1.3 MEPS for non-residential buildings

DIRECTIVE (EU) 2024/1275 in article 9(1) introduced MEPS for non-residential buildings on the basis of maximum energy performance thresholds (EPBD (Recast) 2024).

MEPS established mandatory energy performance thresholds for existing non-residential buildings, requiring Member States to ensure that the worst-performing segments of their building stock are renovated to achieve minimum levels of energy efficiency within defined timeframes. Member States are required to identify the worst-performing buildings using a reference year, set at 2020, and ensure that at least the worst-performing 16 % of non-residential buildings meet a minimum energy performance threshold by 2030, increasing to 26 % by 2033.

Each Member State shall set a maximum energy performance threshold as a whole or per building type or category of buildings. The Directive allows Member States to define MEPS thresholds using either primary or final energy indicators, provided that the chosen metric is consistent based on national energy performance data.

The maximum energy performance threshold for non-residential buildings may be set as a value for the whole stock, or buildings may be grouped into categories to reflect differences in function or usage patterns, enabling differentiated thresholds across building types such as offices, educational buildings, healthcare facilities, and commercial premises.

2.2 Implementation of EPBD in Sweden

2.2.1 Transposition of the EPBD into Swedish law

The Swedish National Board of Housing, Building and Planning (Boverket) issues detailed rules through Boverket's Building Regulations (BBR). Energy performance requirements for buildings have been regulated through BBR since 2006, with successive revisions between 2006 and 2017 progressively tightening energy performance standards for new constructions. These developments established a regulatory foundation aligned with the objectives of the EPBD, particularly regarding improved energy efficiency and performance-based requirements (Karlsson Hjorth et al. 2021)

Sweden had already implemented most elements of the EPBD by 2014. Following the 2010 and 2018 revisions of the EPBD, Sweden further developed its regulatory framework focused on developing and refining the regulations for NZEB. NZEB requirements were introduced into the Planning and Building Ordinance (PBF 2011:338) in December 2016 and subsequently implemented in BBR (BFS 2011:6) in

2017. These changes introduced the primary energy number (primärenergital) as the main indicator for assessing building energy performance, and the NZEB framework was further extended in 2018 to the Swedish system for EPCs, regulated through Boverket's provisions (BED, BFS 2007:4). Subsequent revisions in 2020 introduced weighting factors for different energy carriers and further strengthened overall energy performance requirements (Karlsson Hjorth et al. 2021).

In 2017, Sweden's building stock accounted for 39 % of final energy usage. Temperature-corrected statistics, normalized by building surface area, reveal a positive trend from 1995 to 2017: energy use declined by 33 % in single-family houses, 22 % in residential apartment buildings, and 21% in non-residential buildings (Karlsson Hjorth et al. 2021).

In preparation for the implementation of the EPBD recast (Directive (EU) 2024/1275), Boverket has been assigned responsibility for analysing how new requirements, including MEPS for existing non-residential buildings, can be integrated into the Swedish regulatory framework. As part of this process, Boverket delivered the first interim report on MEPS in October 2024. According to the national implementation timetable, the transposition of the recast EPBD into Swedish law is required to be completed by May 2026, in accordance with EU obligations (Boverket 2026a).

2.2.2 Swedish energy performance certification and regulatory framework

EPCs were introduced by the EU's EPBD in 2002. The directive requires member states to use standardized methods to assess and certify building energy use, helping owners, tenants, and policymakers make informed decisions about building energy performance (EPBD 2002). In Sweden, the Energy Declaration Act introduced EPCs in 2006, with data collection starting in 2007. EPCs became mandatory for buildings that are sold or rented, frequently visited by the public, or newly constructed (Energy Declaration Act 2006).

BBR, issued by Boverket, provides the detailed regulatory framework for building performance in both new builds and renovation projects in Sweden. These regulations include mandatory requirements and general guidelines, with Chapter 9 specifically addressing energy performance (BBR 29 2011).

In Sweden, energy performance assessment begins during the design phase, when calculated energy performance is submitted to the municipality as part of the building permit application. After completion, the building's actual energy use must be measured, and an EPC is issued by a certified energy expert. During the first two years of operation, energy performance is monitored and adjusted to ensure compliance before the final EPC is issued (Bandak et al. 2025). According to BBR (BFS 2011:6), Chapter 9:25, compliance with the primary energy requirement in Section 9:2 must be verified in the completed building. The measured data for existing buildings are normalized to represent "normal use" and a "normal year," in accordance with Boverket's BEN regulations (BFS 2017:6) (Boverket 2016; BBR 29 2011).

Boverket defines a building's energy use under normal use during a normal year, as the energy needs to be delivered to a building (usually referred to as purchased energy) for heating, comfort cooling, domestic hot water, and the building's property energy (Equation (1). Boverket's BEN regulations (BFS 2017:5) specifies that measured energy must be corrected to account for typical user behaviour, indoor temperatures, internal gains, and a reference climate year (Bandak et al. 2025). In short, measured use is "normalized" so that the energy performance reflects standard conditions, thus making EPCs comparable across buildings. BBR then requires that compliance with the Planning and Building Act's energy requirement (section 9:2 in BBR) be verified using those BEN-corrected values.

$$E_{bea} = E_{uppv} + E_{kyl} + E_{tvv} + E_f \qquad (1)$$

Where E_{bea} is building's total delivered energy in kWh/yr, E_{uppv} is energy for space heating in kWh/yr, E_{kyl} is building's energy for comfort cooling in kWh/yr, E_{tvv} is delivered energy for domestic hot water in kWh/yr, and E_f is building property electricity in kWh/yr.

The Sveby programme (initiated in 2006) is a joint industry effort supporting these rules by providing standardized contracts, calculation templates, and measurement protocols (Sveby 2026). These tools have influenced key official rules, such as BEN guidelines (Wahlström 2008). Sveby offers standardized input data recommendations derived from statistical analysis. In short, Sveby interprets BBR 9:2–9:25 for practitioners. For designers, Sveby supplies the default inputs for a "normal-use" energy calculation, and for operators it gives procedures to verify performance. Swedish building professionals widely use Sveby to reduce uncertainty and improve compliance (Bandak et al. 2025).

Under BBR, a building's energy performance is expressed as a primary energy number (EP_{pet}), in kWh per heated floor area per year. EP_{pet} is calculated by summing each end-use energy demand (heating, cooling, hot water, and building electricity) weighted by primary energy factors, correcting space-heating by a geographic factor, and dividing by heated area (areas heated to more than 10°C) (Equation (2)). The climate correction factor equalizes heating needs across climates, so that identical buildings have the same EP_{pet} regardless of location. BBR sets maximum allowed EP_{pet} by building category (Bandak et al. 2025).

$$EP_{pet} = \frac{\sum_{i=1}^{6} \left(\frac{E_{uppv,i}}{F_{geo}} + E_{kyl,i} + E_{tvv,i} + E_{f,i}\right) \times VF_i}{A_{temp}} \tag{2}$$

EP_{pet} is primary energy number of the building in kWh/(m²·yr), i is index representing different energy carriers, $E_{uppv,i}$ is delivered energy for space heating in kWh/yr, F_{geo} is geographical adjusting factor, $E_{kyl,i}$ is delivered energy for space cooling in kWh/yr, $E_{tvv,i}$ is delivered energy for domestic hot water in kWh/yr, $E_{f,i}$ is building property electricity in kWh/yr, VF_i is primary energy factor, and A_{temp} is heated floor area in m².

2.2.3 Boverket's MEPS interim report (2024)

In October 2024 Boverket published an interim report on Sweden's MEPS for existing non-residential buildings (Boverket 2024). This study uses the Swedish EPC register to characterize the 2020 non-residential stock and to compute preliminary primary-energy-based thresholds in kWh/(m²·yr) for MEPS by 2030 and 2033.

Boverket's analysis is based on a comprehensive dataset that merges EPCs from multiple years to cover as much of the 2020 building stock as possible. The dataset includes EPCs issued before and after 2020 but explicitly excludes buildings constructed after 2020. Only buildings whose declared floor area is ≥ 50 % non-residential are included; protected heritage buildings are also excluded. Boverket notes important uncertainties in this data: older EPCs may not reflect post-declaration efficiency measures, while newer EPCs may not represent 2020 conditions. Some non-residential buildings lack EPCs altogether (e.g. if ownership or tenancy never changed since the 2006 EPC law), and adjustments between different EPC calculation methods introduce further errors.

It should be noted that the dataset reflects the scope of the Swedish energy declaration regulation, which excludes several building categories that are also expected to be exempt from the MEPS requirements under Article 9(6) of the EPBD. These include industrial buildings, workshops, agricultural buildings with low energy demand, buildings used for religious activities, temporary buildings, buildings with a floor area below 50 m², and certain defence buildings (Boverket 2024).

To account for functional differences, Boverket groups the stock into seven building categories: Offices, Education, Hospitals, Accommodation and Restaurants, Sports facilities, Commercial and Culture buildings, and other energy-using buildings. These categories follow the spirit of EPBD Annex I classification and allow each category's energy use distribution to be analysed separately. Energy use intensity (kWh/m²) varies greatly by function, so category specific thresholds are needed to set realistic MEPS. For each category, Boverket set MEPS limits so that 16 % of buildings fall above the threshold by 2030 and 26 % by 2033. The resulting preliminary primary-energy limits in kWh/(m²·yr) are as follows as shown in Table 1. These thresholds are expressed in primary energy, matching the metric used in Swedish EPCs and Boverket's analysis.

Table 1- Preliminary limit values of primary energy (primärenergital) for MEPS 2030 and MEPS 2033 across different building categories, based on Boverket's MEPS Interim Report (Boverket 2024)

Building Category	**Preliminary limit value MEPS-2030/** (kWh/(m²·yr))	**Preliminary limit value MEPS-2033/** (kWh/(m²·yr))
Office buildings	214	174
Educational buildings	238	188
Hospital buildings	239	194
Accommodation and restaurant buildings	334	271
Sports buildings	278	223
Commercial and cultural buildings	220	178
Other types of energy-using buildings	243	190

The report emphasizes that these MEPS values are based on an updated calculation method aligned with the recast EPBD (Directive 2024/1275). Boverket adopted fixed "category typical" usage factors for ventilation and domestic hot water by building category. In effect, this creates standardized energy profiles per category, allowing each MEPS limit to be set as a fixed energy value for that category. Because of this shift to category typical assumptions, the resulting performance ratings will not be directly comparable to existing EPC values. In other words, a building's EPC rating under current rules cannot be used to predict how it would score under the new MEPS calculation method.

2.2.4 Non-residential building categories and their relevance under MEPS

The condition of the Swedish non-residential building stock in the baseline year 2020 is described based on the analysis presented in Boverket's MEPS Interim Report (2024) (Boverket 2024). The report evaluates the characteristics and energy performance of the national building stock in preparation for the implementation of MEPS under the revised EPBD.

The analysed database represents approximately 87 163 non-residential buildings, corresponding to a total floor area of just under 200 million m². This dataset is derived from the national EPC register and is used to represent the condition of the building stock in the baseline year. Figure 1 illustrates the breakdown of non-residential building stock per premises type by Count and percentage of total.

The report indicates that these worst-performing segments are defined based on the number of buildings rather than their floor area. Consequently, the buildings falling within the lowest 16% and 26 % account for only 7.8 % and 15 % of the total floor area, respectively. This suggests that the least energy-efficient buildings in Sweden tend, on average, to be smaller than the better-performing buildings.

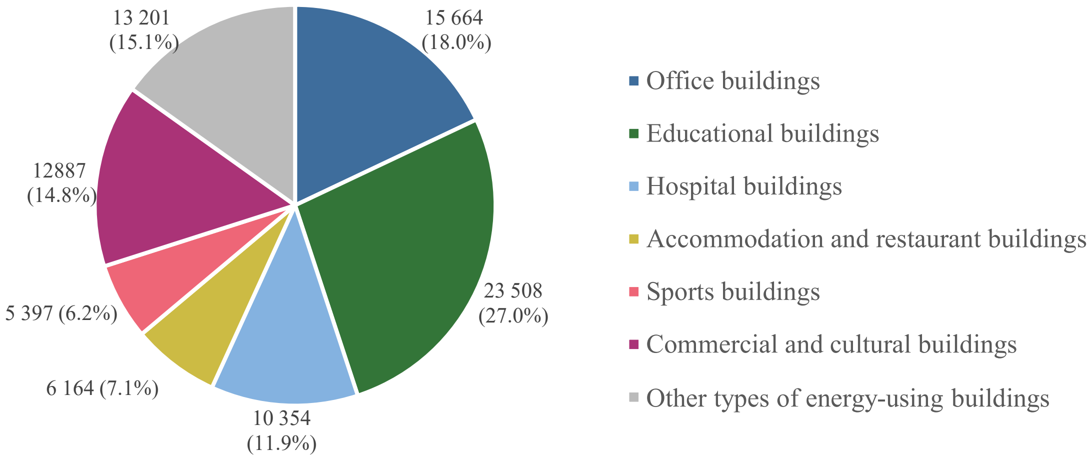

Figure 1 - Distribution of the non-residential building stock in Sweden by building category, showing number of buildings and percentage share of the total stock based on Boverket's MEPS Interim Report (Boverket 2024)

The distribution of the building stock varies depending on whether it is measured by number of buildings or total floor area as presented in Table 2. According to the baseline dataset of 87 163 buildings, educational buildings represent the largest category in terms of building count, with 23 508 units, followed by office buildings with 15 664 units.

However, when the stock is assessed by total floor area, a different pattern emerges. Office buildings constitute the largest segment, representing approximately 47 million m² of floor area. This is followed by commercial and cultural buildings with about 43 million m², and educational buildings with about 37 million m². These numbers indicate that although educational buildings are more numerous, office buildings dominate the non-residential building stock in terms of total floor area.

Table 2 - Distribution of the non-residential building stock by category, including the total number of buildings, total floor area (million m² and the quantity of buildings exceeding the proposed MEPS-2030 and MEPS-2033 energy performance thresholds based on Boverket's MEPS Interim Report (Boverket 2024).

Type of buildings	Total number (Area / (10^6 m²))	Number over limit value MEPS-2030 (Area / (10^6 m²))	Number over limit value MEPS-2033 (Area / (10^6 m²))
Office buildings	15 664 (47)	2 506 (3.3)	4 073 (7.2)
Educational buildings	23 508 (37)	3 761 (6.6)	6 112 (4.9)
Hospital buildings	10 354 (28)	1 657 (2.2)	2 692 (4.6)
Accommodation and restaurant buildings	6 162 (8.3)	986 (0.6)	1 602 (1.2)
Sports buildings	5 397 (9.5)	864 (1.0)	1 403 (1.6)
Commercial and cultural buildings	12 877 (43)	2 060 (3.8)	3 348 (6.9)
Other types of energy-using buildings	13 201 (26)	2 112 (2.1)	3 432 (3.8)
All non-residential buildings	87 163 (200)	13 946 (16)	22 662 (30)

3 Literature review

3.1 Literature review structure

The literature review was conducted identifying relevant sources through keyword-based searches in databases such as Google Scholar, Scopus, ScienceDirect, and the Lund University publication database. The search followed a geographic prioritisation, drawing first from Swedish sources including Lund University publications, followed by Nordic studies, and then broader European literature when sufficient regional evidence was not available. Studies presenting statistical analysis across multiple buildings were prioritised over single building case studies; the latter were included only where broader evidence was insufficient to establish a finding.

For EPG the terms for the search included “energy performance gap”, “measured vs predicted energy use”, and “non-residential buildings”. The review was subsequently extended to cover energy renovation measures and strategies relevant to the selected building category. Sources were identified using search terms including "energy renovation", "office buildings", "HVAC retrofit", "envelope renovation", and "Renovation non-residential buildings".

The review of renovation measures was structured in two stages, beginning with general renovation strategies for non-residential buildings before narrowing to each specific intervention category: envelope measures, ventilation and HVAC system upgrades, and auxiliary measures including lighting and circulation pumps. Relevant regulations and industry guidelines were also consulted where peer-reviewed evidence was limited.

3.2 Performance gap

3.2.1 Scope and relevance, definitions, and magnitude

Across the building-energy literature, the term “energy performance gap” (EPG) is commonly used to describe the mismatch between predicted energy performance, derived from simplified regulatory calculations or detailed building performance simulations, and the actual measured energy use during building operation. This discrepancy is widely recognised as a persistent issue in buildings and is increasingly understood as a combined technical and socio-organisational challenge, rather than solely a modelling error (De Wilde 2014).

A key conceptual distinction in defining the EPG concerns the difference between design intent and realised performance. During the design stage, energy performance is predicted based on assumptions regarding building use, systems, and boundary conditions. In contrast, post-construction assessments reflect the performance of the building as actually built and operated over time. The EPG therefore represents the difference between the predicted performance of the design intent and the observed performance of the completed building in use (De Wilde 2014).

Building on this definition, different types of EPG can be identified. According to Zou et al. (2018), two main forms are commonly distinguished: (1) the discrepancy between predicted (or simulated) and measured (actual) energy use, and (2) the difference between performance targets defined by standards or specifications and the measured performance of the building (P. X. W. Zou et al. 2018). These distinctions highlight that the EPG is not a single phenomenon but depends on the reference baseline used for comparison.

In a Swedish context, additional distinctions are made between different definitions of energy use. Bandak et al. (2025) conceptualise the EPG using three terms: Calculated Energy (design-stage prediction), Measured Energy (actual metered use), and Declared Energy (normalised values reported in energy performance certificates). The “legal” energy gap refers to the difference between Declared and Calculated energy, while the “actual” energy gap refers to the difference between Measured and

Calculated energy. This distinction highlights how regulatory frameworks can influence both the interpretation and magnitude of the EPG (Bandak et al. 2025).

The scope of energy performance analysis further influences how the EPG is interpreted. Energy use can be assessed at different levels of detail, ranging from heating and cooling demand to broader system boundaries including lighting, equipment, and domestic hot water. Similarly, performance can be evaluated at different temporal resolutions, from annual to hourly data. These variations affect both the magnitude and interpretation of the performance gap (De Wilde 2014).

The relevance of the EPG extends beyond technical discrepancies. Closing the gap between predicted and actual performance is essential for ensuring that buildings meet their intended targets, including high-performance, zero-carbon, and net-zero energy standards. It is also critical for maintaining long-term performance, enabling buildings to remain resilient and adaptable to changing conditions such as evolving occupant behaviour and climate (De Wilde 2014). Furthermore, addressing the EPG is fundamental for the development of performance-based approaches in building delivery and facility management, where the focus shifts from delivering components to achieving measurable performance outcomes (Zhang and Gao 2010).

More broadly, the existence of a persistent performance gap undermines confidence in the design and engineering sectors and contributes to scepticism toward high-performance building concepts (De Wilde 2014). This erosion of trust can weaken support for energy efficiency initiatives and broader decarbonisation strategies (Li et al. 2023).

Evidence from Sweden-specific research highlights that the direction and magnitude of the gap vary substantially by building type, end-use boundary, and baseline definition, especially whether predictions represent regulatory/compliance conditions, design purpose, or a calibrated performance model reflecting actual operation (van Dronkelaar et al. 2019).

The magnitude of the EPG varies significantly across studies and contexts. According to Li et al. (2023), there is no universal value for the EPG, as it depends on building type, methodological approach, data sources, and temporal scope. Reported values range widely, from approximately 20 % to over 500 %, although the gap is consistently found to be substantial. This variability reflects both the complexity of the phenomenon and the influence of different modelling and measurement approaches (Li et al. 2023).

In non-residential buildings, the performance gap is often particularly noticeable. Studies indicate that discrepancies between predicted and measured energy use are influenced by standardised compliance modelling assumptions, incomplete representation of operational energy uses, and the dynamic nature of real building operation, including controls, schedules, and plug loads (van Dronkelaar et al. 2016).

3.2.2 Causes of the EPG

The causes of the EPG are widely discussed in the literature and can be grouped into four main categories. These include (1) modelling and representation causes, which relate to assumptions and inputs used in energy calculations; (2) construction, commissioning, and system performance causes, which arise from discrepancies between design intent and actual technical performance; (3) operational and management causes, which reflect how buildings are used and managed in practice; and (4) occupant behaviour versus occupant representation, which addresses the mismatch between real occupant behaviour and its simplified representation in energy models.

Modelling and representation causes
These sources address simulation tool limitations, input data accuracy, weather files, occupancy schedule representation, and internal load assumptions.

One part of the EPG is often driven by modelling and representation causes, where the simulation is inconsistent with the actual building or relies on low-quality or standardised input data. Rather than being primarily caused by deficiencies in simulation tools themselves, the literature consistently emphasises that discrepancies arise from the assumptions and inputs used within these models (De Wilde 2014; Menezes et al. 2012).

Ekström et al. (2021) also highlights that the EPG is not merely a product of simulation limitations, but a direct consequence of input data quality. Using a replicated building design across 28 locations in Sweden, the authors show that replacing standardised regulatory inputs (e.g., BEN or Sveby) with object-specific, measurement-based data significantly improves both the accuracy and robustness of simulation results. This indicates that even advanced modelling approaches are unable to reduce the EPG when input data remain biased or overly generic (Ekström et al. 2021).

A detailed investigation by van Dronkelaar et al. (2019) provides further insight into the relative importance of different modelling assumptions in non-residential buildings. The paper uses calibrated dynamic simulation models against high-resolution measured energy data to systematically assess how individual parameters contribute to the performance gap. The results identify internal heat gains (from lighting, equipment, and server loads) and usage profiles (including night-time baseloads and seasonal occupancy variations) as the dominant drivers of discrepancies between predicted and measured energy use (van Dronkelaar et al. 2019).

In addition to parameter sensitivity, a fundamental source of modelling uncertainty lies in the limited predictability of future building use at the design stage. Variables such as occupancy patterns, plug loads, and internal heat gains are inherently uncertain and often cannot be accurately defined in advance (Menezes et al. 2012). As a result, design-stage simulations frequently rely on simplified or assumed values that may not reflect actual operational conditions.

The representation of weather and climate conditions forms another major modelling-related source of the EPG. Many energy simulations rely on Typical Meteorological Year (TMY) data, which are constructed from aggregated historical records to represent typical climatic conditions. However, such datasets do not capture the variability of actual weather during building operation and may therefore introduce systematic deviations in predicted performance (Zheng et al. 2024). Observed studies further show that simulations based on standard weather files tend to overestimate retrofit energy savings compared to models using locally measured weather data (Cuerda et al. 2020).

Construction, commissioning, and system performance causes

These sources address construction quality, thermal bridges, HVAC commissioning, equipment efficiency, auxiliary energy, and performance degradation.

Commissioning and system performance causes refer to situations in which the building, as constructed and delivered, does not operate as assumed in energy calculations due to faults, incomplete commissioning, suboptimal control parameters, or performance drift of building services systems. These causes differ from modelling and representation issues, as they persist even when the simulation accurately reflects the design intent. They arise primarily during the transition from design to construction and operation, and are related to the technical integrity and interaction of systems such as HVAC, controls, sensors, and distribution networks (van Dronkelaar et al. 2019).

A key issue identified in the literature is incomplete or ineffective commissioning. Commissioning processes are often limited to verifying functionality rather than ensuring optimal energy performance, which can result in persistent inefficiencies after handover. A study by Bandak et al. (2025), based on 28 interviews with professionals across the Swedish building sector, identifies insufficient system commissioning and optimization as one of the main contributors to the EPG. Effective optimisation involves calibrating heating and ventilation systems to achieve intended performance, and practitioners recommend a one-year post-construction “tuning” period to address these issues (Bandak et al. 2025).

Airflow imbalance and deviations in ventilation performance are among the most influential system-related causes of the EPG. In many cases, ventilation systems operate with airflow rates that differ from their design values due to inadequate balancing, or commissioning errors. Such deviations can significantly increase heating demand and fan energy use, particularly in low-energy buildings.

Differences between as-built and as-designed system configurations further contribute to these discrepancies, as construction quality may not fully align with specifications (Menezes et al. 2012; Turner 2008).

Control system malfunction or misconfiguration represents another critical system performance issue. While energy models typically assume correctly functioning control logic, real buildings frequently experience incorrect parameter settings, faulty sensors, or incomplete system integration. Poorly configured control systems and inadequate feedback mechanisms are common in practice and can undermine predicted energy performance even when system components meet design specifications (De Wilde 2014)

Construction-related deviations also play a significant role in the EPG. During the construction phase, technical details may be modified, omitted, or inadequately executed, creating discrepancies between design intent and as-built performance. These include the formation of unintended thermal bridges, changes in insulation quality, or alterations in system layout, such as duct routing or pipe insulation (Bell et al., n.d.; Kempe 2025). Such mismatches can lead to significant increases in total energy use.

Another important system-related cause is the underestimation of distribution and auxiliary energy losses. Energy models often simplify or neglect losses associated with hot water circulation, ductwork, piping, and auxiliary equipment such as pumps and fans. Measured studies indicate that hot water distribution losses alone can exceed 12–15 kWh/(m^2·yr), making them a major contributor to measured energy use (Kempe 2025). Practitioner-based evidence further shows that assumed values (e.g. 4 kWh/(m^2·yr)) significantly underestimate real losses due to factors such as poor insulation, construction defects, and insufficient system testing (Bandak et al. 2025).

In addition, discrepancies between expected and actual equipment performance contribute to the EPG. High-performance or "green" building designs often rely on idealised efficiency values derived from laboratory conditions, which are not always achieved in real operation. Equipment performance may be reduced due to installation conditions, system interactions, or operational constraints (Newsham et al. 2009).

Finally, performance degradation over time represents a further source of the EPG. Even when systems initially operate as intended, the gradual ageing of equipment and deterioration of building components can lead to reduced efficiency. Without continuous monitoring and re-commissioning, such degradation remains undetected and contributes to persistent discrepancies between predicted and measured energy use (Zheng et al. 2024).

Operational and management causes

These sources address operating hours, facility management, comfort-driven adjustments, energy monitoring, control overrides, and building handover.

The operational phase is widely recognised as a major contributor to the EPG, as actual building use often deviates from the conditions assumed during design and simulation. While occupants are frequently identified in the literature as key factors influencing building performance, recent studies emphasise that discrepancies arise primarily from how buildings are operated and managed in practice, rather than from inappropriate user behaviour alone (De Wilde 2014; Liang et al. 2016; Yan et al. 2015; P. X. W. Zou et al. 2018).

One of the primary causes within this category is extended or modified operating hours, where actual building use differs from the schedules assumed in energy calculations. In non-residential buildings, operational hours are often variable than standardised assumptions. For example, measured data from Swedish school buildings show extended occupancy periods compared to assumed profiles, resulting in increased heating demand and longer ventilation operation (Simanic et al. 2020).

Closely related to extended schedules are comfort-driven operational adjustments, which further contribute to the EPG. Facility managers are often required to respond to occupant complaints related to thermal comfort or indoor air quality, leading to higher indoor temperature setpoints, prolonged ventilation operation, or reduced use of night setback strategies. Case studies from energy-efficient office buildings in Norway shows that operational decisions frequently prioritise occupant comfort over energy performance targets, resulting in systematic increases in energy use (Pettersen et al. 2017).

A further operational contributor to the EPG is the lack of systematic performance monitoring and feedback. In many buildings, measured energy data are collected but not actively analysed or used to inform operational adjustments. This absence of structured feedback mechanisms limits the ability to identify and correct inefficiencies during operation. In office buildings, insufficient communication between occupants and facility managers, combined with limited use of performance indicators, reduces the effectiveness of optimisation strategies (Liu et al. 2019).

Practitioner-based studies further highlight the importance of feedback loops between measured performance and design assumptions. Interviews conducted within the Swedish building sector indicate that access to operational data from previous projects allows consultants and engineers to refine assumptions and improve future modelling accuracy (Bandak et al. 2025). However, in practice, such feedback mechanisms are often weak or absent, allowing discrepancies between predicted and actual performance to persist over time.

Occupant behaviour vs occupant representation

These sources address the gap between actual occupant behaviour and its representation in models, unsystematic vs. deterministic approaches, and diversity in occupant energy use.

This category focuses on a fundamental mismatch between real occupant behaviour and its simplified representation in energy calculations. In practice, occupants' schedules, presence, and interactions with building systems differ systematically from the standardised profiles used in simulations (Yan et al. 2015).

Energy simulations commonly represent occupants using fixed schedules, average profiles, and deterministic interaction patterns with building systems. Such representations fail to capture the diversity, adaptability, and context-dependent nature of real occupant behaviour. de Wilde (2014) highlights that occupant behaviour is typically treated as a static or average input in stationary calculations, rather than as a dynamic component influencing building performance.

Empirical studies further demonstrate the limitations of these assumptions. For example, a study of an office building by Liang et al. (2016) investigated occupancy prediction using historical data and showed that standard schedules fail to capture actual weekday variability and peak demand. The results indicate that occupant presence is inherently dynamic, stochastic, and highly variable, making it difficult to accurately represent using traditional deterministic approaches (Liang et al. 2016).

This limitation is particularly relevant in non-residential buildings, where occupancy patterns are often non-stationary and influenced by organisational and temporal factors such as working hours, seasonal variations, and after-hours use. As a result, default schedules used in energy models may overlook systematic behavioural patterns, leading to discrepancies between predicted and measured energy use (van Dronkelaar et al. 2019).

3.2.3 Reducing the gap: calibration

Building energy model calibration is commonly defined as an inverse modelling process in which uncertain input parameters are adjusted to reduce discrepancies between simulated and measured energy use (Yang and Becerik-Gerber 2015). However, this definition does not imply that calibration leads to a unique or physically correct representation of the building. Due to the over-parameterised nature of building energy models, a large number of interdependent inputs must be specified despite limited empirical data, particularly in existing buildings. As a result, multiple parameter combinations can produce similar levels of agreement with measured data, a problem widely documented in the literature (Coakley et al. 2014; Yang and Becerik-Gerber 2015)

This problem, commonly referred to as equifinality, implies that statistical agreement between simulated and measured energy use does not guarantee that calibrated parameters accurately reflect the physical characteristics of the building (Coakley et al. 2014). From this perspective, calibrated models represent conditional approximations of reality, constrained by available data and modelling assumptions.

Uncertainty in building energy modelling arises from multiple sources, including uncertain input parameters, measurement error, and simplifications embedded within simulation models. A key distinction in the literature is between epistemic uncertainty, which arises from incomplete knowledge of system properties such as material characteristics or system efficiencies, and aleatory uncertainty, which reflects inherent and irreducible variability such as occupant presence and behavioural patterns (Tian, Heo, et al. 2018). While calibration can reduce epistemic uncertainty by refining model inputs based on available evidence, aleatory uncertainty cannot be eliminated through this process and continues to affect the reliability of model predictions. In addition, discrepancies between simulated and measured performance may arise from model form limitations, meaning that even a well-calibrated model may not fully represent real system behaviour.

Beyond parameter uncertainty, discrepancies between predicted and measured energy use are also linked to broader systemic factors, including construction quality, commissioning processes, and operational management. These factors are central to the concept of the EPG, as examined by De Wilde (2014), who identifies causes across the design, construction, and operational stages of a building's life cycle, arguing that the gap cannot be attributed solely to modelling assumptions. Calibration primarily addresses discrepancies within the model itself, while many real-world influences remain outside its scope (De Wilde 2014).

To manage the complexity of calibration, structured approaches have been proposed that combine sensitivity analysis with targeted parameter adjustment (Yang and Becerik-Gerber 2015). Sensitivity analysis is used to identify influential parameters and reduce the dimensionality of the calibration problem. Without this step, the risk of compensating errors increases, whereby unrealistic adjustments in one parameter may mask inaccuracies in another (Coakley et al. 2014). However, simplified sensitivity methods such as one-factor-at-a-time screening do not fully capture interactions between parameters and therefore provide only a partial characterisation of model behaviour.

Deterministic calibration approaches remain widely used in practice due to their relative simplicity and lower computational requirements. However, they have been criticised for their inability to explicitly represent uncertainty and for relying on single-point estimates of model parameters. The traditional deterministic approach has been characterised as insufficient on its own, given that a single simulation run cannot provide adequate information about the range of plausible system behaviours (Tian, Heo, et al. 2018). In contrast, probabilistic or Bayesian calibration methods represent parameters as distributions and update them using measured data, allowing uncertainty in both inputs and outputs to be quantified. Despite their theoretical advantages, these approaches require extensive data and computational resources, which often limit their application in practice.

Calibration approaches can be broadly categorised into analytical, statistical learning-based, and integrated methods (Yang and Becerik-Gerber 2015). Analytical or heuristic calibration relies on iterative adjustment of model inputs based on expert judgement and observed discrepancies but lacks reproducibility and depends heavily on analyst experience (Coakley et al. 2014). Statistical learning-based approaches apply mathematical models to identify relationships between inputs and outputs, offering computational efficiency but without a direct link to physical building parameters. Integrated approaches combine these methods with sensitivity analysis or optimisation techniques to systematically explore the parameter space (Yang and Becerik-Gerber, 2015). These methods are widely applied in practice but remain subject to the limitations of non-unique solutions arising from equifinality.

The limitation of non-unique solutions is particularly relevant when a single parameter set is selected as the calibration outcome, as this obscures the existence of alternative configurations that provide comparable agreement with measured data. Probabilistic and Bayesian calibration methods address this directly by representing uncertain parameters as distributions and updating them using measured data, thereby quantifying uncertainty across both parameter estimates and model predictions (Tian, Heo, et al. 2018). Despite their methodological strengths, the computational and data demands of these approaches constrain their applicability in many practical contexts.

The choice of calibration approach in practice is shaped by trade-offs between data availability, computational demands, and intended use of the model. Deterministic parametric approaches are widely used in applied calibration work due to the compatibility with limited empirical datasets and their capacity to systematically explore the influence of uncertain parameters without requiring prior probability distributions (Yang and Becerik-Gerber 2015). However, as established earlier, such approaches do not yield a unique solution. The appropriate response, as reflected in a growing body of calibration literature, is not to treat the calibrated model as a definitive representation but to define a set of plausible configurations that collectively satisfy the statistical performance criteria applied.

Sensitivity analysis is commonly employed as a preliminary screening step in calibration workflows to reduce the number of parameters requiring adjustment. One-factor-at-a-time approaches, such as the Morris method applied by Yang and Becerik-Gerber (2015), offer a computationally efficient means of ranking parameter influence without requiring predefined probability distributions. However, these methods assess each parameter in isolation and therefore do not capture interaction effects between variables. The results of such analyses are consequently treated in the literature as indicative of relative parameter importance rather than as a complete characterization of model sensitivity (Yang and Becerik-Gerber 2015; Tian, Heo, et al. 2018).

The definition of parameter variation ranges is an acknowledged challenge in calibration practice. Where statistically derived distributions are unavailable, some studies have adopted uniform percentage deviations from baseline or default values as an alternative (Yang and Becerik-Gerber 2015). While this approach facilitates a structured exploration of parameter space, it may encompass non-physical combinations that do not reflect realistic building behaviour. In such cases, additional screening based on physical plausibility has been proposed to reduce unrealistic parameter combinations.

Calibration performance is commonly assessed using the Normalized Mean Bias Error (NMBE) and the coefficient of variation of the Root Mean Square Error (CV(RMSE)), with accepted thresholds defined by ASHRAE Guideline 14, the International Performance Measurement and Verification Protocol (IPMVP), and the Federal Energy Management Program (FEMP).

As documented by Yang and Becerik-Gerber (2015), acceptable calibration accuracy depends on the temporal resolution of the data. For hourly data, calibration is typically considered acceptable when NMBE lies within ±10 % and CV(RMSE) within 30 %, whereas stricter thresholds of ±5 % for NMBE and 15 % for CV(RMSE) are recommended for monthly data. These thresholds provide standardized criteria for assessing the statistical agreement between simulated and measured energy use. However, they assess statistical fit rather than physical validity and do not distinguish between models that satisfy the criteria through physically plausible parameter values and those that do so through compensating errors (Coakley et al., 2014). A model that meets ASHRAE thresholds, therefore, cannot be assumed to provide a physically correct representation of the building.

Even where calibration criteria are satisfied, residual uncertainty persists in calibrated models. Sources of discrepancy that lie outside the scope of parameter adjustment, including measurement error, model form simplifications, and unconsidered operational factors, are not resolved through the calibration process and remain embedded in the results (Tian, Heo, et al. 2018; De Wilde 2014). Furthermore, the existence of multiple parameter combinations capable of satisfying the same calibration thresholds means that the outcome of any calibration exercise is inherently non-unique. This observation has led several authors to advocate for the reporting of solution sets rather than single parameter configurations, and for the application of additional physical plausibility checks to filter candidate solutions (Coakley et al. 2014; Yang and Becerik-Gerber 2015).

Taken together, the literature establishes that calibrated building energy models should be interpreted as one of several plausible representations of building performance consistent with available data, rather than as verified descriptions of physical reality. While calibration can improve agreement between simulated and measured energy use, it does not eliminate uncertainty or resolve the broader causes of the EPG (De Wilde 2014; Coakley et al. 2014). This limitation is particularly significant in the context of existing buildings, where incomplete documentation, restricted measurement data, and evolving operational conditions constrain the reliability of model-based representations.

3.3 Renovation measures and strategies

Energy renovation in existing buildings encompasses a wide range of interventions that can be grouped into different categories depending on their function and impact on building performance. A commonly adopted conceptual distinction is between measures targeting the building envelope, technical systems, energy supply, and operational conditions.

Technical measures aimed at improving building energy performance include, among others, improvements to the building envelope (e.g., reducing transmission losses), upgrades to technical systems such as ventilation and heating, and the integration of renewable energy systems (Shaikh et al. 2017). Similarly, renovation strategies in office buildings have been shown to include envelope-related actions (e.g., glazing improvements), system-level interventions (e.g., heat recovery installation), and combined solutions addressing multiple aspects simultaneously (Valdiserri and Biserni 2016).

In addition to purely technical interventions, energy performance improvements can also be achieved through energy management practices and behavioural changes. These include operational strategies and occupant-related factors, which are explicitly identified as contributors to energy efficiency alongside technical measures (Shaikh et al. 2017; Gangolells et al. 2020).

3.3.1 Envelope renovation measures in office buildings

Envelope renovation measures aim to reduce transmission losses and improve thermal performance by modifying the building's external components, including walls, roofs, floors, and windows. Typical interventions include additional insulation, air-tightness improvements, and façade or roof upgrades.

From a building physics perspective, the performance of envelope measures cannot be evaluated solely based on thermal transmittance (U-value). Additional insulation alters the hygrothermal conditions within the construction, which may introduce risks of moisture accumulation, reduced drying capacity, and material degradation. For example, a study on traditional masonry buildings shows that interior insulation reduces heat flow through the wall and lowers wall temperatures, which under certain conditions can increase the risk of moisture-related damage, including freeze–thaw effects and biological growth (Lång and Sandgren 2016). Similarly, adding insulation without adequate control of air leakage and moisture transport has led to condensation and mould problems in attics and crawl spaces (Sundlöf 2022).

In heritage buildings, these technical considerations are further constrained by conservation requirements. A study focusing on Swedish heritage buildings highlights that energy efficiency measures must be balanced against the preservation of character-defining elements, such as façade materials and architectural detailing (P. Johansson et al. 2020). This creates a limitation for certain interventions, particularly external wall insulation, which can alter the external appearance of the building.

In this context, European guidelines for historic buildings emphasize that energy renovation measures cannot be evaluated in isolation, but must be assessed through a systematic, case-specific process that considers both technical performance and heritage significance. The standard explicitly states that each building should be treated as an individual case requiring detailed investigation, and that measures should be selected based on a structured assessment of risks and benefits rather than predefined solutions. This assessment framework includes multiple criteria, such as hygrothermal risks, structural compatibility, impact on heritage significance, energy performance, economic viability, and indoor environmental quality

The implications of this approach are evident in the case of interior insulation, which is frequently identified as a high-risk intervention due to its impact on temperature gradients and moisture transport within the wall. However, its applicability depends on the specific construction type, material properties, and indoor conditions, requiring a detailed assessment prior to implementation

In heritage buildings, these technical considerations are further constrained by conservation requirements. A study focusing on Swedish heritage buildings highlights that energy efficiency measures must be balanced against the preservation of character-defining elements, such as façade materials and architectural detailing (Moshfegh et al. 2018).

Roof and attic insulation represent another common envelope intervention. These measures can be implemented either by insulating the attic floor (creating a cold attic) or insulating the roof structure (creating a warm attic). However, both approaches involve moisture-related risks if not properly designed. For example, insufficient airtightness or uncontrolled air leakage can transport humid indoor air into colder parts of the roof construction, increasing the risk of condensation and mould growth (Lång and Sandgren 2016).

The role of air leakage is further highlighted in a study analysing building infiltration, which reports that uncontrolled air infiltration may account for approximately 20–50 % of total building energy demand, while also emphasizing large variability in airtightness performance across buildings (Martín-Garín et al. 2020). The same study notes that airtightness cannot be reliably inferred from construction characteristics alone and must be determined through in-situ measurements, introducing uncertainty in predicting the impact of envelope retrofit measures.

3.3.2 HVAC system retrofit measures.

HVAC systems represent a significant electricity end use in Swedish office buildings. According to a national inventory of office buildings conducted by the Swedish Energy Agency, fan electricity use averages 13.2 kWh/m² per year, representing between 22% and 30% of total electricity use (Persson et al. 2025). Within this, ventilation systems represent a major component, both through thermal conditioning of outdoor air and through electricity consumption for air transport.

In 1995, fan electricity use was estimated to account for approximately 7–8 % of total national electricity uses in Sweden, highlighting the significance of air-handling processes within the building sector at that time (Nilsson 1995). The same study also documents a structural shift in non-residential buildings from natural or exhaust ventilation systems towards mechanical balanced ventilation, particularly in buildings constructed after the late 1970s Fan electricity savings follow from the fundamental relationship governing fan power, where demand scales proportionally with both pressure loss and airflow, and inversely with fan efficiency. Given that pressure loss scales quadratically with fan power scaling cubically, even moderate reductions in average airflow yield substantial reductions in fan electricity use directly with both pressure loss and airflow, and inversely to fan efficiency. Given that pressure loss scales quadratically with power scaling cubically, even moderate reductions in average airflow yield substantial reductions in fan electricity consumption (Maripuu and Jagemar 2005). This evidence should be interpreted as representative of the technological and operational context of the late 20th century rather than current practice. Its relevance in this study lies in providing a baseline for understanding the characteristics of older ventilation systems, which remain present in parts of the existing building stock undergoing renovation.

The regulatory framework governing these systems has evolved substantially from the prescriptive technical norms of Svensk Byggnorm (SNB) (Statens planverk 1980)**,** which specified system types, minimum outdoor airflow rates by room use, and detailed installation criteria**.** Boverkets Byggregler introduced performance-based functional requirements on 1 January 1994

Under BBR, buildings must be designed to provide acceptable indoor air quality in regularly occupied rooms. The minimum outdoor airflow requirement of 0.35 l/s per m² floor area has applied since BBR 94 (Boverket 1993). In residential buildings where ventilation can be controlled separately per dwelling, BBR additionally permits flow reduction to no less than 0.10 l/s per m² during unoccupied periods; no equivalent quantified lower bound applies under BBR to non-residential buildings. For workplaces, airflow requirements are governed separately by Arbetsmiljöverket's regulations (Arbetsmiljöverket 2023) which require at least 7 l/s per person plus 0.35 l/s per m² floor area for sedentary work in continuously occupied premises.

Obligatorisk Ventilationskontroll (OVK), established through Plan-och byggförordning (Plan- Och Byggförordning 2011) requires recurring inspections of ventilation systems in office buildings at intervals that depend on the type of system installed. Buildings equipped with mechanical supply and exhaust ventilation (FT) or mechanical supply and exhaust with heat recovery (FTX) must be inspected every three years. Buildings equipped with natural ventilation (S), mechanical exhaust ventilation (F), or mechanical exhaust with heat recovery (FX) must be inspected every six years. During each recurring inspection, the functional inspector is also required to identify measures that could improve energy management in the ventilation system without deteriorating indoor climate (Plan- Och Byggförordning 2011)**;** inspectors must also propose energy efficiency measures based on readily assessable functional and energy impacts (OVKAR 1 2012) A system is assessed at OVK against the requirements in force at the time of its original installation, unless the scope of a renovation triggers reassessment (Plan- Och Byggförordning 2011).

Explicit energy performance requirements were introduced with BBR 12 (Boverket 2006), which also first defined and quantified the key metric Specific Fan Power (SFP), total fan electrical power divided by the larger of supply or extract airflow, in kW/(m³/s). Recommended limits were set at 2.0 kW/(m³/s) for supply-and-extract with heat recovery and 0.6 kW/(m³/s) for exhaust-only systems (Boverket 2006). BBR 18 (Boverket 2018) extended these limits to alterations of existing buildings, establishing them as recommended targets. BBR 29 (BBR 29 2011) then, tightened the values across all system types, reducing the FTX limit to 1.5 kW/(m³/s) and the exhaust-only limit to 0.5 kW/(m³/s). No equivalent metric existed under SBN(Statens planverk 1980), meaning systems from the 1980s and 1990s were not designed against any standardised fan efficiency target; a comparison with current SFP limits therefore contrasts a regulatory benchmark against the typical performance of an older equipment generation rather than two sets of requirements.

The renovation measures relevant to this context**,** Air Handling Unit **(**AHU) replacement, duct upgrades, heat recovery (HR) efficiency retrofits, and controls improvements**,** are examined in the following sections.

Constant Air Volume (CAV) to Variable Air Volume (VAV)

In a CAV system, air is exchanged at a constant airflow designed for peak load conditions that rarely occur, meaning energy is used for air distribution and supply air heating at unnecessarily high rates for most of the year. By converting to VAV operation, the average airflow is reduced, decreasing both fan electricity use and heating demand for supply air conditioning. Reduced average airflow also improves the effective efficiency of the heat recovery unit (Maripuu and Jagemar 2005).

Fan electricity savings follow from the relationship between fan power and airflow, where power demand scales strongly with flow rate, meaning even moderate reductions in average airflow yield substantial reductions in fan electricity consumption (Maripuu and Jagemar 2005). A study of pump and fan operation in Swedish non-industrial buildings indicates a calculated energy saving potential of approximately 40 % for fan systems through improvements to SFP and system design (Markusson 2011).

Variable-speed high-efficiency fan models can reduce fan electricity use substantially, with savings potential scaling with the difference between existing and improved fan efficiency (Markusson 2011). However, such a conversion only becomes meaningful if the system as a whole is adapted to the new operating principle. Critical components include supply air terminal devices, control dampers for airflow regulation to individual zones, variable speed drives for fan control, duct balancing, and control systems. A reconstruction that addresses only fan speed while retaining unsuitable terminal devices or lacking proper zone control will not realise the expected savings (Maripuu and Jagemar 2005)

During unoccupied periods, airflow can be reduced to minimum hygienic levels to limit ventilation heat losses. However, evidence from a Swedish study of a newly constructed residential building indicates that reducing airflow to 0.1 $l/(s \cdot m^2)$ for more than four hours during unoccupancy can result in unacceptable indoor air quality in terms of volatile organic compound concentrations, a concern primarily associated with high material emissions in new construction (Hesaraki and Holmberg 2015). These finding underlines that the duration and timing of airflow setback strategies must be assessed in relation to building-specific conditions. The authors note that Volatile Organic Compound (VOC) concentrations in new buildings are typically higher than in older buildings, suggesting that extended unoccupied setback strategies may be more readily applicable in existing building stock with lower residual material emissions (Hesaraki and Holmberg 2015).

Cooling Demand

Although Swedish office buildings are predominantly heating-dominated, cooling demand has been shown to occur consistently even in cold-climate conditions. Based on dynamic energy simulations of archetypal Swedish office buildings, internal heat gains from lighting and equipment have been shown to produce a cooling demand alongside the dominant heating load, even in buildings designed to meet the Swedish building code Year-round cooling loads have similarly been reported in simulated reference buildings from the 1970s–1980s, with interior zones requiring cooling continuously due to plug loads and occupancy, including during winter months (Arghand et al. 2021).

Several renovation measures aimed at reducing heating demand can have contradictory effects on cooling loads. Improving envelope insulation reduces heating demand while simultaneously limiting the dissipation of internal heat gains, thereby increasing cooling demand (Flodberg et al. 2012). Furthermore, reducing envelope *U*-value in isolation has been shown to produce a less favorable outcome in terms of borehole system sizing compared to a combined package that also addressed solar heat gains and internal gains (Arghand et al. 2021). These simulation-based results suggest that renovation measures are best evaluated as packages rather than in isolation, though validation against measured building data remains limited.

Heat recovery (HR)

HR in AHUs is widely implemented in mechanically ventilated non-residential buildings to reduce heating demand associated with outdoor air supply. The increasing importance of ventilation heat losses in well-insulated and airtight buildings has led to broader adoption of mechanical ventilation with HR, particularly in larger and more complex buildings (Roulet et al. 2001).

Pre-2000 systems commonly integrated HR in AHUs, but the performance of installed systems was highly variable. Measured real efficiencies reached between 60–70% in the best-performing units but fell below 10% in poorly functioning systems, despite nominal efficiencies around 80% (Roulet et al. 2001). These results are linked to older buildings where infiltration, leakage, and system malfunctions were more prevalent (SINTEF Building and Infrastructure 2016). This indicates that older AHUs cannot be characterised solely by their nominal efficiency or design type but rather carry significant performance uncertainty due to installation quality and building conditions.

Current Swedish design practice has largely converged around nominal temperature efficiencies of approximately 80%, with plate heat exchangers typically achieving slightly below this value and rotary heat exchangers slightly above under comparable conditions. Higher efficiencies are technically achievable but are associated with increased pressure drops and space requirements, leading to practical optimisation around this level in Swedish applications Available Swedish and Nordic literature does not provide a strict decade-based classification of AHU heat recovery types for non-residential buildings. HR has been used extensively in office buildings for several decades, typically through plate heat exchangers or rotary systems, both reported as common solutions in practice (D. Johansson 2023).

3.3.3 Pump replacement

Circulation pumps in district-heated office buildings represent a smaller electricity end-use compared to ventilation fan systems, but their relevance depends on pump type, control mode, and whether the existing pump meets current efficiency requirements. Older constant-speed pumps typically operate at fixed speed against throttling valves, which is an inherently inefficient control strategy. Similarly to ventilation fans, replacement with variable-speed high-efficiency models can reduce pump electricity consumption substantially, with savings potential scaling with the difference between existing and improved pump efficiency (Markusson 2011)

EU Ecodesign Directive regulations have progressively tightened minimum efficiency requirements for circulator pumps, expressed through the Energy Efficiency Index (EEI). Glandless circulators placed on the market from August 2015 must meet an EEI of 0.23 or below (European Commission 2012). Pumps that predate these requirements or operate at constant speed therefore represent a greater improvement potential than pumps already meeting current standards. Where existing pumps are already compliant or operate limited hours, pump replacement is a lower priority compared to ventilation system upgrades.

3.3.4 Lighting measures

From a renovation perspective, lighting upgrades, especially LED retrofits, require relatively low investment compared to envelope or HVAC measures and can be implemented with minimal disruption to building operation. The literature highlights that a large proportion of existing lighting installations in industrialised countries still rely on inefficient technologies, indicating a significant remaining retrofit potential.

Furthermore, LED systems enable retrofit strategies ranging from simple lamp replacement to full luminaire upgrades. While full system replacement is generally recommended for optimal performance, cost-effective intermediate solutions such as LED retrofit kits are widely available and commonly used in practice. Given these characteristics, lighting renovation plays a strategic role in energy renovation packages, often contributing to immediate energy savings and improving economic indicators such as return on investment.

While the reduction in electricity consumption is a primary benefit of LED retrofits, a critical and often overlooked aspect is the impact on internal heat gains. Lighting systems contribute to internal heat loads within buildings, as a large fraction of the electrical energy consumed is converted into heat. Traditional lighting technologies, particularly incandescent and fluorescent lamps, generate significant heat during operation. In contrast, LEDs are substantially more efficient, meaning that a larger share of the input energy is converted into visible light rather than heat.

As a result, the transition to LED lighting leads to a reduction in internal heat gains, which has important implications for building energy performance:

• Reduced cooling demand: Lower internal heat gains can decrease cooling loads, particularly in office buildings with high internal gains and significant cooling requirements.

• Increased heating demand: In heating-dominated climates such as Sweden, the reduction in internal heat gains may lead to an increase in space heating demand, as less “free heat” is available to offset transmission and ventilation losses.

This interaction highlights the need to consider lighting retrofits within the broader building energy balance. Building energy simulation frameworks explicitly account for this effect through parameters such as the fraction of lighting energy contributing to internal heat gains (e.g., radiant and convective fractions). Therefore, although LED retrofits reduce electricity consumption, the net impact on total energy use, particularly in district-heated office buildings, depends on the balance between reduced cooling loads and increased heating demand.

The literature consistently identifies LED retrofits as a highly effective and widely applicable energy renovation measure in non-residential buildings. Empirical evidence from Sweden (STIL3) confirms that this transition is already well advanced, with significant reductions in lighting energy use achieved across the building stock (Persson et al. 2025).

However, from a system-level perspective, lighting renovation cannot be evaluated in isolation. The reduction in internal heat gains introduces interactions with heating and cooling systems that must be considered in both energy modelling and techno-economic assessment. In cold climates, this may partially offset the benefits of reduced electricity use, particularly in buildings connected to district heating. Consequently, LED retrofits are best understood as part of integrated renovation strategies, where their effects on both electricity demand and thermal loads are explicitly accounted for.

3.3.5 Combined renovation packages and evaluation approach

Building energy renovation involves complex interactions between multiple building systems and components. The performance of the building envelope, technical systems, and energy supply measures are interdependent, and the combined effect of renovation measures cannot be assessed in isolation. This interdependency means that the identification of cost-effective renovation strategies requires the simultaneous evaluation of combinations of measures, rather than individual interventions considered separately (Almeida and Ferreira 2017).

The IEA EBC Annex 56 project developed a methodology specifically addressing this challenge, providing a framework for the assessment and evaluation of packages of renovation measures intended to improve the energy performance of existing buildings (Almeida and Ferreira 2017). The study further demonstrates that cost-effective renovation does not require maximising the performance of each individual measure, but rather identifying the most advantageous combination across all building elements considered together.

3.4 Economic evaluation

A practically significant contribution to Swedish renovation decision-making for non-residential buildings is the Total Concept method (BELOK 2013). Rather than evaluating individual measures in isolation, the method constructs packages of energy efficiency measures that collectively satisfy the property owner's profitability requirements, expressed as an internal rate of return (IRR). Measures with short payback periods ("low-hanging fruit") are combined with more capital-intensive measures, so that the stronger returns from the former support the viability of the latter. The package assessment is supported by a cumulative profitability diagram in which renovation measures are added sequentially and plotted against IRR reference curves.

The process is structured into three steps: pre-study and action package creation, implementation, and follow-up. Applied across more than 300 buildings in Sweden by 2017, the method has demonstrated energy savings of 30–60 % in many cases. It has also been adapted for use in other Nordic countries, reflecting broader interest in methodologies that make deep renovation financially viable.

This approach illustrates a wider pattern in Swedish and Nordic practice: renovation decision-making tends to balance regulatory compliance with economic viability. While the EU cost-optimal framework specifies a lifecycle cost (LCC) methodology based on net present value (NPV) calculated over a 30-year period for public buildings (*Regulation (EU) No 244/2012* 2012), simplified economic indicators are widely used alongside or in place of full LCC analysis in practice, particularly at the early screening stage of renovation projects. Payback time, return on investment (ROI), and IRR are commonly applied due to their transparency and ease of interpretation for building owners and decision-makers.

The cost-effectiveness ranking of competing renovation measures is sensitive to the chosen discount rate and assumed energy price trajectory, and variations in these parameters can reverse the ranking of otherwise comparable alternatives (Pombo et al. 2016). This sensitivity is a key reason why simplified indicators, evaluated under fixed economic boundary conditions, are frequently preferred at the comparative screening stage, where the goal is to isolate the physical and technical performance of measures rather than to forecast financial outcomes for a specific investor.

These indicators present distinct methodological profiles that are relevant to the choice of evaluation approach in any given study context. Payback time is the most commonly applied indicator in practice: it measures how long it takes for energy cost savings to recover the initial investment, and its simplicity makes it effective for communicating results to non-specialist stakeholders. Its main limitations are that it ignores cash flows beyond the payback point and does not account for the time value of money, which reduces its suitability for long-term comparative assessments. ROI provides a normalised measure of profitability by relating net savings to investment cost, enabling comparison across renovation options, but does not incorporate discounting unless the analysis is explicitly structured to do so. IRR (the discount rate at which the net present value of an investment equals zero) directly addresses the time value of money and is more consistent with the theoretical underpinnings of the EU cost-optimal framework. It is the primary indicator used in the BELOK Total Concept method, where it serves as the basis for package-level assessment rather than individual measure evaluation (BELOK 2017).

A further indicator relevant to comparative renovation analysis is the Cost of Conserved Energy (CCE), an investment metric for ranking energy efficiency measures independently of building scale. CCE expresses the investment required per unit of annual energy saved, and a measure is considered cost-effective when its CCE falls below the prevailing energy price. Unlike payback time or ROI, CCE is dimensionally consistent across measures of different sizes and types, making it particularly suitable for cross-measure comparison. In its simplified form, without discounting, CCE reduces to the ratio of investment cost to annual energy saving, which is the formulation adopted in the present study.

Payback period and IRR are often reported together to balance methodological robustness with interpretability, and this is consistent with the approach taken in the Valencia school renovation study (Liébana-Durán et al. 2021), which reports both payback periods and 30-year global costs for each renovation package, allowing direct comparison of short-term feasibility with lifecycle economic performance.

The selection of appropriate indicators depends on the purpose of the analysis. Where the goal is a rigorous assessment of absolute financial performance, full LCC analysis incorporating discounting and time-varying energy prices is the appropriate instrument. Where the goal is comparative screening of renovation alternatives, particularly at an early stage or across heterogeneous building conditions, simplified indicators offer a consistent and transparent basis for ranking measures.

4 Method

4.1 Overall Workflow

The project began with the selection of a non-residential building category, followed by the choice of two buildings as case studies. In the next step, available data were collected for each building, including information on function, geometry, construction properties, year of construction, measured energy data, and technical systems. Relevant documents such as EPCs, OVK reports, and municipal drawings and permits were also gathered.

Subsequently, the building geometries were modelled in Rhino 8.0 (Robert McNeel & Associates 2025), and energy simulations were initiated in Grasshopper (GH) using Honeybee (HB) ("Ladybug Tools | Honeybee" 2025). The simulations incorporated both regulatory input data and the collected building-specific information. Building energy models were fitted against measured energy data, including sensitivity analysis, followed by parametric simulations using Colibri component.

Based on the fitted results, three energy models were selected for each building. These cases were chosen to reflect different scenarios in terms of unknown envelope properties and technical systems, allowing for the assessment of renovation measures under varying assumptions.

In the following step, suitable renovation measures were identified and defined. All relevant technical and financial data required for implementing each measure were collected. The simulations were then repeated for the selected cases, considering all possible combinations of renovation packages using Colibri within GH. Cost data were also integrated into the GH script at this stage. Finally, the results were exported to Excel for further analysis of energy and cost effectiveness. The overall workflow of method used in the study illustrates in Figure 2.

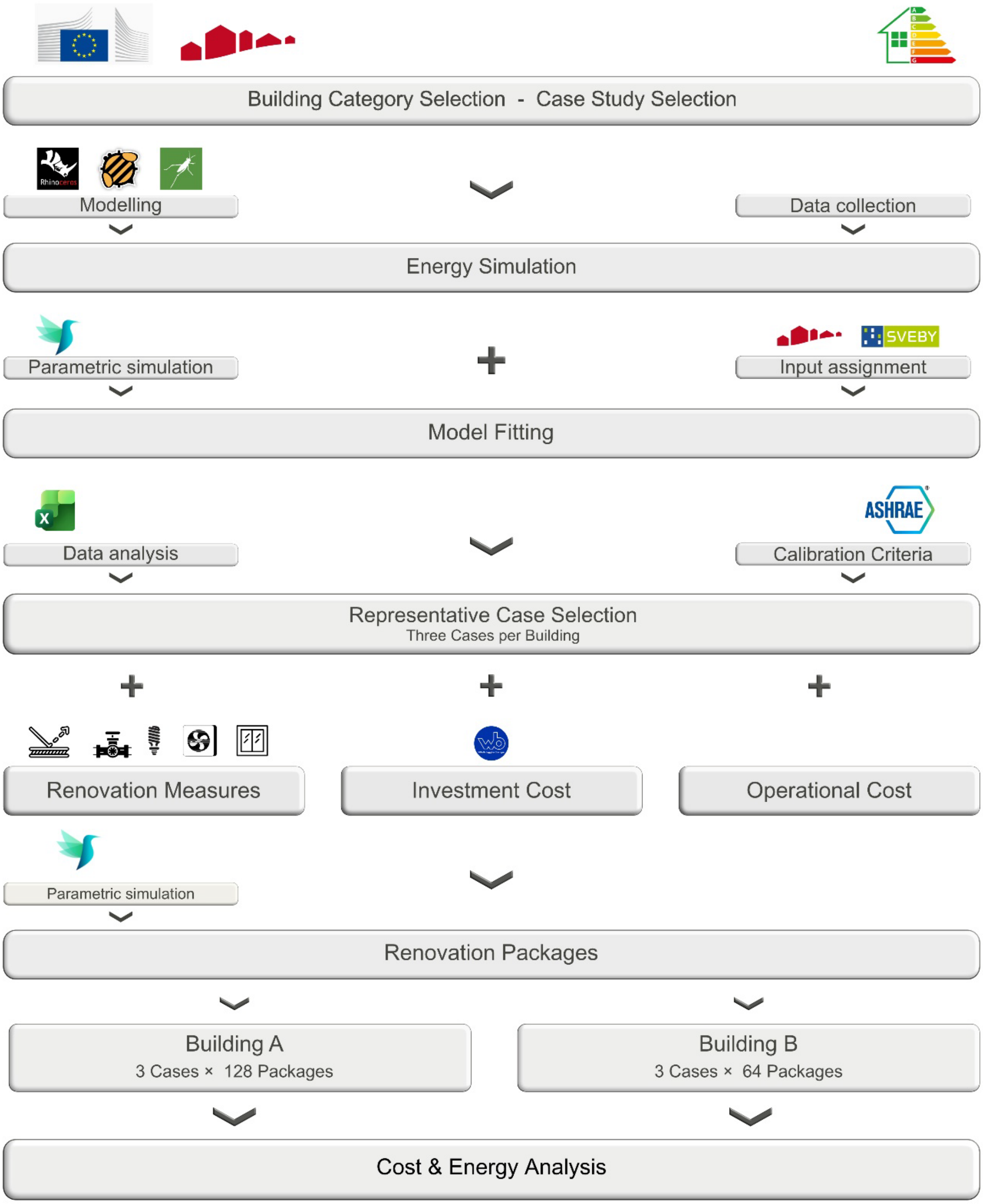

Figure 2 - Method overall framework diagram

4.2 Building category and case selection method

The selection of the building category and the corresponding case studies was guided by three main considerations: the potential influence of the category on energy use at national level, the suitability of its functional characteristics for reliable energy modelling, and the availability of detailed building-specific data.

Building categories that are prominent within the non-residential stock and represent a substantial share of total floor area are prioritised, as they are expected to have a high influence on overall energy use and the achievement of national energy performance targets. In addition, preference is given to building types with relatively homogeneous functional characteristics, avoiding categories with highly complex or mixed-use patterns. This enables more consistent assumptions in modelling and facilitates comparative analysis. Further criteria include the presence of stable and well-defined operational conditions, such as consistent occupancy schedules, standardized internal loads, and typical HVAC system configurations. Such characteristics support the development of reliable energy models.

In selection of case studies, the primary criterion was the availability of measured energy data and detailed OVK documentation to support model fitting. A second criterion was the comparability of building characteristics, including simple geometry, construction period, and no-cooling in the ventilation system. The selected cases present different levels of data completeness, particularly regarding ventilation systems, allowing the study to explicitly address uncertainty in model inputs.

4.3 Case studies: data collection

Building A
Building A is a six-story building with a basement, where the attic is also utilised as rentable space. The structure is a brick masonry building dating back to 1890, located within a central urban block in Stockholm characterized by closed block typology and inner courtyards surrounded by 5–6 story buildings. The building is considered historically protected based on self-assessment documented in EPC.

The building has a rectangular geometry, with two façades oriented towards the north-east and south-west, while the remaining two façades are adiabatic, adjoining neighbouring buildings. The exterior consists of red facing brick, with grey smooth plaster at the ground floor level, and a red sheet-metal roof. According to the EPC, the heated floor area is 1 360 m². All above-ground floors are used as office space, while the basement accommodates archives and technical services, based on documentation from OVK reports.

Building B
Building B is a seven-story structure with a basement, constructed in 1898 and located within a central urban block in Stockholm. The building is classified as protected under the Swedish Planning and Building Act (PBL) stating that "it is designated in the detailed plan or area regulations" in the EPC. The ground floor is occupied by retail and commercial spaces, while the upper floors are used as offices. According to the EPC, 84 % of the building area is designated for office use and 16 % for shops and retail.

The building has a U-shaped configuration that extends around the corner of the block. It features two main street-facing façades oriented toward the north and west, while the remaining façades face an internal courtyard. According to the EPC, the total heated floor area is 3 088 m². No detailed information was available regarding the use of the basement.

Given the predominance of office space, both buildings are treated as office buildings for modelling purposes. Additional document for both buildings, including historical drawings, records of construction permits, and OVK protocols, was obtained from the e-service of the construction and planning authority (Stockholms stad 2026).

4.4 Modelling approach and input parameters

The models were constructed using a combination of building-specific data and standardised assumptions, depending on data availability and reliability. Where detailed and consistent information was available from building documentation, these data were used directly to define model inputs. In cases of incomplete or uncertain information, parameters were defined based on applicable regulations, standardised guidelines, and relevant literature.

The modelling process is structured into three main components: geometric model development, representation of building systems, and definition of model input parameters and assumptions.

4.4.1 Geometry

The company Zerotude AB provided the 3D geometry of the buildings (“Zerotude” 2026). The geometry of both buildings was developed including the surrounding context, with orientation and adiabatic boundary conditions considered. Windows were modelled in a simplified manner based on window to wall ratio (WWR) estimated from drawings. For both buildings, the roof was simplified to a flat geometry, despite the original structures featuring pitched roofs. This approach was applied in line with the broader objective of the project, which aims to assess renovation measures using an automated modelling approach suitable for large building datasets, rather than producing detailed individual geometries. The geometries were modelled in GH, and the energy simulations were performed using HB. Key geometric parameters for both buildings are summarized in Table 3.

Table 3 - Geometrical characteristics of the selected case study buildings regarding heated area, façade and windows.

Parameter	Building A	Building B
WWR / %	24	20
A_{temp} / m²	1 360	3 088
Façade to A_{temp} ratio / %	43	90

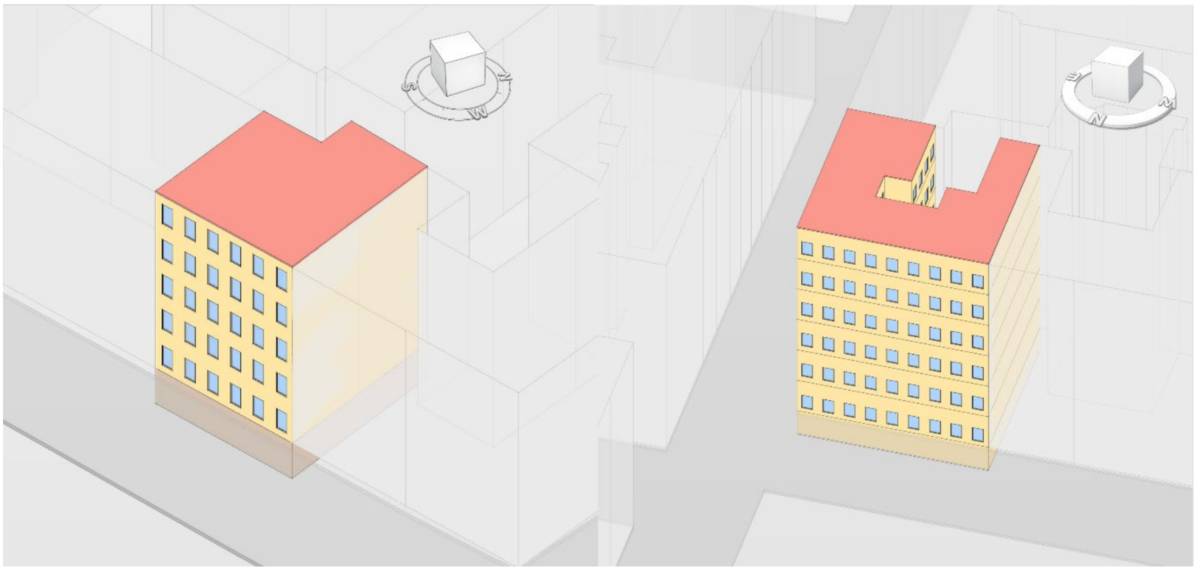

Figure 3 – Left: Geometry representation for the energy model of Building A. Right: Geometry representation for the energy model of Building B

4.4.2 Building systems

The building systems were defined based on available documentation, primarily EPC and OVK inspection reports.

EPC-based data

For Building A, the most recent EPC, issued in 2022, reports a EP_{pet} of 89 kWh/(m²·yr), corresponding to energy class D. The building is supplied by a district heating system. The EPC recommends replacing the existing double-glazed windows with new, more energy-efficient units.

For Building B, the latest EPC from 2019 indicates an EP_{pet} of 234 kWh/(m²·year) and an energy class F. The building is also connected to district heating. Similar to Building A, the EPC recommends replacing the existing double-glazed windows as an improvement recommendation. A detailed breakdown of the building's final energy use (Specifik energianvändning) from EPC and the most recent measured energy data for both buildings is presented in Table 4.

It should be noted that the EPCs are based on different versions of BBR; therefore, the values of EP_{pet} and the assigned energy classes are not directly comparable. This is due to differences in the weighting factors for energy carriers as well as changes in the energy performance requirements for new constructions across the respective versions.

Table 4 - The building's final energy data from EPC and the most recent measured energy data for case studies

Energy Use / (kWh/(m²·yr))	**Building A**		**Building B**	
	EPC (2022)	Measured (2025)	EPC (2019)	Measured (2023)
District heating	103.7	120.0	133.8	170.2
Hot water	2.0	8.9*	2.0	13.8*
Cooling	0.0	0.0	0.0	0.0
Property Electricity	8.5	23.6	41.6	37.5
Total	114.2	152.5	177.4	221.5

*Calculated based on the flow of cold water as explained in 4.5.4.

OVK-based data

OVK inspection reports were used as a primary source for identifying ventilation system types, configurations, and installation periods. This information informed the representation of ventilation systems in the simulation model and the definition of uncertain input parameters, as discussed in Section 4.5.2.

Building A

Two main ventilation systems were identified. The main system serves the majority of the building and consists of a FT system, with a supply air system installed in 1972 and exhaust fans installed in 2005. A second system, serving the attic level, is an FTX system, installed in 2002 representing approximately 19% of total airflow.

The attic FTX system is the only system equipped with heat recovery, representing 19% of total building airflow. An HR efficiency of 60% was assumed for this system based on literature ranges corresponding to its installation period. A weighted average efficiency was derived for the building as a whole based on the proportion of airflow served by this system, resulting in a building-level HR efficiency of 12%. This value was used as the fixed baseline HR condition for Building A in the sensitivity screening.

For airflow, the OVK measured value of approximately 0.75 l/(s·m²) was selected as the reference value for sensitivity screening, as it was considered representative of actual operating conditions. The OVK documentation also reported a projected airflow of approximately 0.68 l/(s·m²) and the EPC indicates 0.66 l/(s·m²). Measured values were consistently higher than projected values across inspections, though the cause could not be clearly identified. The reassessment of airflow values during model fitting, following the identification of inconsistencies in the measured data, is discussed in Section 4.5.2.

No information was available regarding system control strategies. Therefore, the ventilation systems were modelled as CAV systems.

Building B

Three ventilation systems were identified based on the available OVK reports (2018 and 2024). Main system serves the office areas and dates from 1987, while two systems installed in 2013 serve the retail spaces. All systems are FTX.

The OVK documentation for Building B was incomplete and inconsistent. Total airflow values were not reported for the older main system, and building-level airflow was estimated by aggregating room-level data from the available OVK reports. OVK projected airflow values were substantially higher than the EPC value of 1.0 l/(s·m²), and inspection notes indicated that the fan was not running at maximum capacity during the OVK measurement. For this reason, the EPC value of 1.0 l/(s·m²) was selected as the reference airflow for sensitivity screening.

To represent the building at the model, airflow and HR efficiencies were defined at the building scale using weighted values based on system characteristics and building use. HR definition of representative HR values for model fitting is discussed in Section 4.5.2.

No information was available regarding system control strategies. Therefore, the ventilation systems were modelled as CAV systems.

4.4.3 Selected input parameters

The initial simulation model was developed using input parameters derived primarily from available building-specific documentation. When data were not available, input values were defined based on applicable regulations, standardized guidelines and relevant literature for office buildings in Sweden.

The primary regulatory source was BBR (BBR 29 2011), which constitutes the main mandatory framework for buildings in Sweden. In addition, requirements from Arbetsmiljöverket, which is the controlling authority for offices as workplaces, were applied (Arbetsmiljöverket 2023). For input parameters not explicitly defined in regulations, standardized values from Sveby were adopted (Sveby 2012).

In addition, the EPC documentation indicated the absence of active cooling systems, and therefore, cooling was not included in the simulation model.

For parameters that are highly dependent on building-specific conditions, such as thermal bridges, infiltration rates, and HR efficiency, values were derived from relevant literature and empirical studies, prioritizing sources with measured data representative of similar building types and conditions. Inputs for the initial simulation and the source of each value can be seen in Table 5.

Table 5 - selected input parameters for initial energy simulation and their sources for case studies

Input Parameter	Building A		Building B	
	Value	Source	Value	Source
Infiltration/ (l/ (s·m² facade))	0.25	Literature (see 4.5.2)	0.25	Literature (see 4.5.2)
Thermal bridge/ %	25 %	Literature (see 3.5.2)	25 %	Literature (see 3.5.2)
U-value Walls/ (W/(m²·K))	1.43	EN 1745 2020	1.43	EN 1745 2020
U-value Roof/ (W/(m²·K))	0.40	BETSI	0.40	BETSI
U-value Windows/ (W/(m²·K))	3.00	EPC	3.00	EPC
Lighting load/ (W/m²)	5.30 (occupied hours) 1.10 (others)	Sveby	5.30 (occupied hours) 1.10 (others)	Sveby
Equipment load/ (W/m²)	7.20 (occupied hours) 2.10 (others)	Sveby	7.20 (occupied hours) 2.10 (others)	Sveby
People density/ (ppl/m²)	0.05	Sveby	0.05	Sveby
Occupancy Schedule	8 am - 5 pm (weekdays)	Sveby	8 am - 5 pm (weekdays)	Sveby
Ventilation Airflow/ (l/(s·m²))	0.75	OVK	1.00	EPC
HR/ %	12	Literature and OVK age	65	Literature and OVK age
Heating Setpoint/ °C	21 - Constant	Sveby	21 - Constant	Sveby
Cooling	off	EPC	off	EPC

Energy simulations were conducted using the IWEC weather file for Stockholm–Arlanda (WMO 024600), obtained from the Climate.OneBuilding repository ("Onebuilding" 2026). The IWEC file is a TMY and translated into EnergyPlus (EPW) format for building energy simulation. The weather file was applied consistently across baseline modelling, fitting, and renovation scenarios to ensure internal comparability between cases.

4.5 Model fitting method

This section presents the method used to fit the simulation models against measured data. The objective is to align simulated heating demand with measured energy data. The following subsections describe the overall fitting framework, the identification of impactful inputs, the parametric simulation approach used to explore input variations, the data processing applied, and the assessment of property electricity consumption used to support the fitting.

4.5.1 Model fitting framework

The process was structured as a staged and evidence-based framework designed to reduce uncertainty. The framework was developed based on established principles of *uncertainty analysis and inverse modelling in building energy assessment* (Tian, De Wilde, et al. 2018) and *multi-level calibration methodologies for building energy simulation* (Yang and Becerik-Gerber 2015). The overall objective of fitting the energy model was to align simulated space heating demand with measured data to ensure that the model remained reliable for subsequent renovation scenario analysis. The workflow of the fitting process is illustrated in Figure 4.

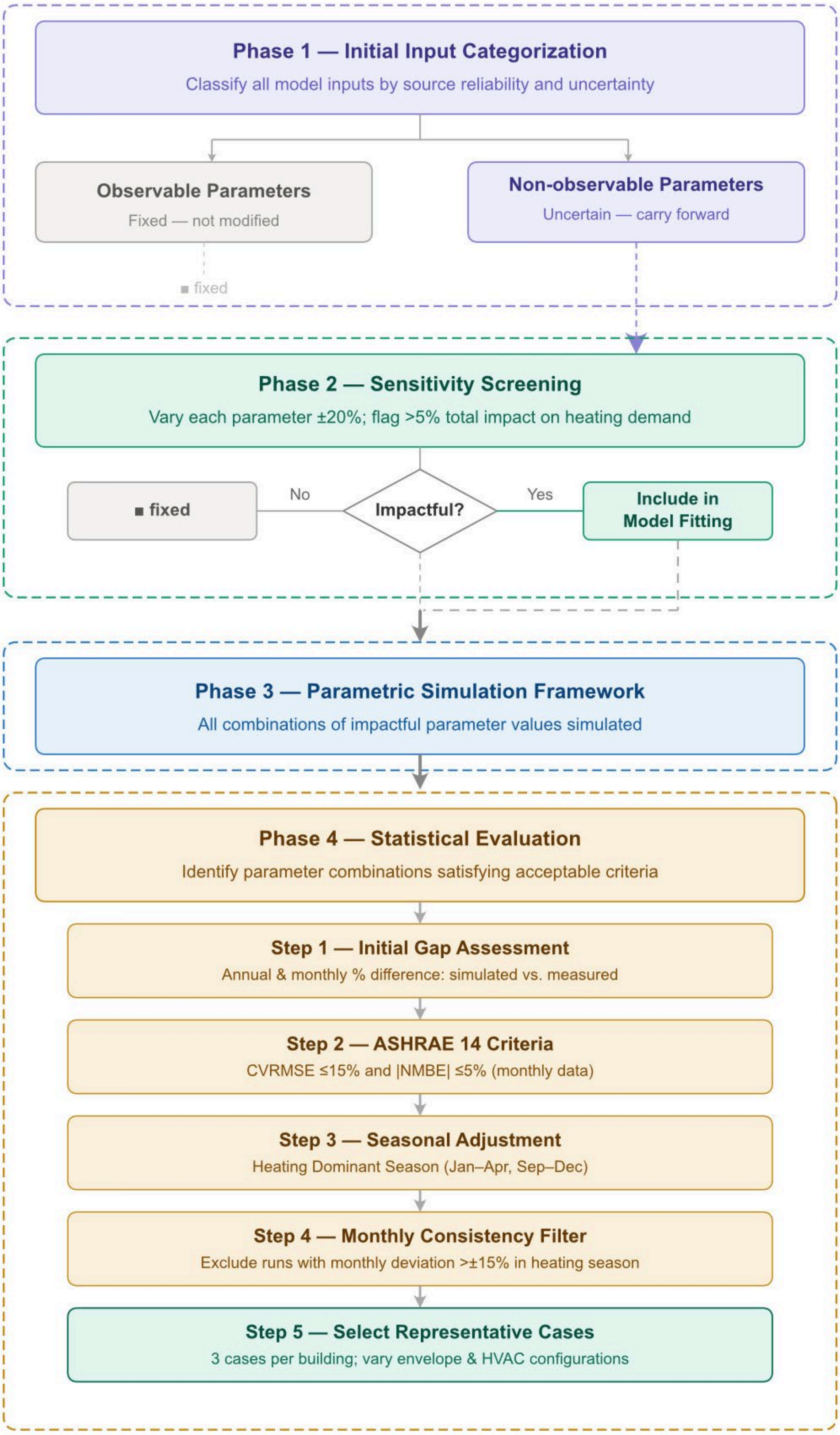

Figure 4 - Overall workflow of model fitting including four phases: (1) Initial input categorization, (2) Sensitivity screening, (3) Parametric simulation, and (4) Statistical calibration evaluation and case selection.

The model fitting was implemented in four sequential phases: (1) Initial input categorization, (2) Sensitivity screening, (3) Parametric simulation, and (4) Statistical calibration evaluation and case selection.

Phase 1: Initial input categorisation

The first phase consisted of classifying all model inputs according to their source reliability and degree of uncertainty. This step was implemented to clearly distinguish between parameters treated as fixed constants and those subjected to the fitting.

Observable parameters: Observable parameters were defined as inputs supported by evidence derived from as-built drawings, technical documentation, site inspections, or geometric data. These included building geometry, floor areas, window dimensions, and envelope constructions when possible. These parameters were treated as constants and were not modified during the process.

Non-observable parameters: Non-observable parameters were defined as inputs characterized by incomplete documentation, operational uncertainty, or limited verification. These typically included: HVAC system efficiencies, infiltration rates, thermal performance of envelopes, and operational loads and schedules.

Phase 2: Sensitivity screening

The second phase aimed to reduce the set of uncertain input parameters of the model fitting by identifying the most Impactful non-observable parameters.

A simplified one-factor-at-a-time (OFAT) sensitivity analysis was performed. Each non-observable parameter was varied individually within its ±20 % range, while all other parameters were kept constant. The relative impact of each parameter was quantified by calculating the percentage change in annual heating demand caused by the variation of that parameter. Parameters that caused more than a 5 % variation in total heating demand, were classified as Impactful. Parameters with negligible influence were fixed at their baseline values and excluded from subsequent tuning. This screening approach reduced the number of uncertain inputs to a manageable subset of limited variables from an initial pool.

It should be noted that the ±20 % variation does not represent realistic input ranges for all parameters and may exceed plausible conditions. However, this range was used as a simplified approach to assess relative influence, while acknowledging that uncertainty levels differ between parameters.

Phase 3: Parametric simulation framework

Following the sensitivity screening, a parametric simulation framework was developed to explore the influence of the impactful non-observable parameters identified in the previous phase. For each impactful parameter, a set of values was defined, while other parameters were fixed at their baseline values.

A set of representative values was assigned to each impactful parameter, reflecting plausible variations within the defined ranges. The combination of these values formed a parametric matrix, within which all possible combinations of parameter values were simulated using Colibri in GH. This process resulted in a dataset representing the variation of simulated heating demand in response to changes in the selected parameters.

Detailed definitions of parameter ranges and selected values are provided in section 4.5.2. In addition, simulation outputs and measured data were processed to ensure consistency in system boundaries and comparability, as described in Section 4.5.4.

Phase 4: Statistical calibration evaluation and case selection

The next phase consisted of analysing the parametric simulation results and identifying parameter combinations that satisfied predefined statistical calibration criteria. For each parametric combination, simulated space heating demand was compared with measured building-level heating data at two temporal resolutions: annual and monthly.

Step 1 – Initial gap assessment

As an initial diagnostic step, the percentage difference between simulated and measured values was calculated at both annual and monthly levels. The annual percentage difference was calculated with Equation (3).

$$\frac{M_{ann} - S_{ann}}{M_{ann}} \times 100 \tag{3}$$

where S_{ann} and M_{ann} represent simulated and measured annual heating demand, respectively. Monthly percentage differences were calculated analogously for each month. This step was used to provide a preliminary overview of the magnitude and seasonal distribution of the deviation between simulated and measured values. However, percentage-based monthly comparison was treated only as an initial screening indicator, while the main assessment was based on statistical indicators.

Step 2 – Statistical calibration based on ASHRAE guideline 14

To ensure methodological rigor, statistical calibration metrics were applied in accordance with ASHRAE Guideline 14 for monthly calibration of energy models (ASHRAE 2014). Two statistical indicators were calculated for each parametric run: CV(RMSE) and NMBE. These were computed using Equation (4) Equation and (5):

$$\text{CVRMSE} = \frac{\sqrt{\frac{\sum_{i=1}^{n}(M_i - S_i)^2}{n-1}}}{\bar{M}} \times 100 \tag{4}$$

$$\text{NMBE} = \frac{\sum_{i=1}^{n}(M_i - S_i)}{(n-1)\,\bar{M}} \times 100 \tag{5}$$

where: M_i is measured monthly heating demand, S_i is simulated monthly heating demand, n is number of months included in calibration, and $\bar{M}$ is mean measured monthly heating demand.

The following ASHRAE acceptance limits for monthly calibration were adopted:

- $\text{CV(RMSE)} \leq 15\ \%$
- $|\ \text{NMBE}\ | \leq 5\ \%$

Step 3 – Seasonal adjustment

Heating demand during late spring and summer months (May–August) was found to be very low, increasing the sensitivity of statistical error metrics to small absolute deviations. In addition, measured values in these periods may include contributions from domestic hot water. To avoid distortion of the statistical indicators, CV(RMSE) and NMBE were calculated using only the primary heating season (January–April and September–December). Accordingly, the value of n in the statistical equations was adjusted to reflect the number of months included in the heating-dominant period.

Step 4 – Secondary monthly consistency filter

Following the identification of parameter combinations satisfying the ASHRAE criteria, an additional filtering step was applied to further improve the consistency of the results. For each retained combination, monthly percentage deviations during the heating-dominant months were evaluated. Parameter sets exhibiting deviations greater than ±15 % in any of the selected months were excluded. This additional filter was not part of the ASHRAE acceptance criteria but was applied where feasible to reduce the number of acceptable cases and identify cases with closer values to measured data. However, where the application of this filter was not possible, the selection was based solely on the ASHRAE statistical criteria.

Step 5 – Selection of representative adjusted cases

From the set of adjusted solutions, three representative cases for each building were selected for further analysis of renovation measures. Where possible, cases with different envelope properties and HVAC configurations were chosen in order to assess the impact of renovation measures under varying conditions and enable comparative evaluation across scenarios.

4.5.2 Impactful inputs for model fitting

This section presents the parameters identified as impactful for the model fitting process, together with the ranges and representative values considered for each parameter. The selected values were selected based on available building documentation, observed building conditions, relevant standards, and variability reported in the literature, ensuring that they reflect realistic operational conditions and typical practice.

***U*-value of walls**

The thermal transmittance (*U*-value) data for the buildings was limited. Based on the building age and the absence of recorded façade-related renovation measures in the Stockholms stad building records (Stockholms stad 2026), it was assumed that no major envelope renovations had been undertaken. Therefore, a bounded range of *U*-values was defined based on typological assumptions and standardised material properties.

The wall construction was first estimated using typological information from the book titled Så byggdes husen (Björk et al. 2021), indicating a solid brick masonry structure with varying thickness by floor. The ground floor was assumed to have a thickness of 0.60 m, while the remaining floors were assumed to have a thickness of 0.45 m. A weighted average thickness was calculated as 0.48 m for external walls. Historical drawings were consulted to support the estimation of wall thickness; however, their reliability is limited due to age and potential inaccuracies in the documentation.

No additional insulation was assumed, as no documentation indicating façade insulation measures was identified in the available renovation records. The *U*-value was calculated using Equation (6).

$$U = \frac{\lambda}{d} \tag{6}$$

Where λ is the thermal conductivity of the brick in W/(m·K) and d is the wall thickness in meters. λ values were selected for solid clay brick based on SS-EN 1745:2020 (EN 1745 2026). Five discrete *U*-values were derived corresponding to the range of clay brick conductivity values reported in the standard, spanning from well-performing stock to conservative solid brick

Accordingly, five discrete *U*-values (0.59, 0.80, 1.00, 1.22 and 1.43 W/(m²·K)) were tested to represent uncertainty in envelope thermal transmittance.

***U*-value of windows**

The *U*-value of the windows was defined based on available documentation, as no direct measurements or detailed specifications were accessible. *U*-values were derived from EPC comments, which provide only indicative values and are subject to considerable uncertainty. A value of 3.00 W/(m²·K) was taken as the upper bound, representing the original windows as indicated in the EPC. A value of 1.30 W/(m²·K) was included as the lower bound, corresponding to the EPC estimate for the renovated condition. An intermediate value of 2.20 W/(m²·K) was introduced based on BETSI survey data (*BETSI* 2010), representing typical window performance for Swedish residential building stock of this typology. Therefore, these three selected *U*-values (1.30, 2.20, and 3.00 W/(m²·K)) were tested for both buildings.

Thermal bridges

Thermal bridges represent a high share of envelope transmission heat losses, and their relative importance depends strongly on building system and insulation level. Therefore, it is not appropriate to apply a single predefined percentage factor for thermal bridges. In Sweden, thermal bridges are sometimes accounted for by a simple +20 % increase in transmission heat transfer; however, this approach is a simplification and may be misleading across different constructions and insulation levels (Berggren and Wall 2013).

Cold-climate studies of multi-storey buildings report that thermal bridges account for approximately 23 % of transmission losses before renovation (Ilomets et al. 2016). Case studies using detailed two-dimensional calculations, commonly report thermal-bridge contributions in the range of 18–30 % of transmission losses (Larsson and Berggren 2015). The Swedish environmental rating system Miljöbyggnad allows a default allowance of at least 30% when thermal bridges are not explicitly calculated (Sweden Green Building Council 2020).

For the studied solid brick buildings from circa 1890 in Sweden, a 25 % share of transmission heat losses due to thermal bridges was considered a technically reasonable baseline assumption, given the relatively high initial *U*-values of the envelope. In the parametric study, a range of 20 % to 30 % was investigated.

Infiltration

No blower-door test results or verified information on envelope airtightness were available for the buildings, and potential retrofits or degradation effects could not be confirmed. The air infiltration rate was defined from literature review. The values from documentation were commonly expressed at ±50 Pa, to approximate operating pressure conditions the standard power-law relationship was used with the Equation (7).

$$Q = C \cdot \Delta P^{\mathrm{n}} \tag{7}$$

Where Q is the airflow rate, C is the flow coefficient, ΔP is the pressure difference across the building envelope, and n is the flow exponent. In this study, a value of n=0.67 was adopted, consistent with engineering practical experience for building envelope leakage. The reported values at ±50 Pa were subsequently converted to a reference pressure difference of 4 Pa to better represent operating conditions. Since the flow coefficient C is independent of pressure, the leakage rate at the operating reference pressure of 4 Pa was obtained from the documented value at 50 Pa as:

$$Q_4 = Q_{50} \cdot (\frac{4}{50})^{0.67} \tag{8}$$

where Q_4 is the airflow rate at the operating pressure of 4 Pa, and Q_{50} is the airflow rate at the test reference pressure of 50 Pa.

The Swedish building regulation applicable to the existing building stock, BBR 7 (BBR 1998:38 1998, 38) mentioned a maximum average leakage of 0.8 l/(s·m²) at ±50 Pa for residential buildings and 1.6 l/(s·m²) at ±50 Pa for other premises, which yields values of approximately 0.15 l/(s·m²) and 0.29 l/(s·m²) at 4 Pa, respectively. It should be noted that these represent maximum permitted values under the regulation, not typical measured performance, and that compliance with this requirement was not universal in practice (Y. Zou 2010; Wahlgren and Sikander 2010).

A value of 0.43 l/(s·m^2_{facade}) at 4 Pa was derived from the default envelope leakage rate specified in ASHRAE Standard 90.1 Appendix G (ASHRAE 2022), converted to SI units and adjusted to operating pressure conditions using the same power-law relationship.

Accordingly, three discrete infiltration rates, 0.25, 0.31, and 0.43 l/(s·m^2_{facade}) at 4 Pa, were evaluated. These values represent a progression from relatively airtight to moderately leaky envelope conditions and draw on regulatory benchmarks and empirical engineering experience.

Equipment load

In Sweden, there is no explicit regulatory requirement in BBR defining a fixed equipment power density for office buildings. Instead, equipment electricity is treated as user-related energy and is standardised through BEN (BFS 2017:6) and industry guidelines. BEN specifies an annual operational electricity use of 50 kWh/(m²·yr) for office premises, intended to represent normal use conditions in energy performance calculations (Boverket 2016).

More detailed breakdowns are provided in Sveby, where internal gains from equipment during office hours (excluding lighting) are estimated at 9.0 W/m² for 100 % occupancy and 6.3 W/m² for 70 % occupancy, with an additional constant server load of 0.9 W/m² and a standby load of 1.2 W/m² outside office hours (Sveby 2012). These values correspond to annual electricity use of approximately 60 kWh/(m²·yr) (100 % occupancy) and 49 kWh/(m²·yr) (70 % occupancy).

Equipment load was identified as an impactful parameter influencing heating demand in sensitivity screening for building A. Accordingly, internal gains from equipment were modelled using the Sveby methodology, considering two representative scenarios: 100 % occupancy and 70 % occupancy.

Ventilation system parameters

Ventilation system parameters include airflow rate and HR efficiency, both of which directly influence space-heating demand in mechanically ventilated buildings. Due to differences in system configuration, documentation quality, and measurement uncertainty, these parameters were defined and implemented differently for each building.

Airflow

For Building A, the available documentation provided three airflow references: the EPC indicates 0.66 l/(s·m²), OVK projected airflow is approximately 0.68 l/(s·m²), and OVK measured airflow is approximately 0.75 l/(s·m²). Since the cause of the discrepancy between projected and measured values could not be clearly verified, both the EPC value and the OVK measured value were retained as representative cases of projected and plausible operating conditions: 0.66 and 0.75 l/(s·m²).

For Building B, airflow was defined under higher uncertainty due to incomplete and inconsistent documentation. The EPC indicates a uniform airflow of 1.0 l/(s·m²), while aggregation of room-level OVK projected data yields a substantially higher estimate of 1.77 l/(s·m²). The cause of this discrepancy could not be clearly identified, and both values were retained as representative cases.

All airflow values were implemented at the building level, representing aggregated ventilation conditions across all systems.

Heat Recovery Efficiency

For Building A, HR efficiency was fixed at 12% as discussed in Section 4.5.2 and was not treated as an impactful parameter in the fitting process.

For Building B, due to the presence of three systems of different ages and the absence of reliable performance documentation, representative HR values were defined based on these literature ranges. Systems measured in the late 1990s showed nominal efficiencies averaging approximately 70% (Roulet et al. 2001), while in 2015 FTX installations ranged from approximately 60% to 92% (Wahlström 2008).

Based on these ranges, the main system of Building B, installed in 1987, was assigned a plausible efficiency range in the lower part of the measured interval for existing FTX systems, while the two systems installed in 2013 were assigned a range consistent with better-performing contemporary Swedish FTX installations. Representative values of 55%, 60%, 65%, 70%, and 75% were selected to cover the plausible range of weighted building-level HR efficiency.

Heating setpoint

Swedish regulations do not prescribe a fixed indoor heating setpoint for office buildings but define performance requirements related to thermal comfort. According to BBR (BFS 2011:6), buildings must ensure satisfactory indoor conditions (BBR 29 2011). Arbetsmiljöverket (AFS 2023:12) indicates that, for light sedentary work, indoor air temperature should typically remain within 20–24 °C during winter, providing a practical reference range for acceptable conditions (Arbetsmiljöverket 2023). Sveby recommends an indoor temperature of 21 °C for simulation purposes unless other values can be justified (Sveby 2012; Ekberg 2006).

For model fitting purposes in this study, a heating setpoint of 21 °C was used as the baseline, while 20.5 °C and 21.5 °C were tested as alternative values. A setpoint of 20.5 °C was considered representative for the entire building, taking into account that the basement, may operate at lower temperatures (approximately 15 °C), while the main occupied spaces are maintained at around 21 °C.

To support this assumption, the temperature correction approach described in BEN (BFS 2017:6) was applied, according to which heating energy demand changes by approximately 5 % per degree difference from the reference indoor temperature (Boverket 2016). Based on this approach, a simplified estimation considering the basement area, its heating demand, and the temperature difference indicates that an average indoor temperature of 20.5 °C provides a reasonable approximation for representing the overall building in the simulation model.

4.5.3 Parametric simulation and input variations for model fitting

Following the sensitivity screening, the parameters identified as impactful were assigned value ranges, as shown in Table 6. Using a parametric simulation workflow in GH with the Colibri component, all possible combinations of these values were simulated to generate the pool of cases from which the adjusted models were identified.

For Building A, a full combinatorial sweep was performed, resulting in 1 080 simulated cases. For Building B, the long computation time associated with a full sweep made this approach impractical; therefore, a more targeted framework was adopted. In this approach, the most impactful parameters, such as *U*-values and airflow rates, were tested at the minimum and maximum bounds of their ranges, in combination with the remaining measures, to establish an initial understanding of where results could fall within the acceptable range. For instance, when a *U*-value for the wall was combined with the lowest values of all other measures (including infiltration rate, thermal bridges, etc.) and the resulting heating demand still exceeded the measured data, no further simulations with higher *U*-values were pursued, as fitting process within the acceptable range was already ruled out for that branch. Through this iterative elimination process, the number of simulated cases for Building B was reduced to 132.

Table 6 - The impactful parameters and their assigned values in parametric simulation in phase 3 of model fitting process

Parameter	Building A	Building B
Infiltration/ (l/(s·m²))	0.25	0.25
	0.31	0.31
	0.43	-
Thermal bridge/ %	20.00	20.00
	25.00	25.00
	30.00	-
U-value Walls/ (W/(m²·K))	0.59	0.59
	0.80	0.80
	1.00	1.00
	1.22	-
	1.43	-
U-value Windows/ (W/(m²·K))	1.30	1.30
	2.20	2.20
	3.00	3.00
Equipment load/ (W/m²)	7.20	7.20
	9.00	-
Airflow/ (l/(s·m²))	0.66	1.00
	0.75	1.77
heating setpoint/ °C	20.50	20.50
	21.00	21.00
HR efficiency / %	12	55
		60
		65
		70
		75

4.5.4 Data processing for simulation and measured data fitting

This section describes the processing of simulated and measured energy data to ensure consistency in system boundaries prior to model fitting. The fitting process, as can be seen in Figure 5, includes the estimation and separation of domestic hot water energy, addition of standardized losses in accordance with Swedish regulations and guidelines.

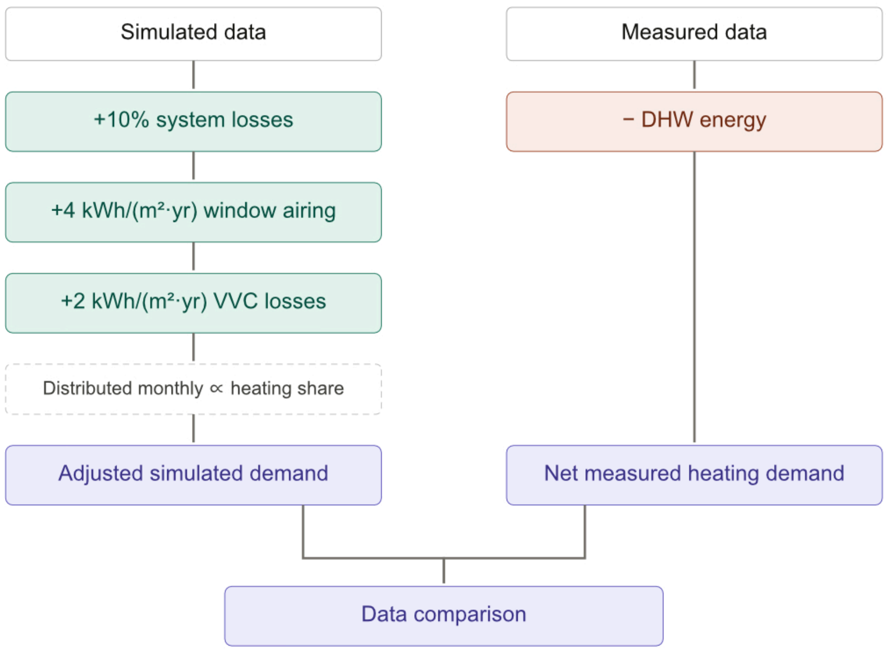

Figure 5 - Data Processing steps for simulation and measured data adjustment

Inclusion of heating system and distribution losses

To account for system inefficiencies in heat generation, control, and distribution A 10 % increase was applied to the simulated space-heating demand. These losses represent the difference between delivered heating energy and useful space-heating demand. This value reflects common engineering practice in energy audits and early-stage simulations, where system losses are estimated when detailed data is unavailable.

Window airing and domestic hot water circulation losses (VVC)

BEN requires that user-related energy in premises be based on intended building function. For non-residential buildings, if window airing losses cannot be determined, an addition of 4 kWh/(m²·yr) shall be included in the calculation.

Sveby also specifies a standardized domestic hot water use of 2 kWh/(m²·yr) for offices, explicitly excluding hot water circulation losses. BELOK 2017 reports measured VVC losses of 1.5–3 kWh/(m²·yr) in offices (BELOK 2017). Therefore, since VVC is not explicitly modelled, an additional 2 kWh/(m²·yr) was added to the simulated space-heating demand.

The annual values for window airing and VVC losses were distributed across months in proportion to the monthly share of space-heating demand.

Separation of domestic hot water Energy from measured data

To enable comparison between measured heating energy and simulated space-heating demand, the delivered energy for domestic hot water (DHW) was separated from the total measured heating energy. In accordance with Boverket's regulation BEN (BFS 2016:12), when measured hot water energy and circulation losses are unknown, but the annual cold-water volume is available, the delivered energy for DHW may be calculated with Equation (9).

$$E_{tvv,lev} = 0.35 \cdot \frac{V_{kv} \cdot 55}{\eta_{tvv}} \qquad (9)$$

where $E_{tvv,lev}$ is the delivered energy for domestic hot water in kWh/yr, V_{kv} is the measured annual cold-water volume in m³/yr, and η_{tvv} is the annual efficiency of the hot water preparation system which was considered equal to 1.0 for district heating. The value of 55 °C corresponds to the assumed temperature increase for domestic hot water based on BEN. The calculated DHW energy was subtracted from the total measured heating energy for each month in building A to obtain the net space-heating energy.

4.5.5 Baseline assessment of property electricity consumption

While the model fitting process was conducted against the space-heating demand, several input parameters, such as ventilation airflow rates, influence both space-heating and electricity consumption. Mechanical ventilation systems, and in particular fan electricity, often constitute a high share of property electricity use and are strongly influenced by factors such as airflow rate, operating hours, and fan efficiency.

Also, to support the subsequent evaluation of renovation measures, a reliable baseline for property electricity consumption was necessary. An additional assessment was therefore carried out to estimate the electricity use of the systems when possible, and to verify the plausibility of the shared input parameters used in the fitting process.

The calculated results were compared with available measured data for property electricity, as well as with statistical benchmarks for office buildings in Sweden. When the calculated values were reasonably consistent with measured and statistical data, the same approach was applied in the renovation scenarios. If calculations were not possible due to insufficient data, statistical values were used as the baseline.

Statistical benchmarks for property electricity

The report STIL3 published by the Swedish Energy Agency (Statens energimyndighet), was used to assess the calculation to reach a reliable baseline. The report is as part of a national effort to develop detailed and reliable energy statistics for non-residential buildings (Persson et al. 2025). The study focuses on office buildings and is based on the third iteration of the STIL program, which collects empirical data from a representative sample of buildings across Sweden.

The STIL3 study reports energy use for different end-use categories as minimum and maximum values observed across the sampled buildings, together with nationally weighted average values. For this study, only the categories relevant to the case studies were selected and their combined contribution was considered to represent the total property electricity. As these categories (fan, pump, elevator) are assumed to be present in all buildings, the national weighted values were considered as a reference benchmarks for typical electricity use in Swedish office buildings. Based on this assumption, the relative share of each category was derived and applied to the measured total property electricity of the building to estimate the initial baseline distribution among end uses. Table 7 shows the statistical value from STIL3 as well as the percentage allocated to each component.

Table 7- Statistical benchmarks for property electricity end-use categories in Swedish office buildings based on nationally weighted average values from the STIL3 study (Persson et al. 2025).

Component	STIL3 Benchmark / (kWh/(m²·yr))	STIL3 Allocation/ %
Fans	13.20	65
Pumps	1.70	8
Elevators	1.10	5
Other	4.30	21
Total	20.30	100

Estimation of fan electricity

Fan electricity use was estimated using SFP, which relates fan electrical power to airflow rate. Annual fan electricity use was calculated with (10):

$$E = SFP \cdot q \cdot t \tag{10}$$

Where E is annual fan electricity in kWh/yr, SFP is specific fan power in kW/(m³/s), q is airflow rate in m³/s, and t is operating time in h/yr. The resulting annual energy use was normalised by heated floor area to obtain kWh/(m²·yr). Due to the CAV system assumption, continuous operation was assumed, corresponding to 8760 hours per year, reflecting practice in older office buildings where ventilation systems operate without scheduled shutdowns.

SFP was derived from available fan data using the general relationship between airflow rate, pressure rise, and total fan efficiency. Where complete fan power data were available, SFP was calculated directly as the ratio of fan power to airflow. Where such data were incomplete or unavailable, SFP was estimated using Equation (11):

$$SFP = \frac{P}{q} = \frac{q \cdot \Delta p}{\eta \cdot q} = \frac{\Delta p}{\eta} \tag{11}$$

Where P is electrical power in W, q is airflow rate in m³/s, Δp is pressure rise in Pa, and η is total fan efficiency.

Discrepancies were identified in the OVK documentation; therefore, measured fan power data were not used as primary inputs. To ensure consistency across all systems, projected airflow rates and fan power values from the OVK documentation were used as the main input data. Measured values were only used for plausibility checks (Table 8).

Table 8- Input parameters used for fan electricity estimation, derived from OVK projected values.

Building	System	System type	Year	Δp/ kPa	η	Fan power/ kW	SFP /(kW/(m³/s))
A	Main	FT	1972/2005	1.5	-	2.14	3.0
A	Attic	FTX	2002	1.0	0.6	-	1.7
B	Main	FTX	1987	1.5	0.5	-	3.0
B	Retail	FTX	2013	-	-	-	2.0

For the main ventilation of building A, fan power data were available in the OVK. However, the measured values showed inconsistencies and were not considered reliable; in several cases, measured values were significantly higher than projected values, and reported units varied between amperes and watts, making direct interpretation uncertain. SFP was therefore calculated directly as the ratio of projected fan power to projected airflow.

For the attic ventilation system, no direct fan power data were available. SFP was instead estimated using assumed values for pressure rise and fan efficiency derived from literature ranges (Nilsson 1995). As this system represents a more recent installation, assumptions corresponding to a relatively efficient and well-designed system were applied, with pressure drop and fan efficiency values selected within standard ranges reported for such systems.

The estimation of fan electricity for Building B was subject to greater uncertainty than for Building A, due to the overall incompleteness of the available OVK documentation. Fan-related information was fragmented across systems and inspection years, with missing total airflow values, incomplete fan power data, and inconsistent reporting formats. In several cases, only room-level airflow data were available, requiring aggregation to obtain building-level values. These limitations prevented direct calculation of SFP from reported data, and SFP values were therefore defined entirely based on literature-based assumptions, applying the same reference framework used for Building A to ensure methodological consistency.

For the main ventilation system, SFP was estimated based on literature describing the typical performance of older ventilation systems, reflecting higher pressure drops and lower overall efficiency characteristic of installations from that period (Nilsson 1995).

For the retail system, which comprises two ventilation units installed in 2013, no pressure, efficiency, or fan power data were available. SFP was defined using the maximum allowable value specified in the BBR 19, which was in force at the time of installation. This regulatory threshold was used as a reference to define a plausible upper performance limit for the system.

4.6 Renovation measures

The renovation analysis was carried out using the selected baseline models developed in the previous section. Renovation measures were applied to these cases by modifying selected model parameter differences while maintaining all other inputs unchanged. This approach ensures that the impact of each measure can be evaluated consistently, isolating the effect of the intervention from the uncertainty associated with the baseline conditions.

4.6.1 Selection of renovation measures

The renovation measures considered in this study were selected based on their relevance to office buildings and their frequency in energy audit recommendations. The selection also reflects practical feasibility, as the proposed measures are commonly implemented in Swedish renovation practice and were confirmed by the building owner as relevant and of interest. The measures include improvements to ventilation systems, lighting, circulation pumps, windows, and roof insulation (Figure 6)

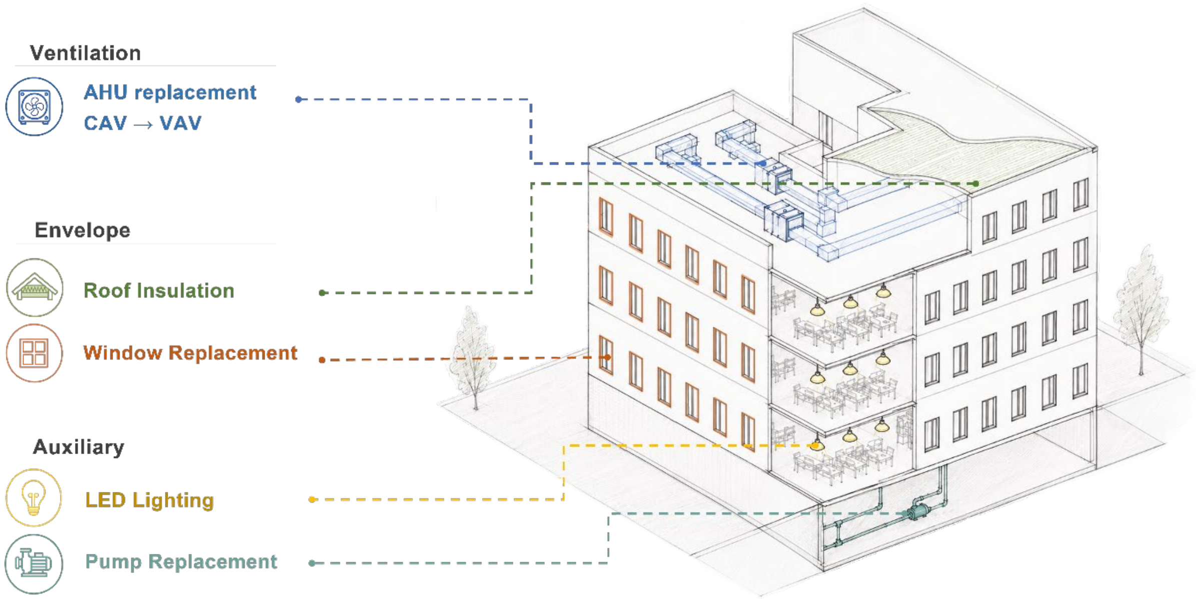

Figure 6 - Isometric illustration of the five energy renovation measures selected for implementation, spanning HVAC, building envelope, and auxiliary systems.

For mixed-use buildings, renovation measures were applied selectively based on functional use. In the case of Building B, measures were applied only to office areas, corresponding to approximately 84 % of the total heated floor area. The remaining 16 %, consisting of retails, was excluded from the renovation scenarios due to differences in usage patterns, operational requirements, and system characteristics. In contrast, Building A consists entirely of office space, and therefore all renovation measures were applied to the full heated floor area.

4.6.2 Envelope renovation measures

Envelope-related measures were limited to window replacement and additional roof insulation.

Roof insulation
An additional 300 mm layer of insulation with a thermal conductivity of 0.04 W/(m²·K) was applied to the roof structure, resulting in an increase in thermal resistance of approximately 7.5 (m²·K)/W. Mineral wool (glass wool or rock wool), commonly used in Nordic climates due to its good thermal performance and fire resistance, was assumed. Based on cost data from the Wikells database, installation constitutes a significant share of total costs; therefore, lower insulation thicknesses were not considered economically justified (Wikells Byggberäkningar AB 2026).

Window replacement
No evidence of window replacement was identified for either Building A or Building B, based on available documentation and construction permits. Therefore, window replacement was included as a renovation measure. To account for different initial conditions, windows with varying thermal properties were selected from the adjusted cases for each building.

Given the historical value of both buildings, it was assumed that new windows would match the existing frame design and colour. Accordingly, the existing windows were replaced with triple-glazed units, reducing the thermal transmittance to 0.9 W/(m²·K).

Windows and doors can represent a significant source of air leakage in buildings, contributing approximately 6–22 % of total infiltration (Martín-Garín et al. 2020). Therefore, in the window renovation scenario, a moderate reduction in infiltration of 10 % was assumed. This value was adopted as a conservative modelling assumption, acknowledging that the actual improvement in airtightness depends on installation quality and detailing.

4.6.3 Auxiliary Renovations

Auxiliary renovation measures include circulation pump replacement and lighting improvement.

Circulation pump replacement
Circulation pumps for space heating and domestic hot water were replaced with high-efficiency units. The effect of this measure was assessed by reducing the corresponding electricity use in accordance with the improved pump efficiency.

An efficiency of 0.6 was assumed for the existing pump, based on typical values reported in engineering practice to reflect performance degradation in older systems, whereas an efficiency of 0.8 was adopted for the new pump in accordance with manufacturer specifications (Grundfos 2026).

The circulation pump for the space-heating system was sized based on the peak heating load from simulation. The required water flow rate was determined using Equation (12):

$$\dot{V} = \frac{\dot{Q}_{peak}}{\rho \, c_p \, \Delta T} \tag{12}$$

where $\dot{V}$ is the volumetric flow rate in m³/s, $\dot{Q}_{peak}$ is the peak heating load in W, ρ is the density of water in kg/m³, c_p is the specific heat capacity of water in J/(kg·K), and ΔT is the temperature difference across the heating system in K. The required pump capacity was then defined based on the calculated design flow rate, and an assumed pressure rise for the system (40 Kpa). Pumps were selected using the online tool of Grundfos (Grundfos Product Center 2026).

For the domestic hot water, it was not possible to determine the circulation pump size based on the available data. Therefore, a typical circulation pump was selected based on the size and function of the building.

Lighting replacement

The existing lighting system was replaced with a more efficient LED-based solution. In addition, the measure was introduced to ensure a consistent representation of internal gains within the renovation cases of the energy simulation model.

The baseline lighting system was assumed to consist primarily of T8 fluorescent lamps, which represent a common technology in existing office buildings and are frequently associated with higher replacement costs and lower efficiency compared to modern systems.

For the renovation scenario, a full replacement with LED lighting fixtures was assumed. The estimation of lighting demand was based on assumed zoning of the office space and standard illuminance requirements derived from SS-EN 12464-1:2021(CEN; SIS 2021). To translate illuminance requirements (lux) into installed lighting power, a value of 80 lm/W was assumed for the baseline fluorescent system, representing the lower bound of typical T8 fluorescent efficacy (*Summary of Linear (T8) LED Lamp Testing* 2014); while 117 lm/W was used for the LED renovation case based on manufacturer data. Table 9 presents the assumed zoning and illuminance requirements applied in this estimation.

Table 9 - Assumed zoning of office space and illuminance requirements based on SS-EN 12464-1:2021

Zone	Share of Total Area / %	Illuminance Requirement / lx
Workstations	70	500
Circulation	20	300
Storage / Support	10	200

To ensure consistency between the lighting renovation measure and the baseline energy model, the resulting installed lighting power density (W/m²) was compared against the Sveby reference values used for internal gains in the baseline simulation (5.30 W/m²). This comparison was necessary because the simulation model requires lighting to be defined as an internal load, and any modification to lighting efficiency directly affects both electricity use and internal heat gains. Accordingly, the calculated lighting power for both baseline and renovation cases was aligned with the Sveby-based internal load assumptions used in the model.

4.6.4 HVAC system

Office buildings are characterized by high ventilation demands, long and regular operating hours, and a major share of property electricity use. Consequently, measures targeting HVAC systems and electricity use are particularly relevant. The replacement of AHUs and the transition from CAV to VAV systems improve both ventilation efficiency and operational control. Enhanced fan efficiency and HR efficiency are inherently included in the AHU replacement.

Ventilation renovation was evaluated at two levels of intervention, distinguished by whether the existing AHU was retained or replaced. The first level, VAV conversion, focuses on upgrading the airflow control strategy while keeping the existing AHU in place. The second level, AHU replacement, involves full unit substitution with improved HR efficiency and fan performance, evaluated under both CAV and VAV operation. Together, these two levels form a progression from lower to higher intervention, allowing the energy impact of each step to be assessed independently and in combination. The two intervention levels and their sub-cases are illustrated in Figure 7.

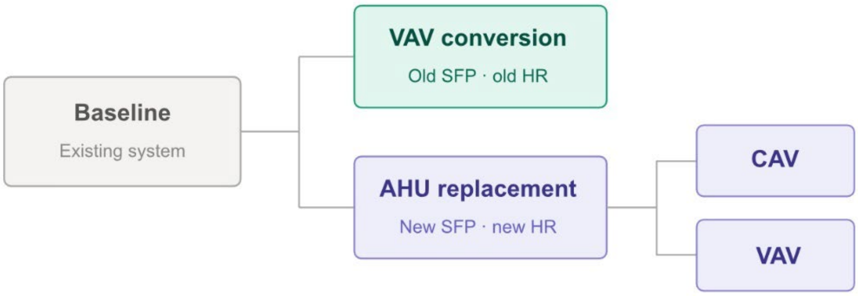

Figure 7 - Ventilation renovation framework showing the two levels of intervention: VAV conversion of the existing AHU and full AHU replacement under CAV and VAV operation

VAV Conversion of existing AHUs

In this approach, the existing AHU was retained, and the system was converted from CAV to VAV operation. Implementing VAV required the addition of control dampers and fan replacement in all cases. Rather than replacing diffusers, airflow control to the occupied zones was achieved through control dampers, which regulated airflow distribution in response to occupancy schedule. Fan replacement included a variable frequency drive (VFD) to enable variable speed operation.

Although fans were replaced as part of this measure, the SFP was maintained at the same level as in the baseline model. This reflected the fact that overall system performance remained constrained by the existing ductwork, pressure losses, and AHU configuration, which limited the achievable reduction in system-level SFP despite improved fan components.

Airflow rates were defined according to occupancy schedule: during unoccupied periods airflow was reduced to a minimum hygienic level of 0.1 $l/(s \cdot m^2)$ to maintain basic air quality while limiting ventilation-related heat losses. For occupied periods, airflow rates were defined per building based on their respective baseline conditions and are described in the building-specific sections below.

AHU replacement

In this approach, the existing AHU was fully replaced. All AHU replacement scenarios assumed an improvement in HR efficiency to 85%. New SFP values were derived using manufacturer-based AHU design tools (Swegon Group AB 2025), combined with assumptions on pressure distribution between the AHU and the existing duct system. Based on literature values (Nilsson 1995), approximately 60% of total pressure drop was attributed to ductwork, allowing the total pressure drop to be scaled consistently with the existing building conditions.

Each replacement scenario was evaluated under both CAV and VAV operation, resulting in two sub-cases per replacement configuration:

- AHU replacement - CAV: new unit operating at constant airflow.

- AHU replacement - VAV: new unit with variable airflow control, with control dampers and VFD added following the same approach as described in the VAV conversion scenarios above.

Application to case building

Building A was served by two AHUs, an attic unit and a main unit, which allowed the replacement measure to be staged. Three replacement configurations were evaluated: replacing only the attic AHU, replacing only the main AHU, and replacing both units simultaneously. Each configuration was assessed under both CAV and VAV operation.

For this building the airflow stated by the EPC and applied during the fitting process was 0.66 l/(s·m²). To ensure compliance with regulatory requirements, the required airflow was recalculated. According to BBR, the minimum requirement is 0.35 l/(s·m²), while the Swedish Work Environment Authority (Arbetsmiljöverket) requires 7 l/s per person. When recalculated based on area, assuming an occupancy density of 0.05 persons per m² from Sveby, the required airflow becomes 0.7 l/(s·m²). Therefore, this value was used in the renovation scenarios.

Combined with the VAV conversion scenario, this resulted in the following renovation packages for Building A:

- VAV conversion (existing AHU, fans replaced)
- Attic AHU replacement (CAV & VAV)
- Main AHU replacement (CAV & VAV)
- Full AHU replacement (CAV & VAV)

The corresponding parameters for Building A are presented in Table 10.

Table 10 - Ventilation renovation parameters, Building A.

System	Scenario	**SFP** / (kW/(m³/s))	**External static pressure ductwork** / kPa
Main AHU	AHU replacement	2.1	0.9
Attic AHU	AHU replacement	1.4	0.4

The ventilation system of Building B was served by a single AHU covering the office area, and renovation was applied to that unit only, in accordance with the scope defined in Section 4.6.1. Due to uncertainties in the baseline airflow conditions, a simplified approach was adopted.

Due to inconsistencies in the documented airflow values for Building B, neither value was considered directly applicable to the office renovation scenarios. The EPC value of 1.0 l/(s·m²) represents a weighted average across all building functions including retail areas and is therefore not representative of office spaces alone, while OVK inspection notes indicated that the main system was not operating at maximum capacity during measurement. A value of 0.8 l/(s·m²) was therefore adopted as an engineering judgement for the office renovation scenarios. Although 0.7 l/(s·m²) represents the minimum requirement in accordance with the occupancy density assumptions from Sveby, this higher value was selected to provide flexibility for potential future changes in airflow requirements.

The corresponding parameters of AHU for Building B are presented in Table 11. The renovation scenarios for Building B therefore include:

- VAV conversion (existing AHU, fans replaced)
- AHU replacement with improved HR efficiency and SFP,
- AHU replacement combined with VAV conversion

Table 11 - Ventilation renovation parameters, Building B.

System	Scenario	**SFP/** (kW/(m³/s))	**External static pressure - Duct work/** kPa
Main AHU	Replacement	2	0.9

4.7 Parametric framework of renovation

To evaluate the various renovation combinations, a parametric simulation workflow was developed within the GH environment utilizing HB and Colibri components. All proposed renovation measures were combined into a single script. For Building A, this approach resulted in the generation of 128 improved cases, while Building B involved 64 cases; the difference in the number of combinations was due to the replacement of AHUs in Building A being modelled in three steps. The Colibri components were utilized to automate the simulation of every possible combination of these parameters, which variables such as HR efficiency, SFP, and infiltration rates were adjusted based on the specific properties of each package. Also, the script integrated economic calculations to determine the investment costs and operational energy costs for every iteration. All simulated data, encompassing energy demand across different categories as well as annual energy and investment costs, were exported to an Excel file for subsequent analysis.

4.8 Economic evaluation

4.8.1 Economic framework and assumptions

The economic analysis in this study deliberately adopts a simplified framework in which economic uncertainties such as discount rates, inflation, and future energy price escalation are excluded. This methodological choice is made in direct support of the research aim, which is to identify patterns in the technical and economic performance of renovation measures in relation to the function, as-used, and physical condition of the building, rather than to produce a financial forecast for a specific investor. Introducing economic uncertainties into the present analysis would therefore risk obscuring the physical and operational-based effects of the renovation measures.

The approach is consistent with established practice at the comparative and screening stage of renovation analysis. Boverket (Boverket 2026b) identifies simplified cost-effectiveness indicators as appropriate tools for the early-stage ranking of renovation alternatives. The BELOK Totalmetodiken (BELOK 2013), widely applied in the energy renovation of Swedish non-residential buildings, similarly relies on a framework in which annual savings are treated as constant and energy prices are taken at their present level.

Therefore, annual cost savings are assumed to be constant over time, reflecting steady-state operation of each measure at current energy prices. Accordingly, all economic indicators in this study are evaluated on an annual basis, without discounting applied.

4.8.2 Investment cost

The cost estimation in this project is primarily based on data from Wikells Sektionsfakta, an online database widely used in the Swedish construction sector (Wikells Byggberäkningar AB 2026). This database was used as the main source for cost data throughout the project. In cases where products with the specified technical requirements were not available within the database, price information was supplemented using data from online retailers.

The investment cost for roof insulation, including both material and installation, was obtained from the Wikells and set at 721 SEK/m². Similarly, the cost for window replacement was derived from the same source, with a value of 5 117 SEK/m² covering both material and installation.

Pump costs were based on the selected models from online retailers, while installation and auxiliary equipment costs were obtained from the Wikells database as shown in Table 12.

Table 12 - Investment required for circulation pump replacement.

Pump application	Building A, cost/SEK	Building B , cost/SEK
Domestic hot water circulation pump	10 863	10 863
District heating circulation pump	14 935	18 052

Lighting investment costs were estimated based on the number of lighting fixtures replaced and a selected unit cost per LED lamp. The quantity was derived from the assumed lighting layout used in the lighting calculation. The renovation case assumed full replacement with simple LED bulbs, using a representative luminous efficacy of 117 lm/W based on supplier data. No separate installation cost was included for lighting replacement, as this measure was assumed to be implementable within routine property maintenance (Table 13).

Table 13 - Investment required for improved lighting system

Case	Cost/ (SEK/st)	Quantity/ units	Total Cost/ SEK
Building A	40	376	15 040
Building B	40	717	28 680

Note: Lighting electricity is reported as a reduction in total electricity use. Due to the difficulty of distinguishing between property electricity (fastighetsel) and tenant-related electricity (verksamhetsel), the saving could not be allocated to a specific electricity category.

For ventilation measures, different estimation approaches were required depending on the type of intervention. For full AHU replacement, unit prices were based on selected AHU sizes corresponding to the required design airflow (Table 14).

Table 14 -Investment required for AHU replacement

System	Building A, cost/SEK	Building B, cost/SEK
Main AHU (900 l/s)	285 948	–
Attic AHU (200 l/s)	53 905	–
Main AHU (3000 l/s)	–	347 205

For Building B, the selected AHU size exceeds the estimated airflow requirement. This simplification was necessary due to the limited availability of cost data for AHUs matching the required capacity. As a result, the selected unit represents a conservative cost estimate for the replacement scenario.

For VAV systems, additional components were required, including VAV dampers and control systems. The number of dampers was estimated based on the number of diffusers derived from the airflow requirements documented in the OVK for each. A unit price of 5 693 SEK per damper was applied, sourced from manufacturer pricing (Swegon A/S 2026). Control system costs were set at 40 000 SEK per retrofitted AHU, representing a simplified estimate (Boverket 2026d).

In retrofit scenarios, where the existing AHUs were retained and adapted for VAV operation, the investment cost included fan replacement in addition to the dampers and control systems. Fan replacement costs were estimated based on available supplier data for systems compatible with variable airflow operation as shown in Table 15.

Table 15 - Investment required for fan replacement.

Component	Building A, cost/SEK	Building B, cost/SEK
Main AHU Fans (900 l/s) (2 fans)	37 288	–
Attic AHU Fans (200 l/s) (2 fans)	16 191	–
Main AHU Fans (2080 l/s) (2 fans)	–	75 105

4.8.3 Operational energy cost

Operational energy costs are calculated using fixed unit prices for the two energy carriers relevant to the studied buildings: district heating and electricity. A price of 1 SEK/kWh is applied to district heating and 2 SEK/kWh to electricity. These values are consistent with reported average prices for non-residential buildings in Sweden during the study period.

According to the annual Nils Holgersson report, the national average district heating price was approximately 0.97–1.12 SEK/kWh for 2023 and 2024 (Nils Holgersson-gruppen 2024), which is rounded to 1 SEK/kWh in this study. For electricity, Statistics Sweden (SCB) reports average prices for non-residential medium consumers in the range of 1.8–2.2 SEK/kWh during the same period (SCB 2024), supporting the adopted value of 2 SEK/kWh.

The electricity-to-district heating price ratio of approximately 2:1 reflects the structural difference between the two energy carriers in the Swedish market. Electricity prices include energy tax, grid fees, and supplier margin, while district heating prices are cost-based and unregulated, consistently resulting in a lower delivered cost per kWh for district heating in commercial buildings (Energimarknadsinspektionen (Ei) 2021).

Both prices are held constant across all simulated cases and buildings, consistent with the simplified economic framework described before.

4.8.4 Economic performance indicators

To assess the cost-effectiveness of renovation measures, below indicators were used in this study. Each indicator was calculated on an annual basis under the described economic framework, with constant energy prices and no discounting applied.

Annual Energy Saving quantifies the reduction in delivered energy demand resulting from a renovation measure. It is calculated as the difference between the simulated energy use of the baseline building and the simulated energy use after applying the measure. The indicator is expressed in kWh/(m²·yr) when evaluating individual building performance, and as percentage improvement (%) when comparing results across two buildings, calculated with Equation (13).

$$Annual\ Energy\ Saving\ (\%) = \frac{(E_{baseline} - E_{measure})}{E_{baseline}} \times\ 100 \tag{13}$$

Where $E_{baseline}$ and $E_{measure}$ are the annual specific energy use of the building before and after the measure, respectively.

Annual Cost Saving translates the energy saving into a monetary value by applying the constant energy prices for electricity and heating used in this study. The indicator is expressed in kSEK/yr.

Return on Investment expresses the annual economic return of a renovation measure relative to its total investment cost. In this study ROI is defined on an annual basis, consistent with the economic framework in which savings are constant over time. ROI was calculated with Equation (14).

$$ROI = \frac{Annual\ Cost\ Saving}{Investment} \times 100 \quad (14)$$

Where $Annual\ Cost\ Saving$ is expressed in SEK/yr and $Investment$ is the total investment cost of the measure in SEK. The indicator is expressed as a percentage (%) and can be interpreted as the fraction of the initial investment recovered through energy cost savings each year. A higher ROI indicates a more economically attractive measure relative to its cost.

Simple Payback Time is the time required for the cumulative annual cost savings to recover the initial investment, without accounting for the time value of money. It was calculated using Equation (15).

$$Simple\ Payback\ Time\ = \frac{Investment}{Annual\ Cost\ Saving} \quad (15)$$

Where $Investment$ is the total investment cost in SEK and Annual cost Saving is expressed in SEK/yr. The result is expressed in years. A measure is considered economically viable when its payback period is shorter than its expected useful lifespan.

The expected useful lifespan assigned to each renovation measure, used as the viability threshold for simple payback time evaluation, is summarised in Table 16. For LED lighting, the nominal manufacturer lifespan was recalculated based on the typical operating hours of office function (Signify N.V. 2024). Ventilation components, window and ump were assigned lifespan values from Annex D of SS-EN 15459-1:2017 (Swedish Institute for Standards 2017).

Table 16 - Expected useful lifespan of renovation measures.

Measure	Expected lifespan / years	Source or reference standard
LED lighting	5	EPD
Ventilation equipment	20	SS-EN 15459-1:2017
Insulation	50	(Boverket 2026c)
Circulation Pump	15	SS-EN 15459-1:2017
Window	30	SS-EN 15459-1:2017

4.9 Result analysis

The results are presented in three parts. The first two parts address Building A and Building B separately, following the same structure. The third part brings both buildings together for direct comparison, using one representative case per building. The structure of result presentation can be seen in Figure 8.

Individual measures
For each building, the analysis begins with an assessment of individual renovation measures in isolation. The graphs present the annual energy saving and the simple payback time for each measure across the three adjusted cases, allowing the energy and economic performance of each intervention to be evaluated independently.

Renovation packages
The package-level assessment is structured in three steps. First, the investment versus annual energy saving is shown for all simulated combinations, 128 cases for Building A and 64 cases for Building B.

Three scatter plots are presented per building, each highlighting a different dimension of the package composition: pump and lighting conditions, envelope conditions, and ventilation system conditions. Second, the Pareto front for each building is presented, combining all three adjusted cases in a single graph to identify the most effective renovation combinations. Third, a profitability diagram presents the cumulative economic performance of measures added sequentially in order of descending ROI, as described in section 4.9.1.

Cross-building comparison
The final part compares both buildings using one representative case per building. The same sequence is followed: individual measures, Pareto front comparison, and the profitability diagram.

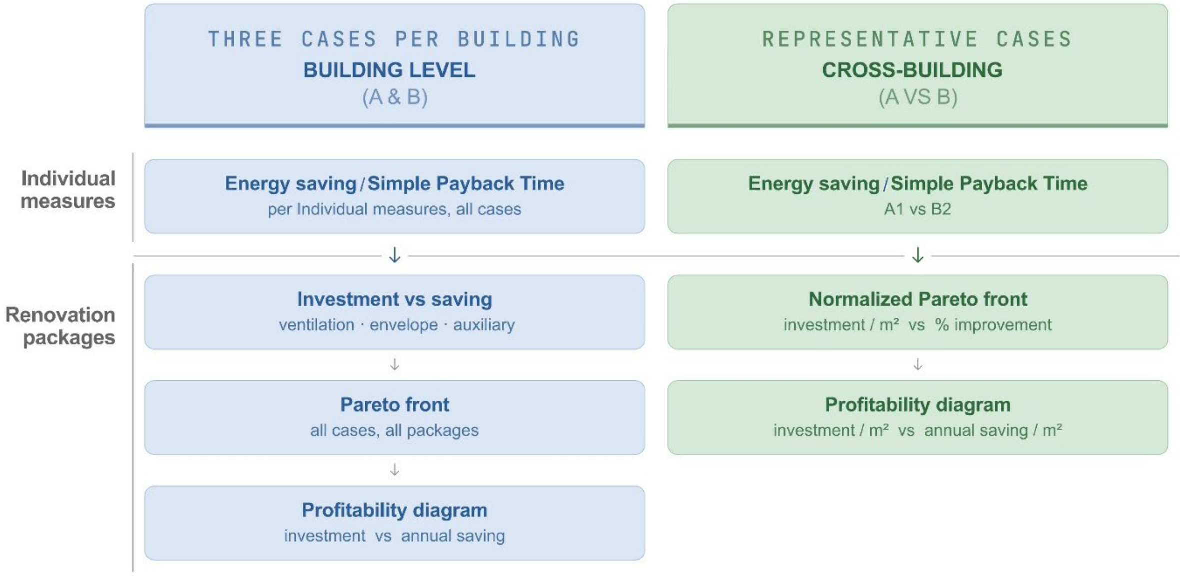

Figure 8 - Structure of result presentation in building-level and cross-building level

4.9.1 Package-level profitability assessment

To evaluate the economic viability of integrated renovation strategies, this study utilizes the profitability diagram framework established by the Swedish Totalmetodiken (BELOK 2026). This method facilitates the assessment of a "total package" of measures by evaluating its IRR against a required threshold.

The diagram's reference grid is constructed using the annuity factor $\mathrm{P}(\mathrm{r},\mathrm{n})$ with Equation (16) (BELOK 2013):

$$P(r,n) = \frac{r}{1 - (1 + r)^{-n}} \qquad (16)$$

Where $P(r,n)$ is the annuity factor, r is the required rate of return, and n is the lifespan of the measures in years.

In this framework, the cumulative annual cost saving S in SEK/yr is determined by the investment of the package I in SEK and the annuity factor $P(r,n)$, as shown in Equation (17):

$$S = I \cdot P(r,n) \tag{17}$$

Each reference line in the diagram acts as a benchmark for the IRR, where steeper lines indicate higher profitability and faster investment recovery relative to the lifespan. A renovation curve situated above a specific line demonstrates that the package meets or exceeds that return threshold, while falling below a line indicates that the cumulative investment no longer satisfies the required interest rate.

A cumulative curve is generated by adding renovation measures sequentially in descending order of marginal ROI. To maintain accuracy as the package composition changes, the weighted average lifespan is recalculated at each step, since different lifespans were assumed for the measures.

By plotting the cumulative investment against annual savings, the resulting curve illustrates the effective IRR of the package at each stage of assembly. This allows for the identification of the economic limit, the point where adding further measures drives the total package return below the owner's required interest rate.

4.10 Limitations

Building Selection and Category Justification

Single city and typology: Both buildings are centrally located in Stockholm and share a similar construction age, dating from the late nineteenth century. Results reflect a specific urban and climatic context, and the building age influences key modelling decisions, particularly the baseline *U*-values for the wall and windows. Findings may not generalise to office buildings of different construction periods or in other Swedish cities.

Adiabatic boundary conditions: Both buildings share party walls with adjacent structures, modelled as perfectly adiabatic. This structurally reduces envelope heat losses relative to freestanding buildings, which limits the representativeness of envelope measure results for isolated or semi-detached buildings.

Two-building sample: Conclusions regarding measure ranking are based on two buildings. No statistical inference about the broader Swedish office stock can be drawn. The framework is intended as a replicable methodology, not a statistically representative survey.

Building Modelling and Input Data

Roof simplification: The thesis includes analysis of roof insulation the simplification of the pitched roof to a flat surface. A pitched roof would introduce a larger surface area and varied surface orientation compared to a flat roof, which may influence the modelled heat loss through the roof assembly. Results related to roof insulation performance should therefore be interpreted with this geometric simplification in mind.

Window-to-wall ratio uncertainty: WWR was estimated from historical drawings, and no uncertainty range was propagated for this parameter, despite its direct interaction with window *U*-value, which was treated as a fitting variable. The resulting interplay between these two sources of uncertainty is unacknowledged.

Model Fitting

OFAT interaction effects: The one-factor-at-a-time screening approach does not capture interaction effects between parameters. For example: Airflow rate and heat recovery efficiency interact directly in determining ventilation heat losses; their combined influence cannot be characterised by independent variation.

Weather file limitation: The measured energy data provided for both buildings included a climate correction factor applied by the data supplier, partially accounting for deviations between the measurement year and a reference climate. However, no corresponding normalisation was applied to the IWEC typical meteorological year file used for energy simulation. This means the model fitting process was performed between climate-corrected measured data and TMY-based simulation results, which may introduce a residual systematic offset in absolute heating demand. Relative comparisons between renovation scenarios remain unaffected, as all cases share the same simulation boundary conditions.

Asymmetric filtering between buildings: A secondary monthly consistency filter of ±15 % for model fitting, was applied beyond ASHRAE Guideline 14 criteria for Building A but had to be abandoned for Building B, as no cases satisfied it. The adjusted cases for Building B therefore carry greater residual uncertainty, representing an inconsistency in the rigour of accepted models across the two cases.

Equifinality: The fitting process does not yield a unique solution. Multiple parameter combinations satisfied the acceptance criteria, and the three representative cases per building are conditional approximations of plausible building states rather than verified physical descriptions. Renovation savings are predicted from these approximations, introducing uncertainty that is bounded but not formally quantified.

Ventilation System Representation

Continuous operation assumption: The OVK protocols available contained mandatory fields for AHU operating schedules (drifttimmar/vecka) that were largely incomplete, providing no reliable basis for establishing actual operating hours. Continuous operation at 8 760 hours per year was therefore adopted based on engineering judgement informed by the age of the installed equipment. This highlights a broader limitation of relying on OVK protocols as a data source for energy modelling of older building stock.

Fan electricity use: The estimation of fan electricity use was subject to limited precision due to inconsistencies and gaps in the available OVK documentation. Where measured or projected fan performance data were incomplete or unreliable, SFP values were derived from literature-based assumptions or regulatory thresholds, which introduces uncertainty in the absolute fan electricity estimates. Additionally, SFP characterises fan performance at a single design operating point and does not capture efficiency variations across the full range of operating conditions, which is particularly relevant for VAV scenarios. The approach is considered appropriate for the comparative purposes of this study, but absolute fan energy estimates should be interpreted with this limitation in mind.

Renovation Measures

AHU Investment cost: Renovation measures involving AHU replacement should be considered with attention to the practical difficulties associated with removing and installing such large equipment. In some cases, this may require structural interventions or modifications to the roof, particularly when the units are located in attic spaces. For historic buildings subject to preservation requirements, such interventions may be restricted or not feasible at all.

Lighting system: The lighting analysis represents a simplified estimation. Factors such as utilisation factor, maintenance factor, daylight availability, lighting controls, and detailed luminaire layout were not explicitly accounted for, and the assumed distribution of space functions introduces additional uncertainty. The baseline was assumed to consist entirely of fluorescent lamps, and the renovation was assumed to involve simple LED lamp replacement carried out as part of routine maintenance. More elaborate lighting designs would imply higher investment costs and potentially different electricity use. Furthermore, due to the difficulty of distinguishing between property electricity (fastighetsel) and tenant-related electricity (verksamhetsel) in the available data, the impact of the lighting renovation was evaluated as a reduction in total electricity use rather than being allocated to a specific category.

Pump Electricity use: No data was available regarding electricity use or technical system of circulation pumps. The estimation of pump electricity use was based on statistical reference values, literature-based assumptions on pump efficiency accounting for degradation of older units, and manufacturer data for new pumps. The actual performance of the existing pumps may differ from these assumptions, as it depends on operating conditions and the actual state of degradation. The results related to pump replacement should therefore be interpreted as indicative rather than precise.

Moisture safety: A moisture safety analysis is recommended to be conducted before implementing the roof insulation measure. However, such an analysis was not carried out in this study, as it falls outside the project scope. In addition, the detailed technical data on the existing roof structure required for such an assessment was not available.

Thermal comfort: According to the available documentation, no cooling system is installed in the building. Thermal comfort and overheating risk were not investigated in this study. Instead, the analysis focused on ensuring that the ventilation system provides airflow rates compliant with the regulatory requirements for office buildings.

Economic Evaluation

Economic Framework: As outlined in the economic assumptions, the adopted approach is optimised for identifying technical patterns and focuses on the comparability of renovation measures, without accounting for time-varying energy prices, discount rates, or maintenance costs. The resulting numerical values should therefore not be interpreted as a direct indication of real-world financial feasibility for a specific building renovation project, nor as an investment recommendation.

Fixed energy price ratio: A fixed electricity-to-district heating price ratio of 2:1 was assumed. This ratio directly determines the relative economic ranking of electricity-saving versus heat-saving measures and has varied substantially in recent years. No sensitivity analysis to energy price assumptions was carried out, meaning the ranking of measures by economic performance may shift under different market conditions.

Investment cost scope: Costs for tenant disruption, project design and management, permitting, transportation or demolition are excluded. These omissions systematically understate the real-world cost of measures requiring more extensive installation work.

No residual value or LCA: No residual value was assigned to renovation measures at the end of the analysis period, which further disadvantages capital-intensive, long-lifespan measures such as window replacement. No lifecycle assessment of embodied carbon or material impacts was performed; such an analysis would be necessary to evaluate the full environmental performance of the renovation packages beyond operational energy use.

Investment cost estimates: Several cost categories were excluded from the investment estimates, including demolition, removal of existing equipment, transport, structural adaptations, system balancing, and constraints related to heritage protection. For AHU replacement in particular, practical difficulties associated with removing and installing large equipment in attic spaces or historically protected buildings may significantly increase actual costs. The estimates should therefore be treated as comparative planning values rather than procurement-level figures.

5 Results and discussion

5.1 Selected building category and case studies

Office buildings were identified as the most appropriate category for further analysis of this study. They represent a high share of the non-residential stock both in terms of building count and total floor area, giving them a meaningful potential impact on aggregated energy use and on the achievement of national energy performance targets. In addition, offices are characterised by relatively homogeneous functional patterns, regular occupancy schedules, standardised internal loads, and commonly documented HVAC configurations, which support consistent modelling assumptions and reliable comparative analysis.

Following the criteria established in the Methods section, two office buildings were selected from the available dataset. The first selected building (Building A) fulfilled the primary selection criteria, including data availability, simple geometry, and sufficient documentation of technical systems.

The selection of the second case study required additional consideration, as not all candidate buildings fully satisfied the defined criteria. Encountered challenges included incomplete system documentation, inconsistencies between available data sources, and uncertainty regarding the presence and configuration of certain technical systems, such as cooling. These limitations introduced uncertainty regarding the suitability of the candidates for detailed energy modelling, and the final selection therefore, involved a higher degree of compromise between representativeness and data reliability.

Despite these constraints, Building B was deemed sufficient for the purposes of this study. Compared to Building A, it is characterised by a more complex geometry and technical configuration, including higher recorded airflow rates and some variation in available documentation.

5.2 Model fitting result

5.2.1 Sensitivity screening

The sensitivity analysis reveals that the parameters identified as impactful are mostly consistent across both buildings, with the ventilation airflow rate, *U*-value of walls, and infiltration showing the highest overall effect on heating demand. Following the ±20 % sensitivity screening, parameters impacting the heating demand by more than 5 % were retained for the fitting step.

While most envelope-related parameters like thermal bridges and window *U*-values were impactful in both cases, two differences were noted, equipment load was impactful only in Building A, and HR efficiency was identified as an impactful parameter only for Building B, which can be justified by its initial low value in building A. The final selection of impactful parameters for each building is highlighted in blue in Table 17.

Table 17 - Results of the sensitivity screening, showing the relative impact of non-observable input parameters on annual heating demand. Parameters highlighted in blue were identified as impactful.

Input	**Effect on heating demand / %**	
	Building A	Building B
Infiltration	6.16	10.13
Thermal bridge	5.08	6.73
U-value wall	7.70	10.38
U-value roof	1.94	1.38
U-value window	5.48	9.10
Lighting load	3.08	2.58
Equipment load	5.84	3.78
People density	1.10	0.79
Occupancy schedule	0.54	2.67
Airflow	25.34	11.53
HR efficiency	3.34	20.83

5.2.2 Parametric simulation for model fitting

The parametric simulation of the impactful input parameters for Building A resulted in 1 080 cases. Applying the ASHRAE 14 acceptance criteria for CV(RMSE) and NMBE reduced the dataset to 60 cases. Further filtering based on a maximum monthly deviation of ±15 % resulted in a final set of 29 cases. As can be seen in Figure 9, the majority of all simulated cases are clustered in the over-prediction zone (negative NMBE). This signifies that the initial pool of parameter combinations resulted in a simulated heating demand that was higher than the actual measured demand.

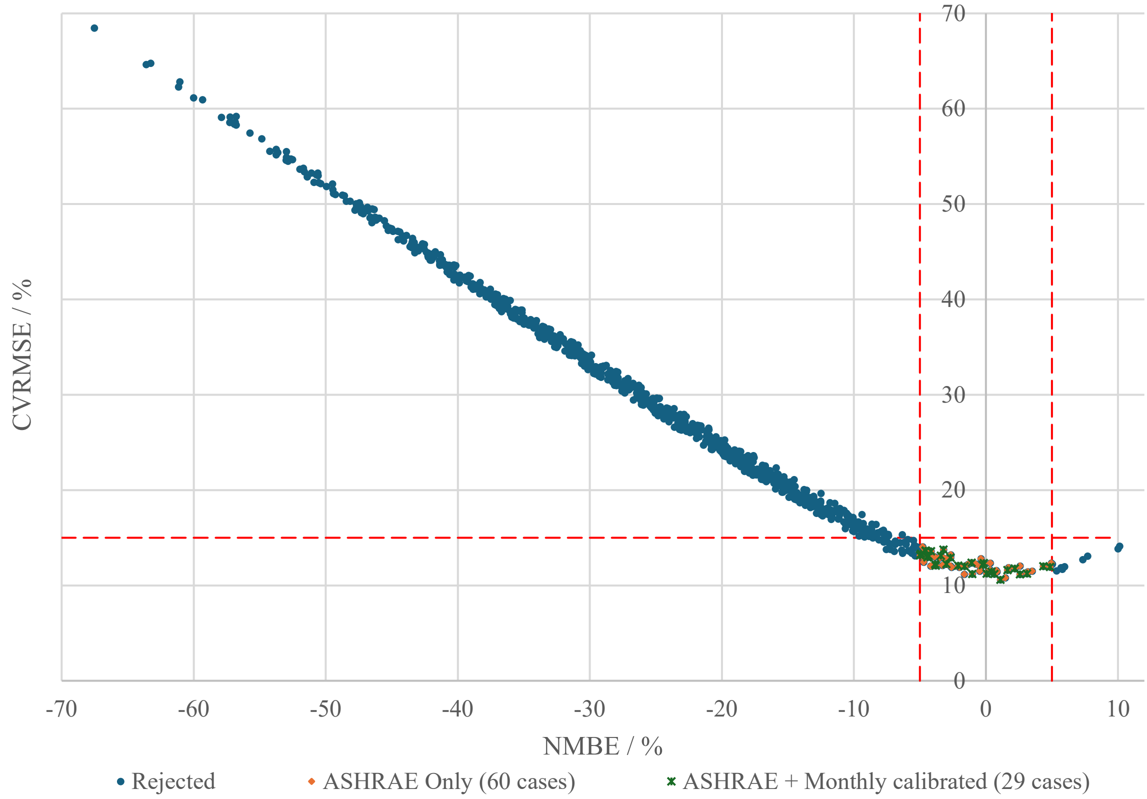

Figure 9 - An overview of 1080 cases for building A with relationship between CVRMSE (%) and NMBE (%).

The fitting of Building B was conducted using a targeted parametric framework as described in the method, resulting in a total of 132 simulated cases, prioritizing the analysis of ventilation airflow as a critical uncertain parameter. The simulation pool was divided between two scenarios, comprising 116 cases with the EPC-based airflow of 1.00 l/(s·m²) and 16 cases with the OVK-based projected airflow of 1.77 l/(s·m²). Applying the ASHRAE Guideline 14 criteria, the dataset was reduced to 19 successful cases, of which 16 belonged to the EPC group and 3 to the OVK group. The secondary filter proposed in method for maximum monthly deviations of 15 % was eliminated for Building B as no ASHRAE 14 accepted cases could pass this filter. It is important to note that, for the cases adjusted according to ASHRAE 14 criteria, the deviation in heating demand for September consistently remained within a range of 80 % – 100 %, whereas deviations for all other months were below 20 %.

The analysis further indicated that cases with an airflow rate of 1.77 l/(s·m²) only met the calibration criteria when combined with high HR efficiencies (70 % – 75 %) and the lowest *U*-values for walls and windows among the tested iterations. In contrast, the acceptable cases with an airflow rate of 1.00 l/(s·m²), typically had moderate *U*-values for walls and windows and HR efficiencies in the range of 55 % – 65 %.

5.2.3 Verification of property electricity baseline

Following the method, property electricity data was first extracted from statistical reports to create a baseline. Percentages for each end-user were then allocated based on total measured electricity. The allocated values of fan electricity were subsequently compared against the calculated value using Equation (10).

As illustrated in Table 18, the calculated fan electricity for Building A and Building B, with EPC-derived airflow, showed close alignment with the estimated values based on statistical allocations. This consistency confirms the reliability of the modelling assumptions adopted for the ventilation systems. In contrast, the fan electricity calculated for Building B using OVK-derived airflow resulted in values exceeding the total measured property electricity. Fitting process results for this case also included overly optimistic assumptions regarding HR efficiency and envelope *U*-values. Therefore, using fan electricity as an additional plausibility check to filter candidate solutions, it was determined that this scenario was not technically plausible. Consequently, adjusted cases based on OVK-derived airflow were excluded from the set of selected cases for the subsequent renovation analysis.

Regarding other categories, due to insufficient data, the weighted value of statistical data was used as the baseline for the next steps.

Table 18 - Baseline assessment of property electricity consumption, comparing estimated allocations based on measured data with calculated values for fan electricity (kWh/m²·yr).

Component	**Building A**		**Building B**	
	Estimated (% allocated)/ (kWh/(m²·yr))	Calculated/ (kWh/(m²·yr))	Estimated (% allocated)/ (kWh/(m²·yr))	Calculated/ (kWh/(m²·yr))
Fans	15.35	16.6	24.40	23.42 (air flow: 1.00 l/(s·m²)) 46.51 (air flow: 1.77 l/(s·m²))
Pumps	1.98	-	3.14	-
Elevators	1.28	-	2.03	-
Other	5.00	-	7.95	-
Total	23.60 (measured data)		37.53 (measured data)	

5.2.4 Addressing the gap under data uncertainty

The model fitting process followed a structured framework consisting of sensitivity screening, parametric simulation, and statistical evaluation against accepted criteria. For both buildings, cases satisfying the acceptance thresholds were identified, from which three representative cases per building were selected to reflect a range of plausible envelope and operational conditions.

Despite the efforts made in data collection and model fitting, limitations related to data availability, measurement uncertainty, and geometric simplifications remain. Therefore, as a natural characteristic of over-parameterised building energy models, model fitting does not yield a unique or physically correct representation of the building. The selected cases should thus be understood as conditional approximations, limited by available data, collectively representing a plausible solution space rather than an accurate physical and operational representation of the building.

Three cases per building were consequently retained for the subsequent renovation assessment to explicitly account for uncertainty in baseline conditions and to evaluate renovation measures across a range of plausible initial states.

5.2.5 Selection of fitted cases

For both Building A and Building B, cases were chosen to reflect varying envelope thermal properties. Specifically for Building B, the selection also prioritized a range of HR efficiency values. The specific parameters for each selected case are detailed in Table 19.

Table 19 - Final selection of fitted cases for Building A and Building B.

	Case	Infiltration rate/ (l/(s·m²$_{facade}$))	*U*-value Wall/ (W/(m²·K))	*U*-value Window/ (W/(m²·K))	HR efficiency/ %	Thermal bridge/ %
Building A	A1	0.25	1.00	1.30	12	25
	A2	0.31	0.59	2.20	12	20
	A3	0.25	0.80	2.20	12	20
Building B	B1	0.25	0.80	1.30	60	20
	B2	0.25	0.59	2.20	65	20
	B3	0.25	0.80	2.20	75	25

The selected cases were clustered around 12-14 % CV(RMSE), indicating moderate agreement with measured data.

Figure 10 presents the energy performance of the three selected cases for both Building A and Building B, where the baseline conditions of all cases remain comparable. While the heating demand varies across all scenarios, the differences between the three cases within each specific building remain relatively small. As mentioned in section 4.5.1, the model was fitted against measured space-heating energy of 120.0 kWh/(m²·yr) and 170.2 kWh/(m²·yr) for Building A and Building B respectively. For Building B, the baseline renovation cases show an approximately 26 kWh/(m²·yr) reduction compared to the fitted model, due to adjusting the airflow from 1.0 l/(s·m²) to 0.8 l/(s·m²) to reflect the office portion of the building only.

Values for equipment, lighting, and domestic hot water are constant across all cases, reflecting the use of identical simulation inputs for these parameters. Similarly, fan and pump electricity consumption are identical for the three cases of each building, as they are derived from the values established during the property electricity assessment.

It should be noted in the analysis section of the renovation results, when presenting results for individual cases per building, A1 and B2 are considered representative of Buildings A and B, respectively. Case A1 is selected as it represents a lower assumed envelope heat loss condition, with relatively low baseline window and wall *U*-values, which enables clearer isolation of system-level measure effects. Case B2 is selected as it represents an intermediate ventilation system configuration, with a HR efficiency of 65 %, allowing evaluation under moderate baseline performance.

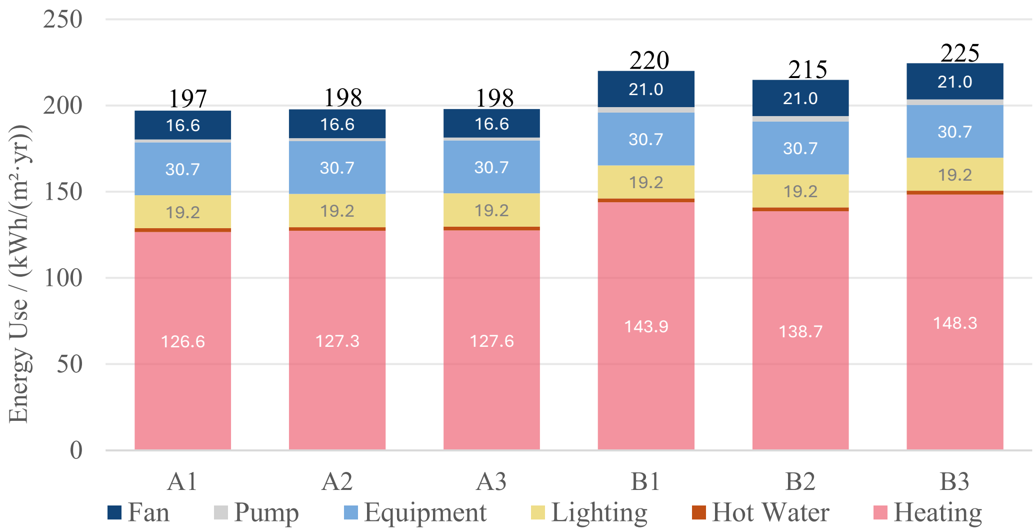

Figure 10 - Baseline final energy use of selected cases for building A and building B.

5.3 Energy and economic performance of renovation measures: within-building

This section presents the renovation results relative to these baseline cases. The analysis first examines the variation between cases within each building, before comparing the overall results between Building A and Building B.

The performance of renovation measures is evaluated in terms of their impact on annual energy use and their associated economic efficiency. The analysis is first conducted at the level of individual measures to assess their magnitude, variability across baseline cases, and sensitivity to modelling uncertainty. It is then extended to combined renovation packages to evaluate interactions between measures and identify cost-performance trade-offs.

5.3.1 Individual measures assessment

Energy performance within individual measures

The impact of individual renovation measures on energy performance improvement is first analysed within each building. Figure 11 and Figure 12 present the annual energy savings in absolute value (kWh/(m²·yr)) to allow direct comparison between cases.

In Building A (Figure 11), the results indicate a clear pattern. Measures targeting the ventilation system, VAV conversion, Main AHU replacement, and Both AHU replacement, deliver considerably higher energy savings than all other measures, with annual savings in the range of 68–73 kWh/(m²·yr). The remaining measures, envelope improvement and auxiliary measures, each contribute between 17 kWh/(m²·yr) for window replacement and less than 1 kWh/m²·yr in circulation pump replacement, forming a distinctly lower-performing group.

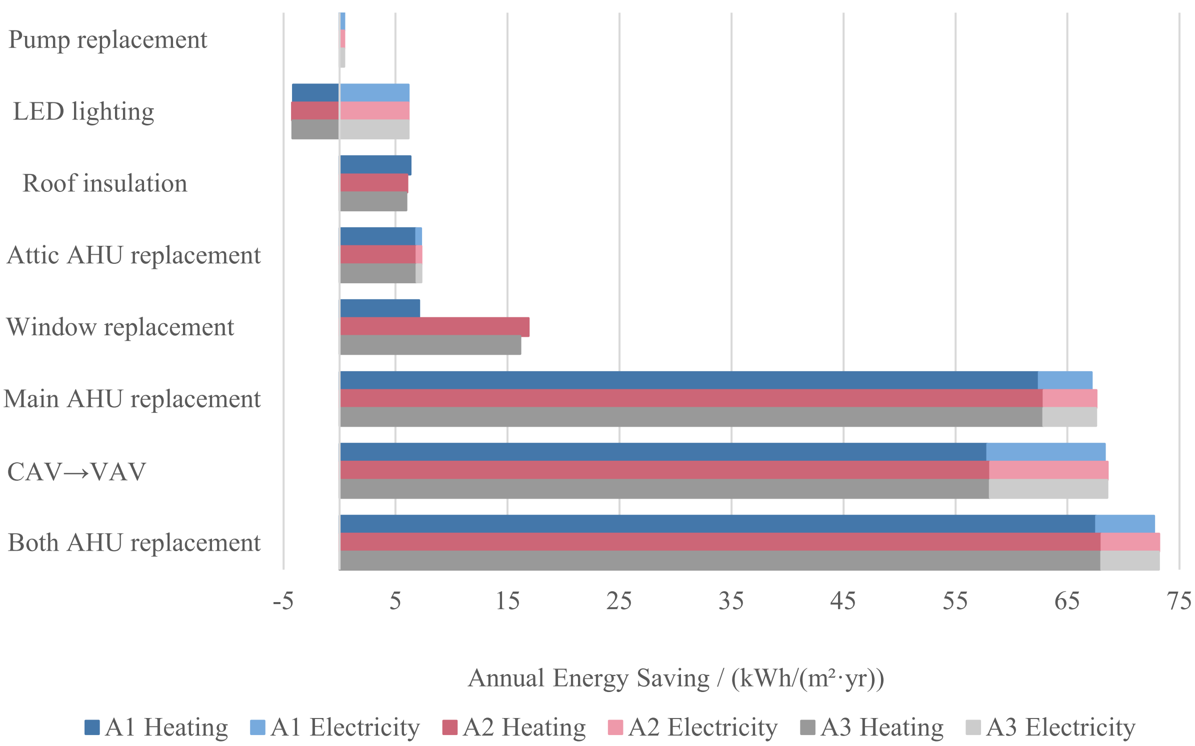

Figure 11 - Annual energy savings (kWh/(m²·yr)) for individual renovation measures in Building A across the baseline cases (A1–A3).

The variation between cases (A1–A3) is negligible for ventilation-related measures, with differences below 2 % across cases. CAV to VAV conversion consistently provides 58 kWh/(m²·yr) of heating savings and 10 kWh/(m²·yr) of electricity savings across all cases, while main AHU replacement yields 62–63 kWh/(m²·yr) reduction in heating demand and 5 kWh/(m²·yr) in electricity consumption. The low inter-case variability for ventilation measures is consistent with the similar AHU initial conditions assumed across cases, suggesting that these measures are largely insensitive to the envelope *U*-value uncertainties that differentiate cases A1–A3.

Window replacement shows the largest variation between cases, with savings ranging from approximately 7 to 17 kWh/(m²·y) from Case A1 to Cases A2 and A3. This reflects the dependence of envelope measures on baseline thermal performance. Roof insulation and attic AHU replacement provide consistent intermediate savings of 6–7 kWh/(m²·yr).

Auxiliary measures have a limited impact. LED lighting produces a reduction of 6 kWh/(m²·yr) in electricity but introduces a heating penalty of -4 kWh/(m²·yr), resulting in a net saving of approximately 2 kWh/(m²·yr). Pump replacement has less than 0.4 kWh/(m²·yr) electricity savings in all cases.

In Building B (Figure 12), a similar ranking of measures is observed where a clear separation between high-impact and low-impact measures is observable, although with greater variability across cases. CAV to VAV and AHU replacement delivers the highest savings, in the range of 17-44 kWh/(m²·yr), while roof insulation, LED lighting, and pump replacement each contribute less than 5 kWh/(m²·yr). Window replacement occupies an intermediate position, with savings varying considerably between cases.

CAV to VAV conversion provides total savings of 44–33 kWh/(m²·yr) for the three cases, combining heating reductions of 31–20 kWh/(m²·yr) with a consistent electricity saving of 13 kWh/(m²·yr). AHU replacement also shows high variation, with total savings across cases decreasing from 33.9 kWh/(m²·yr) in B1 to 17.2 kWh/(m²·yr) in B3. The pattern is consistent with the influence of baseline HR efficiency on the achievable improvement from AHU replacement.

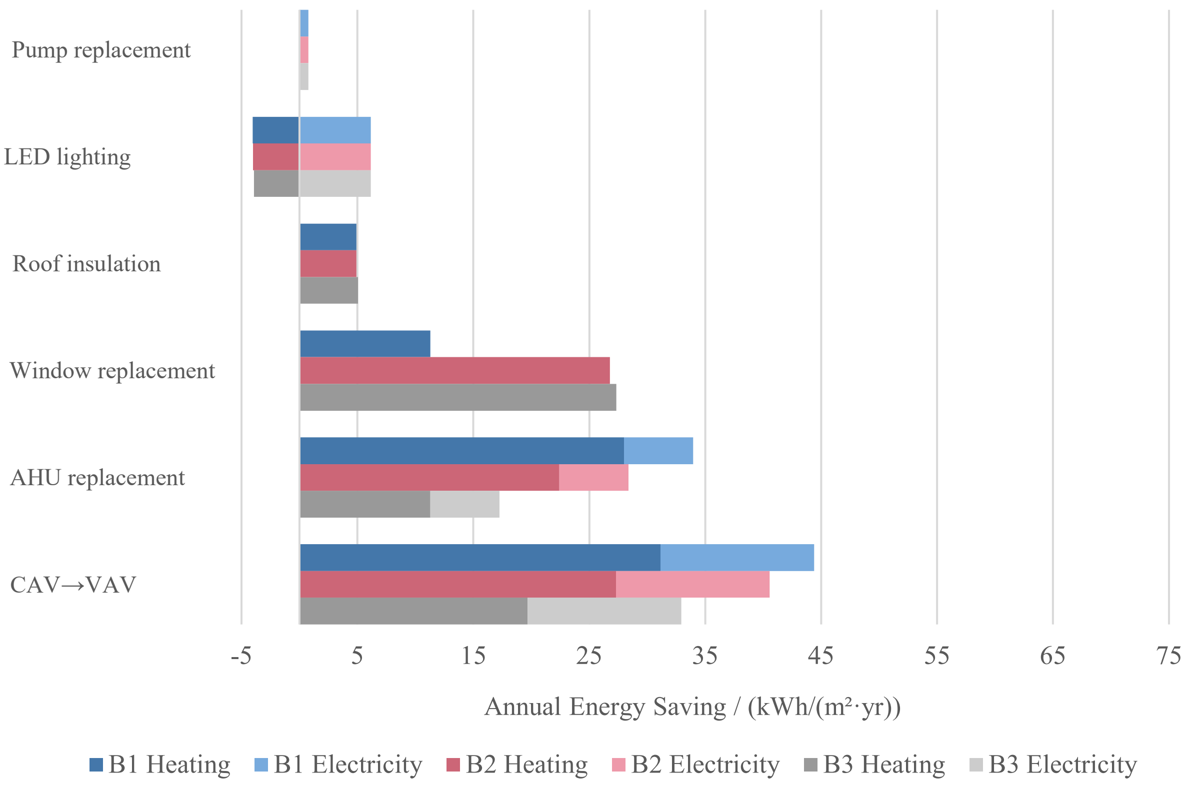

Figure 12 - Annual energy savings (kWh/(m²·yr)) for individual renovation measures in Building B across the baseline cases (B1–B3).

Window replacement exhibits a stronger role in Building B than in Building A, where provides 11 kWh/(m²·yr) in B1 and increases to approximately 27 kWh/(m²·yr) in B2 and B3, making it one of the most effective measures in those cases. Roof insulation remains consistent at approximately 5 kWh/(m²·yr).

LED lighting again produces a net saving of approximately 2 kWh/(m²·yr), combining reduced electricity use with increased heating demand and Pump replacement provides a small but consistent electricity saving of less than 1 kWh/(m²·yr) across all cases.

When comparing building A and building B, Overall ranking of measures by energy saving follows a broadly similar pattern, with ventilation-related measures dominating. The results demonstrate a clear hierarchy in which ventilation measures define the primary structure of energy savings, while envelope measures, particularly window replacement, provide secondary contributions and auxiliary measures have marginal impact.

Despite the similar ranking, the absolute savings differ considerably between the two buildings. Building A yields notably higher savings from ventilation measures, reaching approximately 73 kWh/(m²·yr) for Both AHU replacement and 67 kWh/(m²·yr) for CAV to VAV conversion, compared to 34 and 44 kWh/(m²·yr) respectively for Building B. This difference reflects the higher baseline ventilation heat losses in Building A, associated with its lower HR efficiency in the baseline model.

A consistent pattern across both buildings is the distinction between heating and electricity impacts. Envelope measures affect only heating demand, while ventilation-related measures primarily reduce heating demand with an additional contribution from reduced fan electricity. In contrast, LED lighting introduces a trade-off, where reductions in electricity use led to increased heating demand due to lower internal heat gains.

Economic viability of individual renovation measures

The economic viability of individual renovation measures was assessed using the simple payback time. Figure 13 presents the simple payback time for each measure across the three baseline cases for Building A. Measures with shorter bars represent faster cost recovery relative to their expected useful lifespan, whereas longer bars indicate that a higher investment is required relative to the achieved annual cost saving.

Ventilation measures consistently achieve the shortest payback times across all cases. Main AHU replacement, CAV to VAV conversion, and Both AHUs replacement each return payback times of approximately 3 years, well within their expected lifespan. Attic AHU replacement follows with a payback time of approximately 5 years. The consistency of these values across Cases A1, A2, and A3 reflects the limited sensitivity of ventilation measure viability to the assumed baseline condition.

LED lighting achieves the shortest payback time of all measures at 1.4 years, substantially below its assigned lifespan. However, as noted in previous section, its net energy saving is negligible due to the associated heating penalty, and its economic viability is driven primarily by its low investment cost rather than significant energy impact.

Roof insulation shows a payback time of approximately 20 years across cases, considered economically viable over the long lifespan of the material.

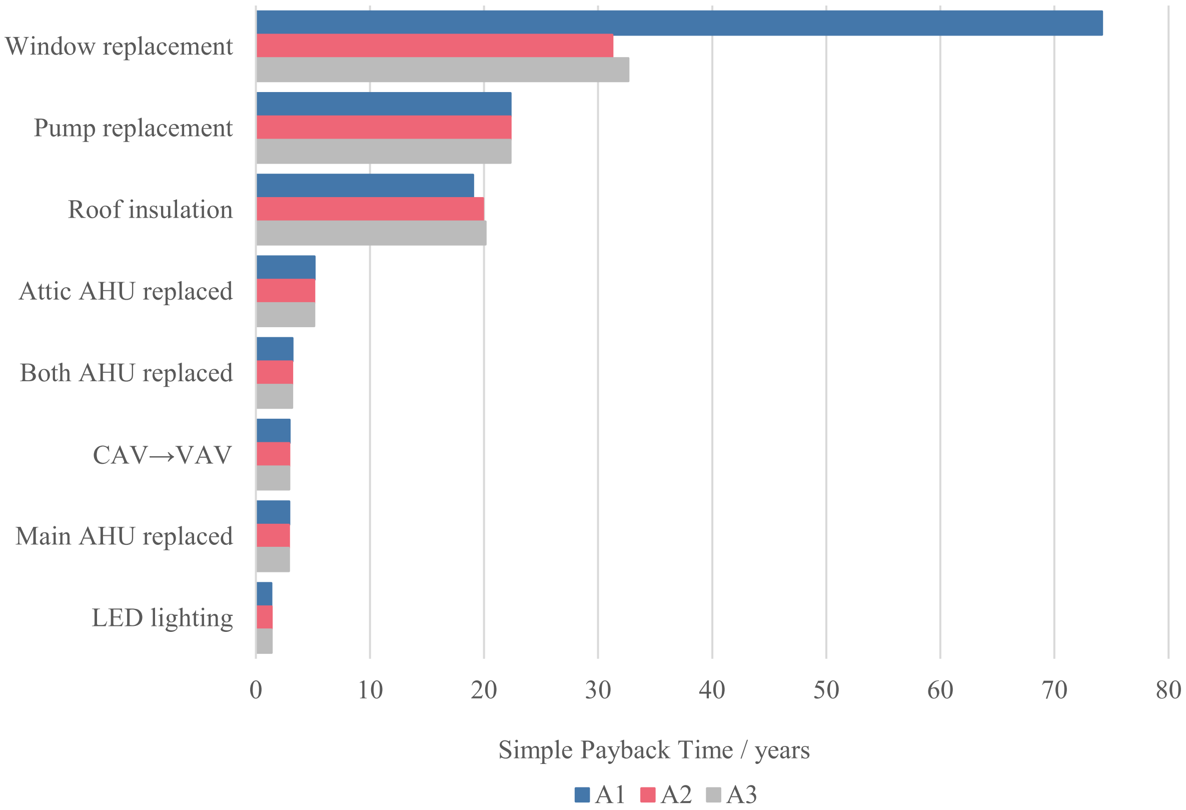

Figure 13 - Simple Payback Time (years) for individual renovation measures in Building A (A1-A3).

Pump replacement presents a payback time of approximately 22 years, which exceeds its expected lifetime of 10-20 years. This confirms that pump replacement is not economically viable as a standalone measure under the assumed conditions, indicating that low investment cost alone does not ensure cost-effectiveness when energy savings are negligible.

Window replacement exhibits the longest payback time and the greatest variability across cases. In Case A1, the payback time reaches 74 years, while in Cases A2 and A3 it falls to approximately 31–33 years. The shorter payback in Cases A2 and A3 reflects the stronger energy savings achievable when the baseline window U-value is higher; nevertheless, even under these conditions the payback time exceeds the assumed useful lifespan of 30 years, indicating that window replacement is not economically viable within the considered timeframe.

Figure 14 presents the simple payback time for each measure across the three cases for Building B. The overall ranking of measures in Building B follows the same pattern observed in Building A. Ventilation measures and LED lighting achieve the shortest payback times, roof insulation occupies the mid-range, and window replacement remains above its viability threshold across all cases.

CAV to VAV conversion and LED lighting return payback times of approximately 2–2.5 years and 1.3 year respectively, consistent with Building A. AHU replacement shows moderate variability across cases, ranging from approximately 3 years to 6 years across B1 to B3, reflecting the influence of the assumed baseline HR efficiency of the system.

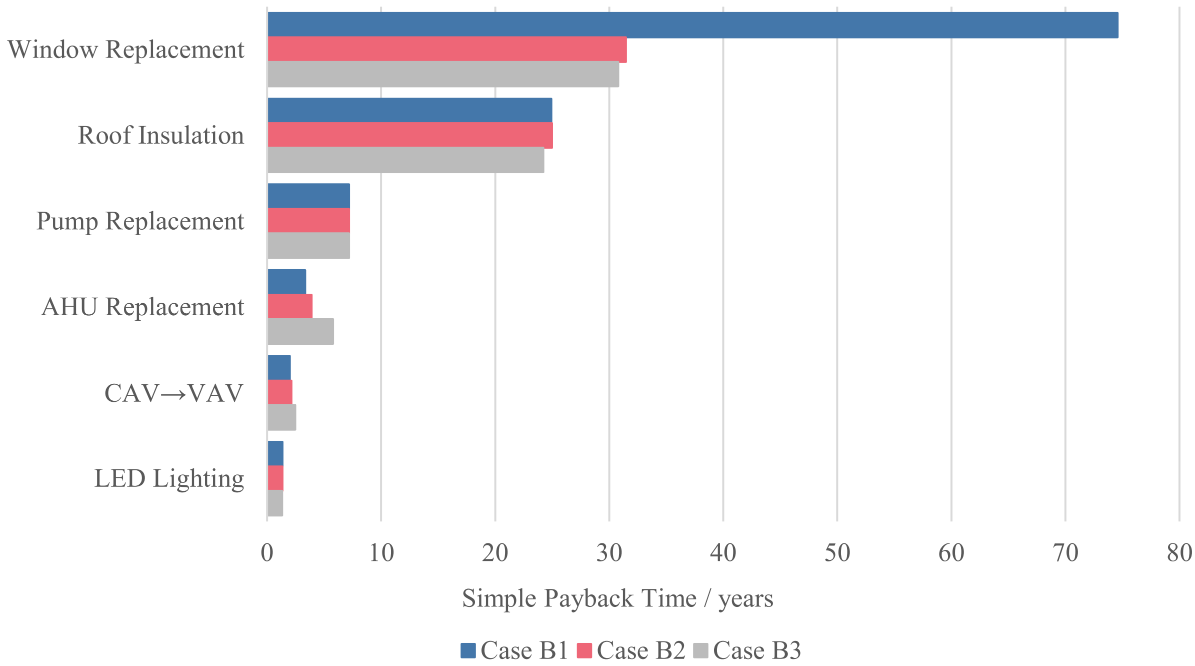

Figure 14 - Simple payback time (years) for individual renovation measures in Building B (B1-B3).

Roof insulation shows a payback time of approximately 25 years, remaining within its lifespan threshold, with low variability across cases as in Building A.

Pump replacement shows a payback time of approximately 6–7 years. Window replacement again exhibits the longest payback time and the greatest case sensitivity. In Case B1 the payback time reaches approximately 75 years. In Cases B2 and B3 it drops to approximately 31 years. Considering an expected lifespan of windows within 30, confirms that window replacement does not achieve economic viability as a standalone measure under any of the baseline conditions examined.

In both buildings, LED lighting and ventilation-related measures consistently achieve the lowest payback time, while envelope and pump replacement show higher payback times.

When combined with the energy results, ventilation measures emerge as both the most energy-efficient and cost-effective interventions. In contrast, envelope measures, particularly window replacement, achieve moderate to high energy savings but at significantly higher cost, resulting in lower economic efficiency.

The investment cost of a measure should not be the sole criterion for evaluating its economic attractiveness. As can be seen in Building A, pump replacement, despite its relatively low investment, delivers savings too small to recover its cost within its expected lifespan, making it an economically unviable measure under the conditions analysed.

5.3.2 Scatter plots of all simulated packages

The combined effect of renovation measures is analysed by relating total investment cost to achieved annual energy saving for one case per building, Building A is represented by case A1 and Building B by case B2. In Figure 15 and Figure 16, each point represents one simulated renovation package, comprising 128 combinations for Building A and 64 combinations for Building B.

Building A

Figure 15 presents the annual energy saving as a function of total investment for all 128 simulated renovation packages of Case A1. Marker colour indicates AHU condition, marker shape distinguishes ventilation control strategy (circle: CAV, triangle: VAV), a magenta border identifies packages with roof insulation added, and the left and right clusters distinguish packages with existing windows retained and packages with window replacement applied, respectively.

The dominant structural feature in the graph is the separation into two vertical performance bands, determined by the ventilation system condition. Within each band, packages are further organised into two horizontal clusters separated along the investment axis, determined by the window replacement decision. Within each cluster, smaller groups of points reflect the influence of roof insulation and auxiliary measures, creating a third level of grouping where packages sharing the same roof insulation condition are visually grouped together.

Ventilation measures:

The graph reveals a clear two-band structure: a lower band with savings below approximately 23 kWh/(m²·yr) and an upper band with savings between approximately 67 and 106 kWh/(m²·yr), separated by a wide gap. This separation is driven by the ventilation system condition of each package, with packages involving main AHU or both AHUs replacement, VAV conversion, or both measures occupying the upper band, and packages retaining the old AHU and control system (CAV) or replacing only the attic AHU remaining in the lower band. Within each band, investment increases progressively as additional measures are added, while energy savings respond only marginally, reflecting the secondary nature of envelope and auxiliary measures.

The highest energy savings are achieved by packages combining replacement of both AHUs with VAV ventilation strategy, reaching approximately 100 kWh/(m²·yr) at a total investment of approximately 781 kSEK (in packages with old windows). The lowest savings are consistently associated with Attic AHU replacement only, which delivers a relatively small improvement of approximately 7 kWh/(m²·yr) for approximately 54 kSEK, regardless of which other measures are included in the package, placing it closer in performance to roof insulation than to the major ventilation interventions.

The most significant jump in energy saving from the baseline occurs when the Main AHU is replaced, delivering approximately 68 kWh/(m²·yr) at an investment of approximately 286 kSEK. Alternatively, converting from CAV to VAV without any AHU replacement can reach a saving level at a marginally higher additional investment of 30 kSEK, confirming that VAV can partially substitute for Main AHU replacement in terms of energy outcome.

In the package including AHU replacement, the energy savings result from improved fan efficiency and enhanced HR efficiency of the system. In the package involving the conversion from CAV to VAV (with existing AHU), the HR efficiency and fan SFP of the existing system remain unchanged, and the savings originate from reduced ventilation heat losses during unoccupied hours due to lower airflow, as well as decreased fan electricity use.

The maximum energy performance of the ventilation system is achieved when the two measures are combined. Adding CAV to VAV conversion to a package that already includes new AHUs contributes an additional improvement of approximately 17 kWh/(m²·yr) at an additional investment of approximately 262 kSEK. This combined effect indicates that the two interventions are complementary, with AHU replacement improving the efficiency of the system and CAV to VAV conversion adapting its operation to actual demand.

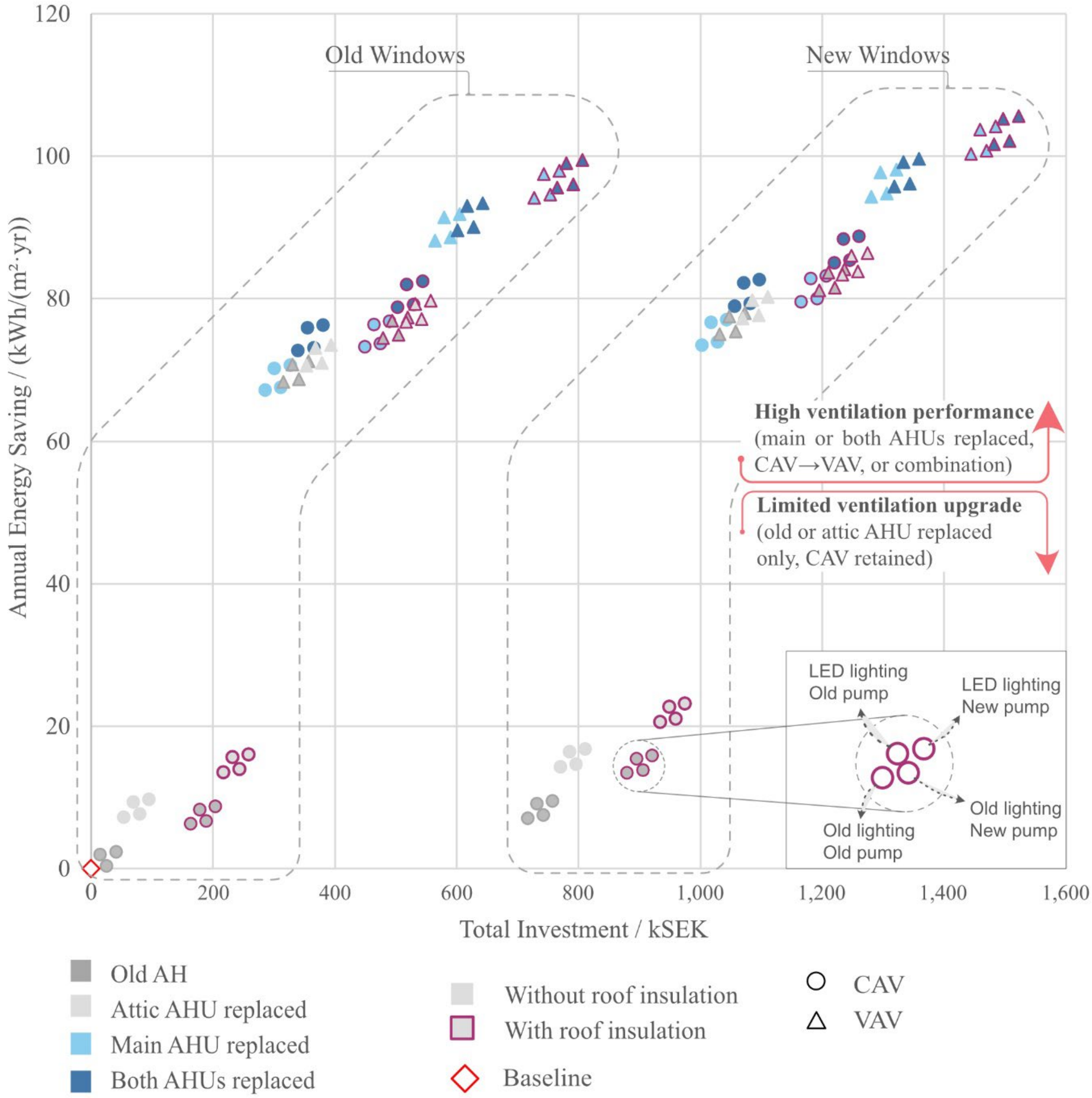

Figure 15 - Investment vs Annual Energy Saving for 128 packages, Case A1. Marker colour: AHU condition. Marker shape: ventilation control strategy (circle: CAV, triangle: VAV). Magenta border: packages with roof insulation added. Left and right clusters distinguish packages without and with window replacement, respectively. The inset shows a magnified view of a representative point grouping, illustrating the four auxiliary combinations resulting from the combination of lighting and pump conditions.

Envelope measures:

Window replacement, by contrast, produces a horizontal shift to the right rather than a vertical uplift A clear pattern is visible in Figure 15, where the 128 packages form two distinct horizontal clusters separated along the investment axis as shown in the graph. Every package without window replacement appears in the left cluster, and each of these packages is duplicated in the right cluster with window replacement added at an additional investment of approximately 716 kSEK and an additional saving of only approximately 7 kWh/(m²·yr).

Packages including roof insulation are shown with a magenta border. Roof insulation produces a consistent upward shift of approximately 6 kWh/(m²·yr) at an additional investment of approximately 163 kSEK, regardless of which other measures are included in the package. This shift is visible as a systematic pattern within every point grouping across the full investment range, confirming that roof insulation behaves as a stable and predictable measure.

Auxiliary measures:

As can be seen in the graph, auxiliary measures introduce only minor variations within existing configurations. Their effect is limited to small shifts in energy savings and does not influence the overall structure of renovation performance. Throughout the graph, packages appear in groups of four, each group representing the combination of lighting and pump conditions applied to an otherwise identical renovation package. The inset shows a magnified view of one such group, illustrating the four combinations resulting from lighting and pump conditions.

LED lighting produces a small but consistent increase in energy savings, typically around 2 kWh/(m²·yr), visible as a slight upward shift when moving from old to new lighting within each group. In contrast, pump replacement has a negligible effect, generally below 1 kWh/(m²·yr), producing only a marginal horizontal displacement and does not notably alter the position of the points.

Building B

The same approach applied to Building A is followed for Building B, presenting the 64 simulated renovation packages of Case B2.

Figure 16 presents the annual energy saving as a function of total investment for all 64 simulated renovation packages of Case B2. Marker colour indicates AHU condition, marker shape distinguishes ventilation control strategy (circle: CAV, triangle: VAV), a magenta border identifies packages with roof insulation added, and the left and right clusters distinguish packages with existing windows retained and packages with window replacement applied, respectively.

The graph reveals a similar spatial organisation to Building A, with packages grouped into distinct clusters reflecting the hierarchical influence of the different renovation measures. The dominant feature is again the separation into two horizontal performance bands, determined by the ventilation system condition. Within each band, packages are further organised into two horizontal clusters separated along the investment axis, determined by the window replacement decision.

Ventilation measures:

The graph reveals a two-band structure consisting of a lower band containing packages with no ventilation improvement, and an upper band containing packages involving AHU replacement or CAV to VAV conversion or a combination of these two measures.

The most significant jump in energy saving from the baseline occurs when the AHU is replaced, delivering approximately 28 kWh/(m²·yr) at an investment of approximately 347 kSEK. Converting from CAV to VAV with existing AHU can reach a higher saving level of approximately 41 kWh/(m²·yr) at a lower investment of approximately 297 kSEK, with the saving originating from lower ventilation heat losses during unoccupied hours and reduced fan electricity consumption.

When a package already includes new AHU, converting from CAV to VAV brings the package to a higher saving level, with an additional improvement of approximately 21 kWh/(m²·yr) at an additional investment of approximately 222 kSEK.

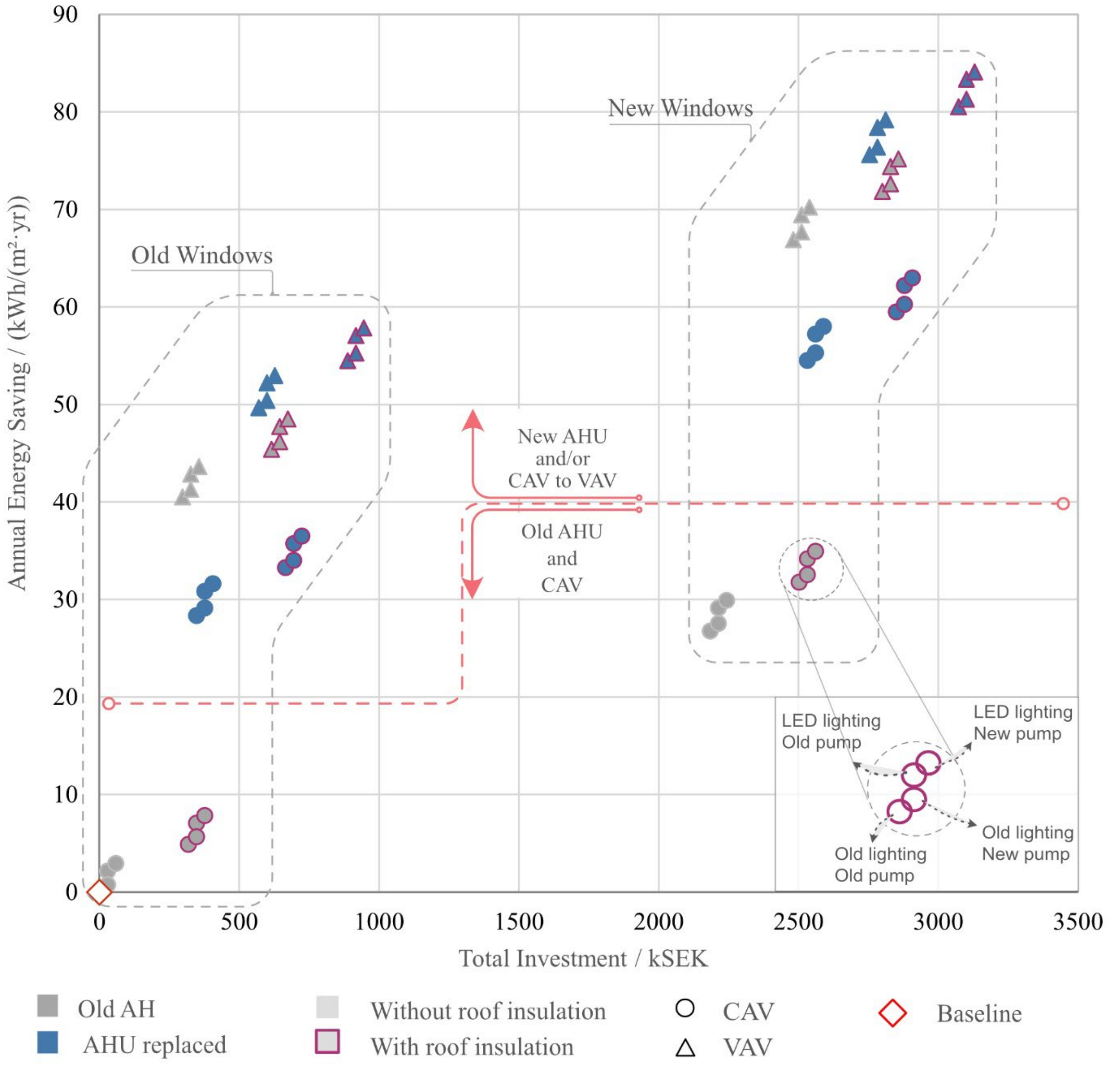

Figure 16 - Investment vs Annual Energy Saving for 64 packages, Case B2. Marker colour: AHU condition (grey: old AHU, blue: new AHU). Marker shape: ventilation control strategy (circle: CAV, triangle: VAV). Magenta border: packages with roof insulation added. The inset shows a magnified view of a representative point grouping, illustrating the four auxiliary combinations resulting from the combination of lighting and pump conditions.

Within each AHU cluster, VAV packages consistently sit above equivalent CAV packages, confirming the additive benefit of variable ventilation. The horizontal spread within each cluster is driven by window replacement, which involves a substantially higher investment and provides approximately 27 kWh/(m²·yr) of additional energy savings.

Unlike Building A, where the transition between bands is driven by a single dominant threshold, the upper band in Building B shows a more gradual progression, reflecting the combined and partial contributions of AHU replacement and VAV conversion.

Envelope measures:

The same duplication pattern observed in Building A is visible in Building B. Every package without window replacement appears in the left cluster and is duplicated in the right cluster with window replacement added, at an additional investment of approximately 2 184 kSEK and an additional saving of only approximately 27 kWh/(m²·yr). This measure also differentiates the packages in terms of energy performance, distinguishing between low-investment packages (achieving up to 58 kWh/(m²·yr) of energy savings) and high-investment packages (achieving up to 84 kWh/(m²·yr)).

Roof insulation adds a consistent upward shift of approximately 5 kWh/(m²·yr) at an additional investment of approximately 318 kSEK across all package compositions.

Auxiliary measures:

Auxiliary measures have negligible influence on overall performance, producing only minor variations within existing configurations. Similar to Building A, throughout the graph, packages appear in groups of four, each group representing the four combinations of lighting and pump conditions applied to an otherwise identical renovation package. The inset shows a magnified view of one such group, illustrating these combinations clearly. LED lighting adds a small but consistent upward shift of approximately 2 kWh/(m²·yr) at an additional investment of approximately 29 kSEK, while pump replacement contributes an even smaller saving of less than 1 kWh/(m²·yr) with the same investment.

In both buildings, ventilation-related measures define the primary structure of renovation performance, while window replacement produces the largest incremental investment step. The relative contribution of window replacement to total energy savings is greater in Building B than in Building A, reflecting the higher baseline window *U*-value in the cases selected for Building B.

5.3.3 Pareto front analysis

To evaluate how modelling uncertainty influences renovation strategies, Pareto representations are constructed for selected case within each building. Rather than identifying a single optimal solution, the analysis compares how the set of optimal trade-offs between investment cost and energy savings varies depending on baseline assumptions.

The shape of each Pareto front is described using three regions: the knee, defined as the initial inflection point where the front rises steeply; the transition region, corresponding to the rising portion of the front beyond the knee where the main performance gains are achieved; and the diminishing returns region, where the front flattens and additional investment yields progressively marginal gains.

Building A
Figure 17 presents the Pareto-optimal solutions for Building A across Cases A1–A3. The number of optimal solutions is consistent (30–31 out of 128), indicating that the structure of efficient renovation strategies is generally stable across cases.

At low investment levels below approximately 200 kSEK, the Pareto fronts overlap almost completely. This convergence indicates that early-stage renovation packages are less sensitive to the baseline, and the result of these low-cost interventions can be done with confidence in the result of energy savings, regardless the uncertainty of the initial parameters.

The three Pareto fronts exhibit a pronounced “knee” at an investment level of approximately 280–300 kSEK, where energy savings increase sharply from around 10 to 67–70 kWh/(m²·yr). The transition region corresponds to the introduction of ventilation system upgrades in the renovation packages, confirming their dominant role identified in 5.3.2. The consistency of this knee point across all three cases implies that the identification of the ventilation upgrade as the primary cost-effective intervention is not conditioned on the specific baseline condition of this building.

As investment increases, divergence between cases becomes visible, particularly near the 800 kSEK where packages that include window replacement represent a larger incremental investment. This divergence is linked to differences in the assumed baseline envelope. Case A1 is characterised by a lower initial window *U*-value, meaning the marginal benefit of window upgrades is less pronounced compared to Cases A2 and A3.

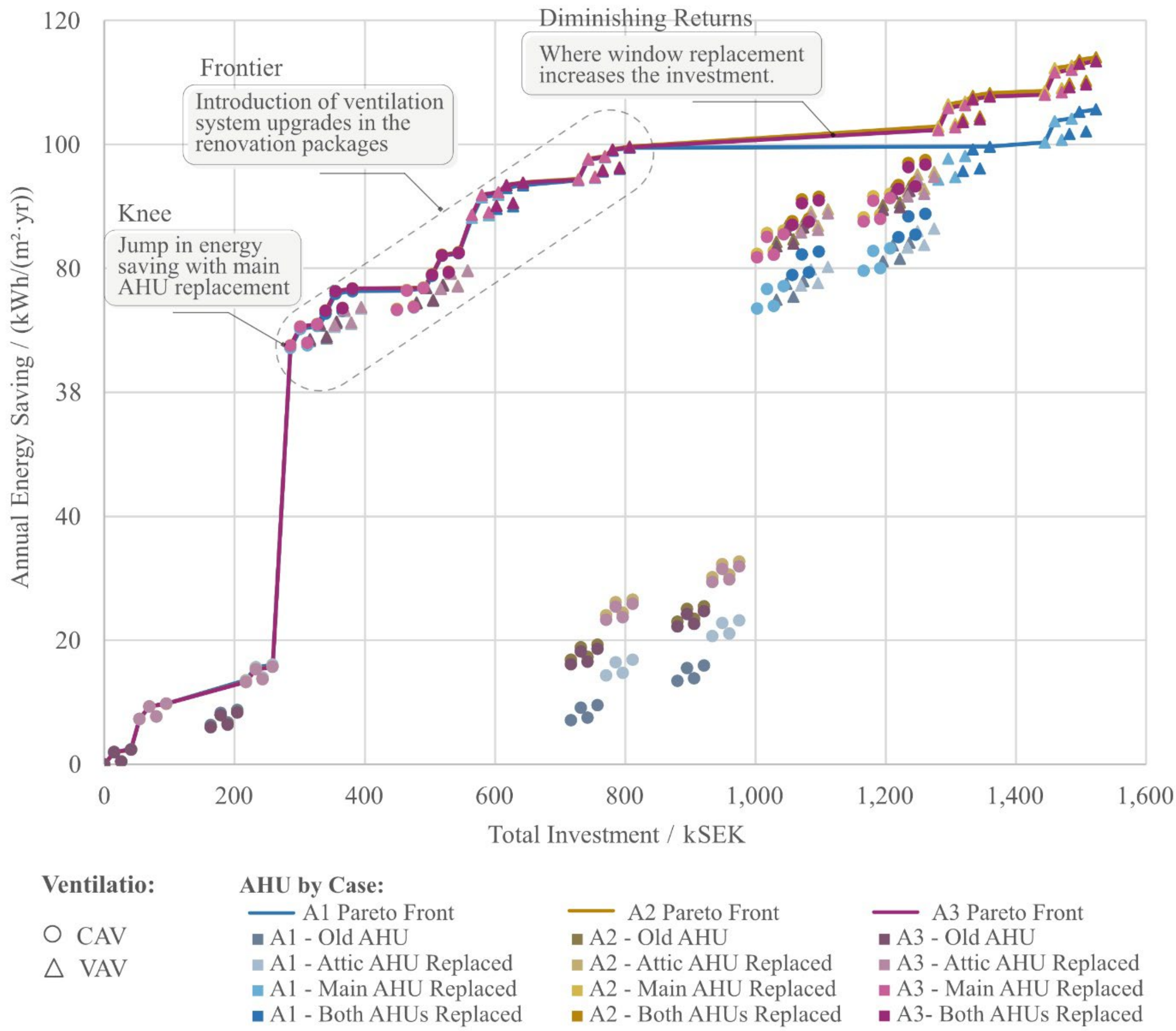

Figure 17 - Investment vs Annual Energy Saving for all 128 simulated renovation packages per case, Cases A1, A2, and A3. Solid lines indicate the Pareto front for each case.

Despite these differences, the overall shape, position, and slope of the Pareto fronts remain consistent. Maximum energy savings range from 105 to 113 kWh/(m²·yr), and all cases exhibit a clear flattening into the diminishing returns region beyond approximately 800 kSEK.

Based on the Pareto structure of Building A, the residual uncertainty following model fitting has a limited effect on the overall renovation strategy. The primary source of divergence between cases can be attributed to differences in the assumed baseline window *U*-value, which directly influences the estimated benefit of window replacement packages. Cases with a higher baseline window U-value show greater energy savings potential in the high-investment region where window replacement is included, accounting for the visible gap between fronts beyond 800 kSEK. Outside of these window-related packages, the Pareto fronts remain closely aligned, suggesting that cases uncertainty has a localised effect, most visible in the window replacement region where differences in baseline window U-value determine the magnitude of achievable savings.

Building B

Figure 18 presents the Pareto-optimal solutions for Building B across Cases B1–B3. The number of optimal solutions ranges from 24 to 28 out of 64 simulated cases, indicating a slightly broader set of efficient combinations compared to Building A.

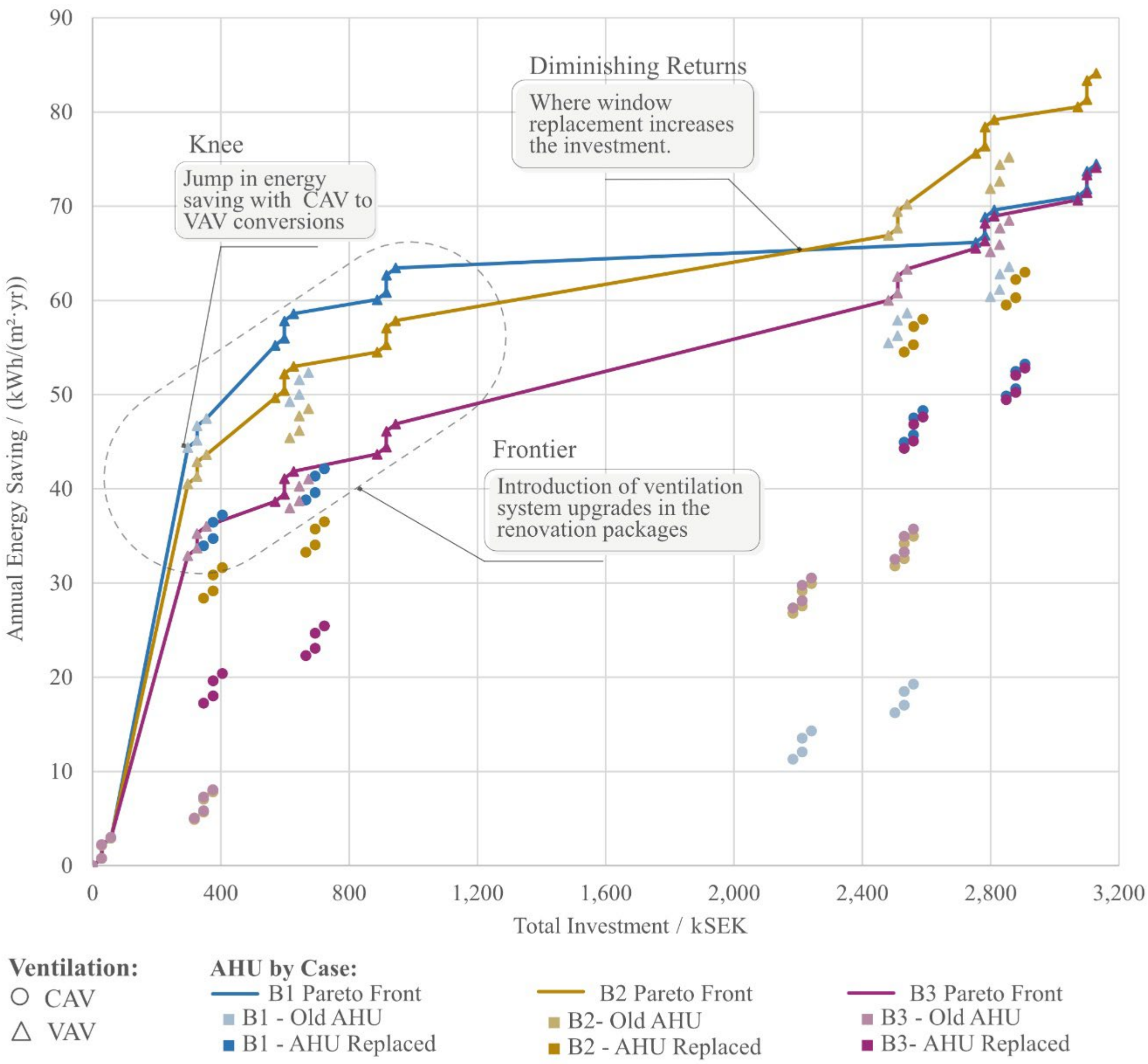

Figure 18 - Investment vs Annual Energy Saving for all 64 simulated renovation packages per case, Cases B1, B2, and B3. Solid lines indicate the Pareto front for each case.

Consistently with Building A, auxiliary renovation measures show closely aligned energy savings across all three cases, indicating that the effectiveness of these measures is largely independent of baseline parameterisation.

The three Pareto fronts exhibit the knee point at approximately 290-330 kSEK, where energy savings increase rapidly as ventilation-related measures are introduced. As established in Section 5.3.2, The transition region extends from approximately 300 to 1,000 kSEK, broader than observed in Building A. This transition reflets the combined effect of AHU replacement and CAV to VAV conversion. The progression in Building B across the transition region is consistent with the stronger influence of baseline HR efficiency on the magnitude of ventilation-related savings. Divergence between cases is already visible at the knee, with Case B1 achieving the highest savings at this point, consistent with its lower baseline HR efficiency (60 %) providing greater room for improvement; and Case B3 sitting lowest due to its higher baseline HR (75 %). This earlier inter-case divergence, compared to Building A, reflects the greater sensitivity of the Pareto structure to ventilation system uncertainty when HR efficiency varies significantly across cases.

Beyond approximately 2 400 kSEK, where window replacement packages are introduced, the ordering of cases shifts. Case B2 achieves the highest maximum energy savings of approximately 84 kWh/(m²·yr), while B1 and B3 remain closer to 74–75 kWh/(m²·yr). As shown in previous sections, window replacement delivers substantially higher savings in cases with a higher baseline window *U*-value (2.20 W/(m²·K) in B2 and B3) compared to B1 (1.30 W/(m²·K)). The higher maximum savings of B2 relative to B3, despite sharing the same baseline window *U*-value, can be attributed to its lower baseline wall *U*-value (0.59 W/(m²·K)) and moderate HR efficiency (65 %), which together produce a higher total accumulated saving across the full renovation package.

Cases B1 and B3 show a tendency to converge near an investment level of approximately 2,700 kSEK, where packages combining full ventilation upgrades and window replacement are present. Since the baseline difference between these two cases is based on HR efficiency and thermal bridge, and the screening sensitivity analysis indicates a smaller influence of thermal bridge variation on energy performance, a plausible interpretation is that the greater benefit of window replacement in B3 is approximately offset by the greater benefit of ventilation upgrades in B1 due to the HR improvement.

The performance gap between cases is most pronounced in the transition region of the Pareto front, where the ordering of cases is governed by baseline HR efficiency. The spread in estimated savings per unit of investment across cases is larger in Building B than the equivalent spread driven by window *U*-value uncertainty in Building A, indicating that HR efficiency is a more impactful source of baseline uncertainty when evaluating renovation strategies. In Building B, the assumed baseline ventilation performance directly shapes the estimated cost-effectiveness of the primary renovation interventions. Accurate modelling of the existing ventilation system therefore carries greater weight in the estimation of renovation savings potential than envelope parameters alone.

5.3.4 Profitability diagram for renovation packages

To support decision-oriented assessment, the results are analysed as cumulative renovation pathways, representing the sequential implementation of measures. This approach allows evaluation of how total investment and annual cost savings evolve as measures are progressively added, rather than treated as isolated interventions or as a single combined investment.

The profitability diagram presents the cumulative economic performance of renovation measures added sequentially in descending order of marginal ROI. Each point on the renovation path represents the cumulative investment and cumulative annual cost saving of the package at that stage of assembly. The reference lines correspond to fixed return rates of 5 %, 10 %, 20 % and 30 %, constructed using the annuity factor with a weighted average lifespan recalculated at each step. A package point situated above a reference line meets or exceeds that return threshold, while a point falling below it indicates that the cumulative investment no longer satisfies the required rate. The slope of the renovation path at each step reflects the marginal return of the measure added at that stage, with steeper segments indicating higher marginal profitability.

It should be noted that the absolute ROI values presented in these diagrams are subject to uncertainty, as the investment cost estimates may not capture all associated costs as referred in the limitations Section 4.10. However, since such hidden costs are likely to affect all measures in a structurally similar way, the relative differences in ROI between measures and between buildings remain comparable in terms of trends and relative cost-effective measures.

For each building, two profitability paths are presented. The distinction arises from the relationship between CAV to VAV conversion and AHU replacement. Implementing CAV to VAV requires retrofitting the existing AHU with variable-speed fans, meaning that a subsequent full AHU replacement would make the retrofit investment redundant. Accordingly, the two paths are defined as follows:

- CAV to VAV conversion is included with retrofitted AHU and no full AHU replacement follows.
- AHU replacement is prioritised and CAV to VAV conversion is subsequently applied to the new system.

Building A

Figure 19 presents the profitability diagram for Case A1, following the renovation path without AHU replacement. Each point on the path represents the cumulative investment and cumulative annual cost saving after adding each measure in sequence.

The renovation path starts steeply, with LED lighting delivering a cumulative annual cost saving of approximately 11 kSEK/yr at an investment of approximately 15 kSEK. Next measure was system conversion to VAV with existing AHU, which represents the largest single step on the path, bringing cumulative annual cost saving to approximately 118 kSEK/yr at a cumulative investment of approximately 331 kSEK, while remaining above the 30 % reference line, confirming a high marginal ROI.

Beyond this point, the slope of the renovation path decreases progressively. Roof insulation and pump replacement maintain the path above the 20 % threshold, with more flatten line compared to VAV conversion. At this stage, the curve exhibits a clear change in slope, where cumulative savings increase disproportionately relative to investment. This indicates that VAV conversion step represents the transition from high-impact to low-impact interventions.

The final step, window replacement, adds a significant increase to cumulative investment while increasing cumulative annual cost saving by only approximately 10 kSEK/yr, causing the path to flatten and place the whole package above the 10 % reference line.

The economic limit of this path, defined as the point where adding further measures drives the package return below a required threshold, is reached at the window replacement step for any owner requiring a return above 20 %.

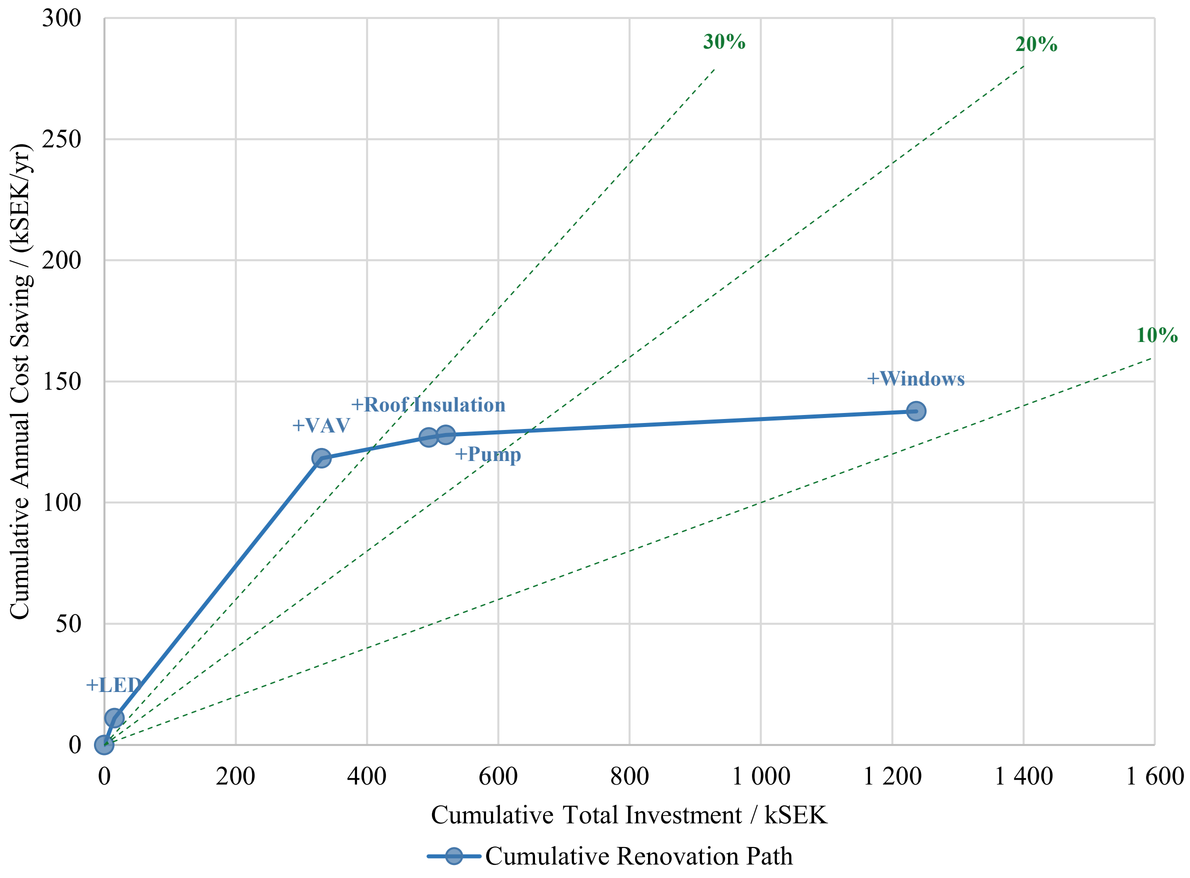

Figure 19 - Profitability diagram for Case A1, without AHU replacement. Renovation measures in descending order of marginal ROI. Reference lines correspond to annual return rates of, 10 %, 20 %, and 30 %.

Figure 20 presents the profitability diagram for Case A1, following the renovation path this time including AHU replacement.

As in the previous path, LED lighting starts well above the 30 % reference line. Main AHU replacement represents the largest single step, with the cumulative saving reaching approximately 109 kSEK/yr at approximately 301 kSEK, while the path remains above the 30 % line, confirming it as the most economically attractive measure in this path. The addition of Attic AHU replacement brings the cumulative saving to approximately 119 kSEK/yr at approximately 355 kSEK, with the path remaining above the 30 % line.

CAV to VAV produces another jump in energy saving, bringing the cumulative saving to approximately 152 kSEK/yr at approximately 617 kSEK investment, causing the path to cross below the 20 % line and settle between 10 % and 20 %. Roof insulation and pump replacement again contribute modest upward shifts, keeping the path place right above the 20 % reference line.

Window replacement causes the path to flatten significantly, settling between the 10 % and 20 % thresholds at the final package level, consistent with the pattern observed in the previous path. Window replacement is the measure that drives the largest drop in package return, and the economically optimal stopping point is before window replacement for any owner requiring a return above 20 %.

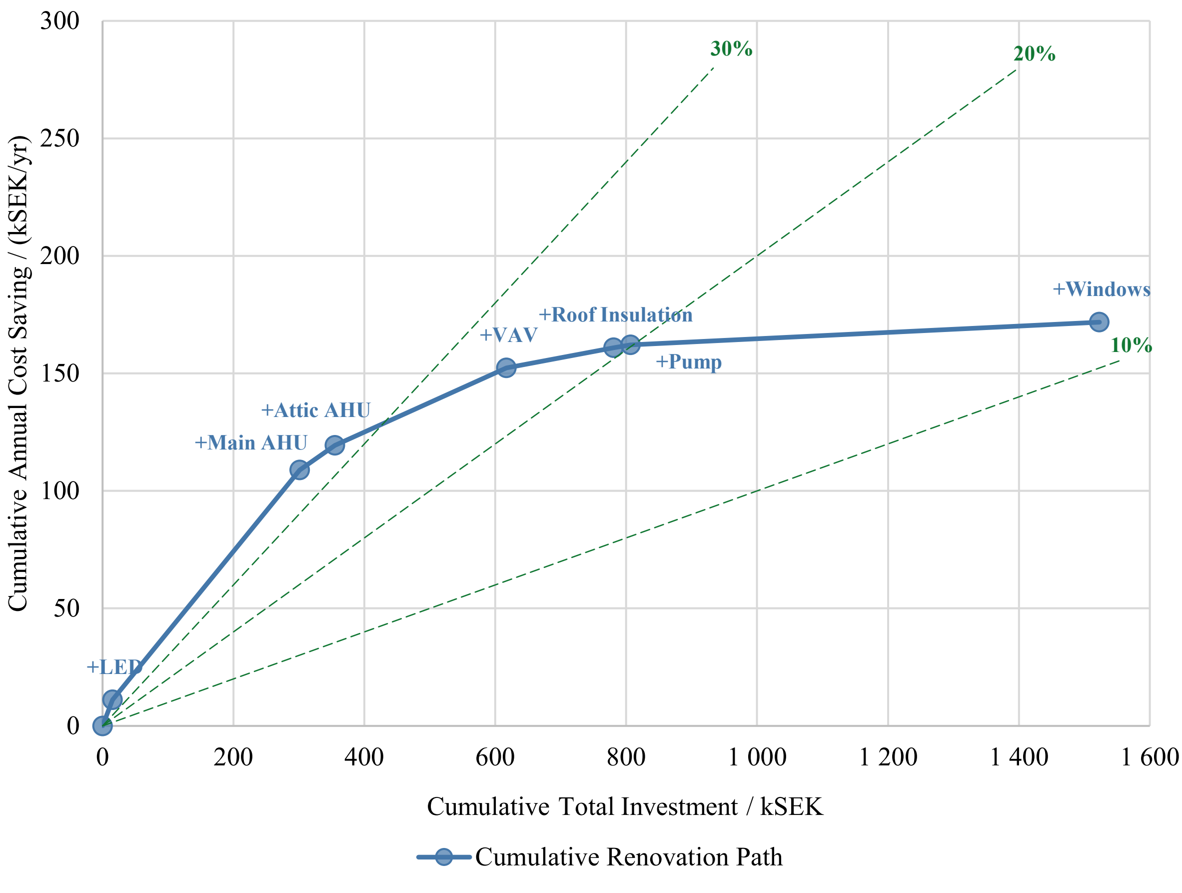

Figure 20 - Profitability diagram for Case A1, with AHU replacement. Renovation measures in descending order of marginal ROI. Reference lines correspond to annual return rates 10 %, 20 %, and 30 %.

When comparing both paths, the inclusion of AHU replacement shifts the entire pathway upward, resulting in higher cumulative savings at each stage. The most notable difference occurs at the VAV step. In the path without AHU replacement, the VAV conversion is applied to the existing AHU and yields cumulative savings of approximately 118 kSEK/yr. In contrast, when the VAV conversion is implemented after the replacement of both AHUs, the cumulative savings at this step increase to approximately 152 kSEK/yr.

The higher cumulative savings from VAV conversion in the second path reflect the combined effect of improved HR efficiency and lower SFP of the new AHUs, together with the benefits of VAV. In the first path, the same conversion is applied to the existing system with lower baseline performance. As a result, despite the implementation of VAV, significant ventilation heat losses persist due to lower HR efficiency, and fan electricity use remains higher due to higher SFP, leading to a smaller absolute gain.

The difference in cumulative investment of the two paths, approximately 286 kSEK, corresponds to the additional cost of complete AHU replacement compared to upgrading only the fans to VFD units in the AHU.

Despite this difference, both paths reach a comparable final cumulative saving level before window replacement, confirming that the two sequences achieve similar energy outcomes through different investment trajectories. The path with AHU replacement reaches this level at a higher cumulative investment, while the path without AHU replacement achieves saving more efficiently in terms of investment per unit of annual cost saving.

Building B

Figure 21 presents the profitability diagram for Case B2, following the renovation path without AHU replacement, with the sequence: LED lighting, VAV conversion (existing AHU), Pump replacement, Roof insulation, and Window replacement.

The path starts steeply with LED lighting above the 30 % line, followed by VAV conversion with existing AHU, which represents the dominant step, bringing the cumulative saving to approximately 162 kSEK/yr at approximately 336 kSEK, while remaining above the 30 % reference line. Pump replacement contributes a small addition.

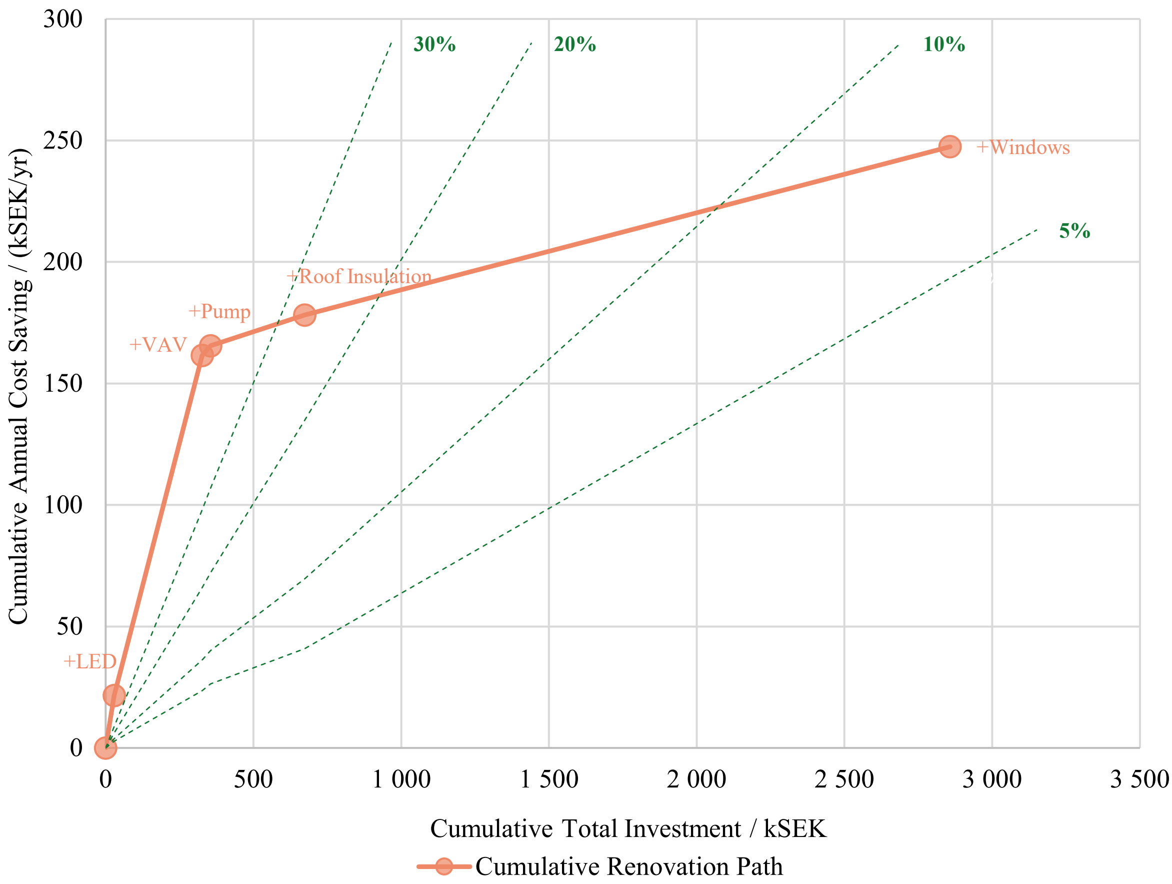

Figure 21 - Profitability diagram for Case B2, without AHU replacement. Reference lines correspond to annual return rates of 5 %, 10 %, 20 %, and 30 %.

Roof insulation, which follows as the next step, brings the cumulative saving to approximately 178 kSEK/yr at approximately 673 kSEK, causing the path to drop below 30 % and settle just above the 20 % reference line. The window replacement step adds approximately 2 184 kSEK to cumulative investment while contributing only approximately 69 kSEK/yr in additional saving. This causes the path to flatten dramatically and cross even below the 10 % reference line, settling between 5 % and 10 % at the final package level.

Figure 22 presents the profitability diagram for the Case B2, following the renovation second path including AHU replacement, with the sequence: LED lighting, AHU replacement, VAV conversion, Pump replacement, Roof insulation, and Window replacement.

The path starts as the previous one with LED lighting. AHU replacement represents the large next step, bringing a marginal saving of approximately 90 kSEK/yr with 347 kSEK additional investment, aligning with the 30 % reference line. The path continues with VAV conversion which is another significant jump in cost saving to 192 kSEK/yr at 598 kSEK investment.

Pump replacement follows, contributing a similarly negligible increase in both investment and savings. Up to this point, the package remains positioned just above the 30 % reference line.

Roof insulation brings the cumulative saving to approximately 208 kSEK/yr at approximately 945 kSEK, with the path dropping below 30 % and settling between 20 % and 30 %. Window replacement again dominates the final investment step, causing the path to flatten and settle just above the 5 % reference line at the final package level, consistent with the pattern observed in the previous path.

As in Building A, the VAV step results in a larger increase in cumulative savings in this path compared to the path without AHU replacement, reflecting the combined benefit of VAV ventilation when applied to the new AHU.

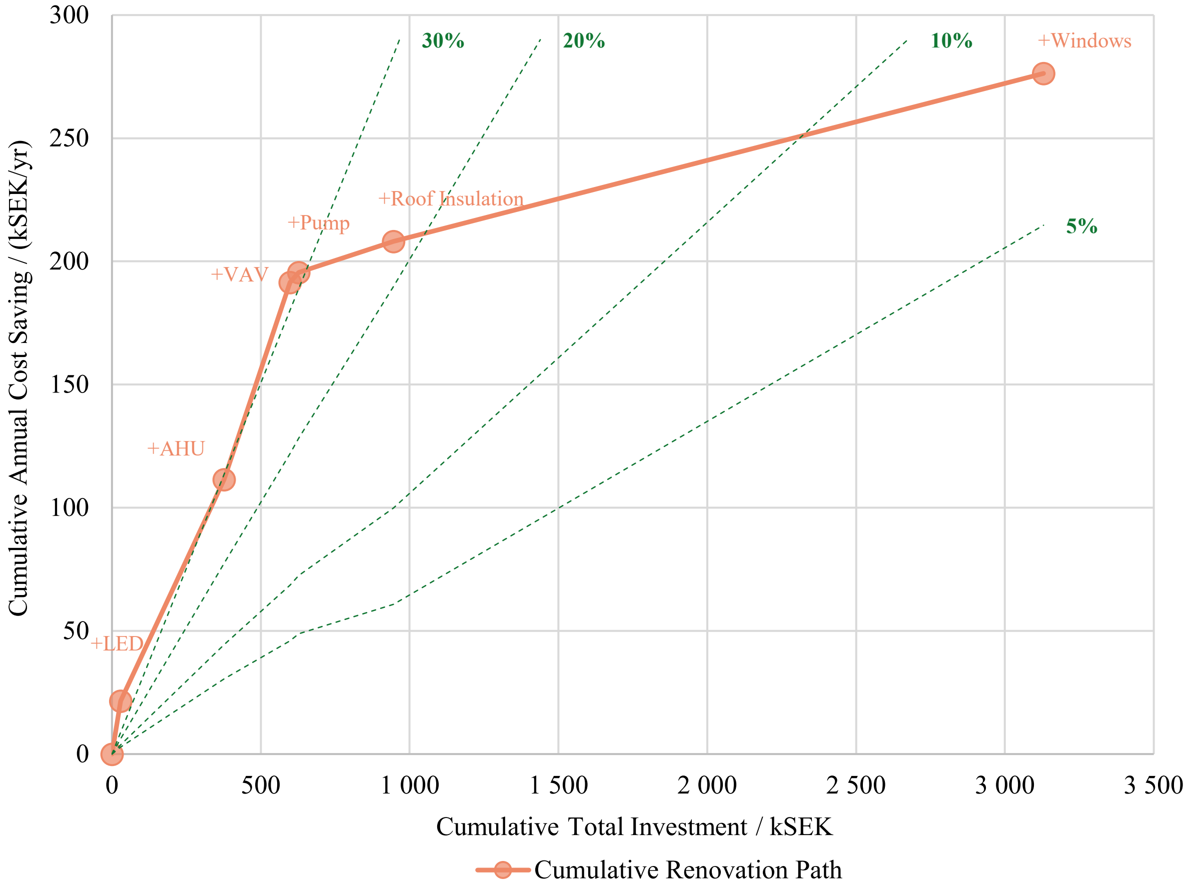

Figure 22 - Profitability diagram for Case B2, with AHU replacement. Reference lines correspond to annual return rates of 5 %, 10 %, 20 %, and 30 %.

5.4 Energy and economic performance of renovation measures: cross-building

The following section presents a direct comparison between the two case study buildings, using Case A1 and Case B2. While the individual analyses highlighted the behaviour of renovation measures within each building, this section evaluates how the same measures perform across different building characteristics.

To enable meaningful cross-building comparison, annual energy saving is expressed as percentage improvement relative to each building's baseline energy use, and both total investment and annual cost saving are normalised by heated floor area.

5.4.1 Individual Measures Assessment

Energy performance within individual measures

Figure 23 presents the percentage energy improvement from baseline for each individual renovation measure, comparing Case A1 and Case B2. Bars are divided into heating and electricity components.

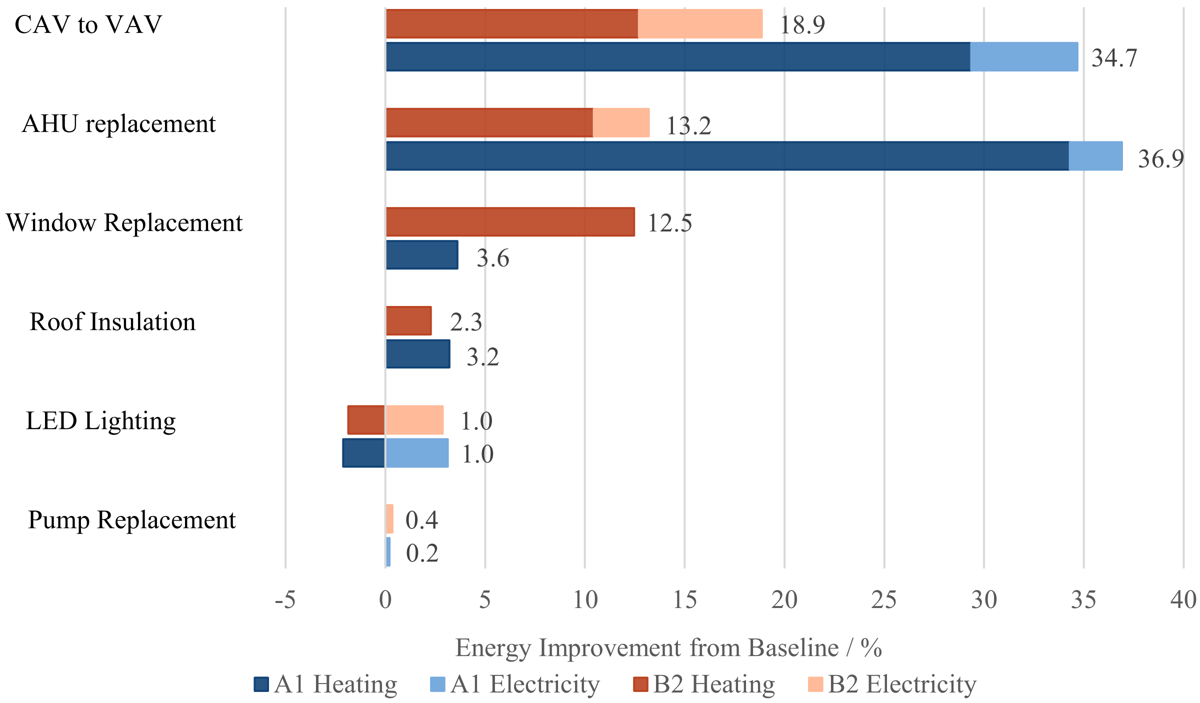

Figure 23 - Percentage energy improvement from baseline for individual renovation measures, Case A1 vs Case B2.

Ventilation-related measures provide the largest contribution in both buildings; however, their relative impact differs substantially. In Building A, AHU replacement and CAV to VAV conversion achieve total reductions of 36.9 % and 34.7 %, respectively, while in Building B the corresponding values are 13.2 % and 18.9 %. In both cases, the dominant share of savings is associated with heating demand. The lower impact in Building B is consistent with its higher baseline HR efficiency (65 % vs 12 % in A1), which limits the additional reduction achievable through ventilation improvements.

In contrast, envelope measures show a stronger effect in Building B. Window replacement contributes 12.5 % of total energy reduction in B2, compared to only 3.6 % in A1, which is the outcome of the higher baseline window *U*-value in B2.

Roof insulation provides a limited contribution in both buildings (2 % - 3 %), suggesting that its impact is relatively insensitive to system configuration.

Auxiliary measures show consistently low contributions across both cases. LED lighting results in a net improvement of approximately 1 % in both buildings, combining electricity savings (3 %) with a small negative heating contribution due to reduced internal gains. Pump replacement contributes less than 0.5 % in both cases.

Overall, the comparison shows a clear dependency between measure effectiveness and baseline conditions. Ventilation measures dominate in systems with low initial efficiency, while envelope measures become more relevant in buildings with higher system performance and higher transmission losses. Auxiliary measures remain marginal in both cases, with limited impact on total energy use.

Economic viability of individual renovation measures

Figure 24 compares the simple payback time of individual renovation measures between the representative cases A1 and B2.

The cross-building comparison confirms that the ranking of measures by economic viability is consistent between the two buildings. Ventilation measures and LED lighting occupy the low-payback range in both cases, roof insulation the mid-range, and window replacement the high range.

LED lighting, CAV to VAV conversion, and AHU replacement show closely comparable payback times across both buildings, 1.3 vs 1.4 years, 2.1 vs 2.9 years, and 3.9 vs 3.2 years respectively, confirming that the economic viability of ventilation and lighting measures is largely independent of building-specific baseline conditions. However, despite the substantially higher investment required by ventilation measures compared to LED lighting, their significantly greater impact on annual energy saving confirms that ventilation upgrades deliver a proportionally larger energy return.

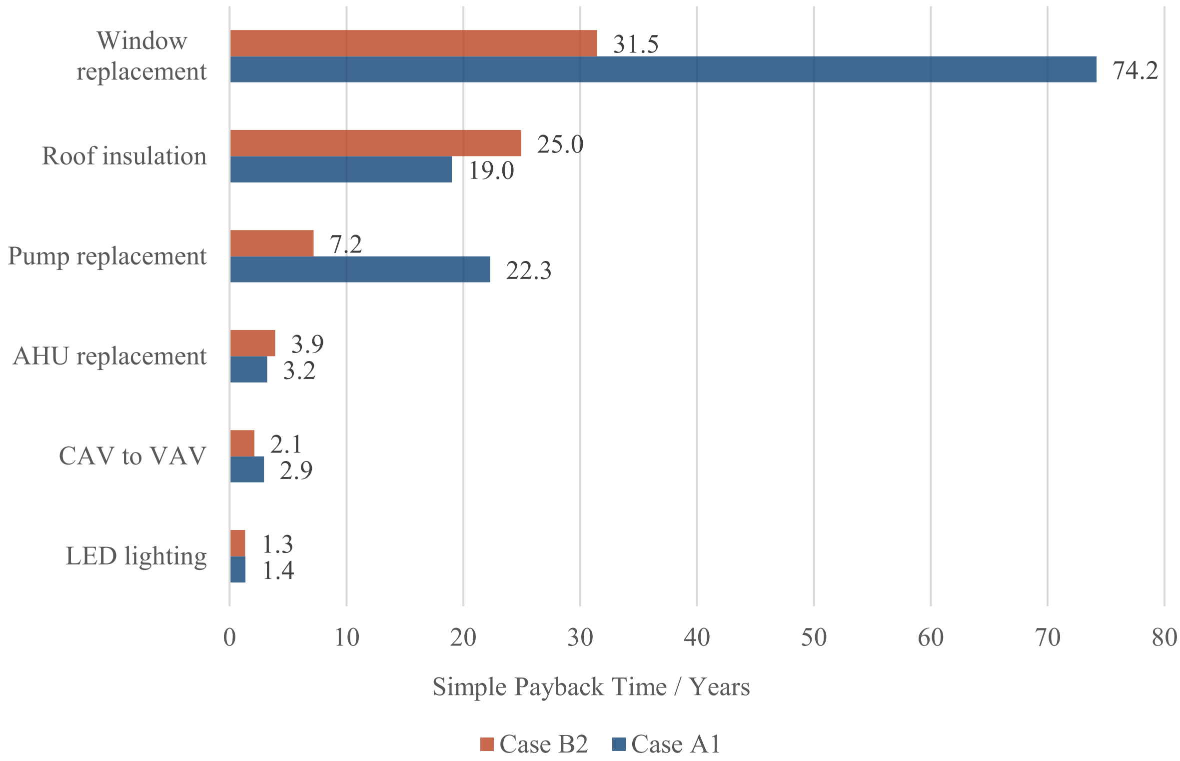

Figure 24 - Simple payback time (years) for individual renovation measures, comparing representative cases A1 and B2.

Roof insulation shows a moderate difference, with a payback time of 19 years in Case A1 and 25 years in Case B2. Both values remain within the lifespan threshold of insulation material and are therefore viable, but the higher payback in Building B reflects a proportionally larger investment cost relative to the achievable heating saving under its baseline condition.

Pump replacement exhibits the high difference between buildings, with a payback time of 22.3 years in Case A1 and 7.2 years in Case B2. This difference reflects the higher energy savings achieved by pump replacement in Building B, against a comparable investment cost in both buildings. Given the relatively low absolute contribution of pump replacement to total building energy use, however, its economic performance remains case-specific and should be assessed individually for each building.

Window replacement has the longest payback time and is the most sensitive to the baseline *U*-value, reaching 74.2 years in Case A1 and 31.5 years in Case B2. However, this difference cannot be interpreted solely on the basis of the baseline window *U*-value, since Building B has a higher window-to-floor area ratio than Building A. When comparing cases with similar baseline window thermal performance, such as A2 and B2, the payback times are similar. Considering that the investment cost per m^2 is higher in Building B, this similarity indicates that window replacement delivers a greater energy saving per unit of floor area in Building B, consistent with its larger heat loss surface relative to the heated area. Although window replacement achieves a lower payback time of approximately 31 years in cases with lower baseline window thermal performance, this still exceeds its expected lifespan of 30 years, indicating that window replacement is not economically viable under any of the conditions analysed.

5.4.2 Pareto front analysis

Figure 25 compares the Pareto fronts of Case A1 and Case B2, with investment normalised per heated floor area and energy improvement expressed as percentage from baseline.

Both Pareto fronts follow a similar overall shape, characterised by a knee point at low investment levels, a transition region in the mid investment range, and a flattening into the diminishing returns region at higher investment levels. However, the absolute position of the two fronts differs across the full investment range, with Building A consistently achieving a higher percentage energy improvement than Building B at any given investment per m². Case A1 reaches a maximum improvement of approximately 54 %, whereas Case B2 is limited to around 39 %.

Below the knee point, both buildings show similar behaviour, with improvements remaining below 10%. This region is dominated by auxiliary measures, which provide limited impact regardless of building characteristics.

In Case A1, the Pareto front exhibits a discrete transition, where energy improvement increases sharply from approximately 8 % to over 34 % at around 200 SEK/m². This step reflects a single intervention, the replacement of the main AHU, producing a high improvement in performance. After this point, the Pareto front rises gradually through the transition region up to approximately 598 SEK/m², reaching 51% energy improvement. This intermediate region includes 21 Pareto-optimal packages, all characterised by either Main AHU or Both AHUs replaced, with energy improvements ranging from 34 % to 43 % when the system remains CAV, and from 41% to 51 % when the system is converted to VAV. From this point, the front enters the diminishing returns region, an additional investment of approximately 527 SEK/m² is required to reach the next 7 Pareto-optimal packages, with window replacement contributing only an additional 1 % to 5 % in energy improvement.

In Case B2, the knee is less pronounced, with the first major step occurring from 22 to 115 SEK/m², where energy improvement jumps from 1 % to approximately 20 %, reflecting the conversion to VAV with the retrofit of the existing AHU. After this point, the transition region continues with two similar steps, each adding approximately 100 SEK/m² and 3 % energy improvement, the first corresponding to AHU replacement and the second to roof insulation. This pattern of 3 groups of 4 packages is exactly duplicated on the right side of the graph following the application of window replacement. Each Pareto-optimal package is mirrored at an additional investment of approximately 842 SEK/m², with a corresponding additional 12 % energy improvement for the identical configuration. The maximum energy improvement of 39 % is reached at approximately 1 207 SEK/m².

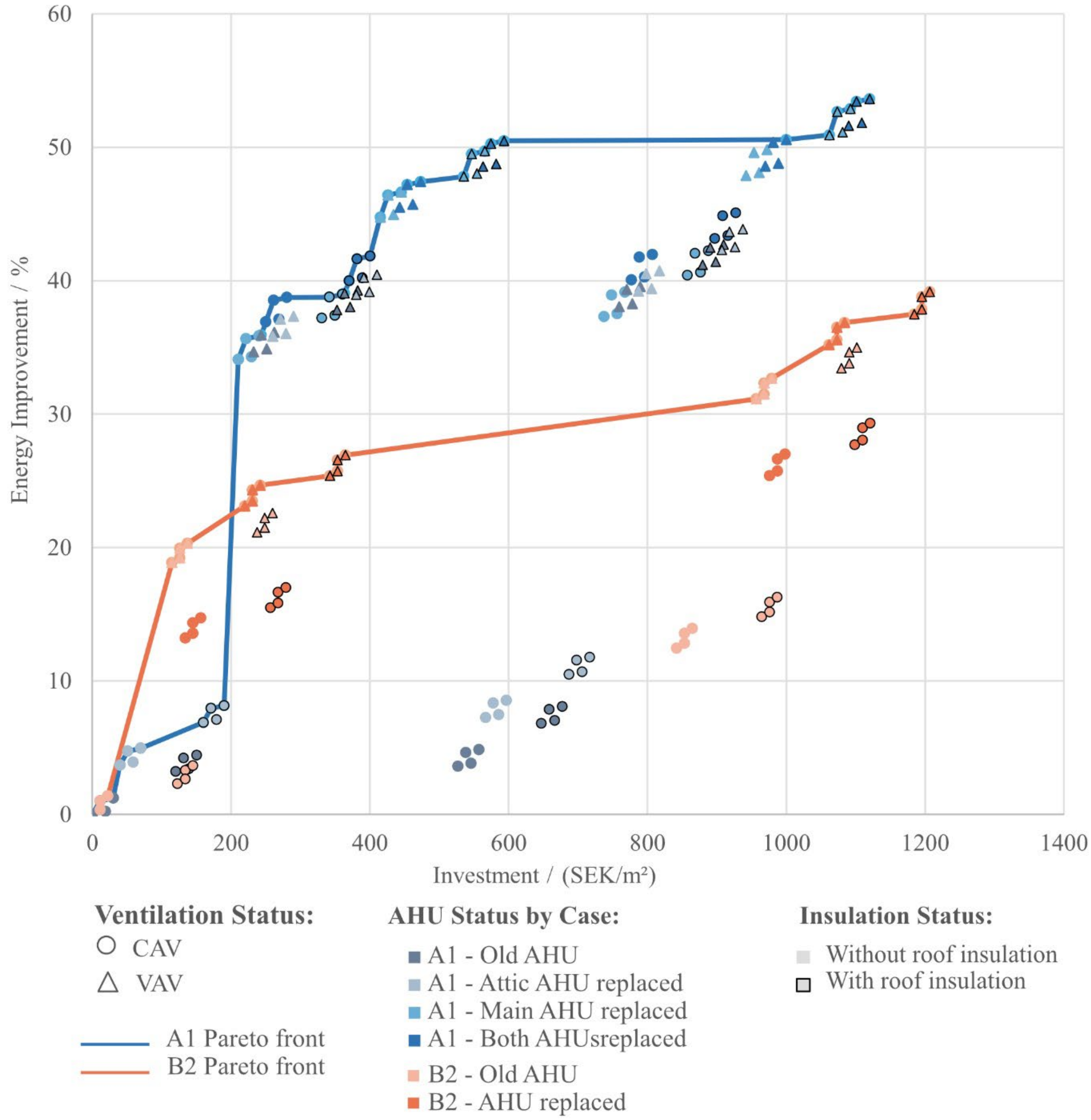

Figure 25 - Pareto front comparison between Case A1 and Case B2. Investment is normalised per heated floor area, and energy improvement as percentage of baseline.

Another key observation is that the total investment per heated floor area at the maximum saving level differs by only 87 SEK/m² between the two buildings. However, this small difference at the package level hides important differences in the cost structure of individual measures. The investment cost of equipment-based measures such as AHU and pump does not scale with floor area, since it depends on system capacity rather than building size. As a result, these measures appear less expensive per m² in larger buildings. For example, AHU replacement, as the one of the most effective measures for both buildings, costs 250 SEK/m² in Building A compared to 145 SEK/m² in Building B. In contrast, area-related measures such as window replacement scale directly with building geometry, costing 842 SEK/m² in Building B and 527 SEK/m² in Building A.

These opposing effects offset each other at the package level, producing a misleading similarity in total investment per m². Cost-effectiveness should therefore be assessed not only at the package level but also on a per-measure basis, in the sequence of implementation.

5.4.3 Profitability diagram for renovation packages

Figure 26 compares the cumulative renovation paths of Case A1 and Case B2, with both investment and annual cost saving normalised by heated floor area to enable direct cross-building comparison. The path including AHU replacement is presented, as it represents the full set of renovation measures. The renovation sequence in each path is ordered by descending marginal ROI within the respective building and is therefore not identical between the two cases. Due to differences in measure order and weighted lifespan between the two paths, a constant lifespan of 25 years was assumed when calculating the IRR reference lines.

Both paths follow a similar overall shape, starting with a steep ascent above the 30 % reference line at the early measures and progressively flattening as additional measures with lower marginal returns are added. However, the position of the paths and the rate of flattening differ between the two buildings.

The A1 path consistently sits above the B2 path for the majority of the investment range, indicating that Building A achieves a higher cumulative annual cost saving per unit floor area for a comparable level of investment. The path remains above the 30 % reference line when both AHUs replaced and above 20 % through the first six measures. It only crosses below 20% at the final window replacement step, where it settles between the 10 % and 20 % lines. The most significant marginal jumps occur with Main AHU replacement and CAV to VAV conversion, reflecting the dominant role of ventilation system improvements in this building.

The B2 path shows a similar steep initial ascent but flattens earlier in the investment range. The path remains above the 30 % reference line through the early measures including AHU replacement and CAV to VAV but begins to drop below 30 % when envelope measures introduced to the package. Window replacement causes a particularly pronounced flattening, with the path settling between the 5 % and 10 % lines at the final package level, lower than the corresponding step in Building A.

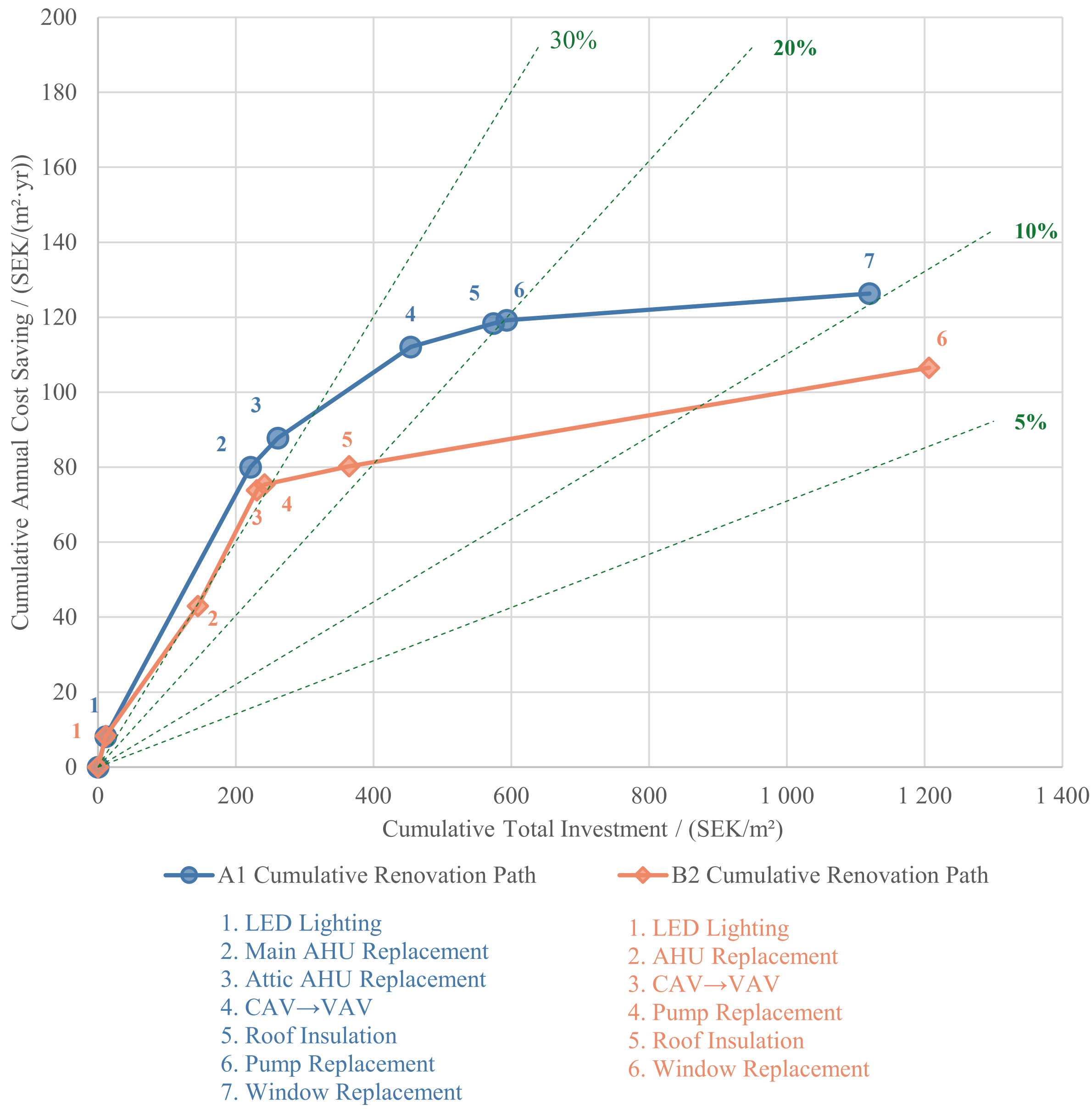

Figure 26 - Profitability diagram comparing the renovation paths of A1 and B2 with AHU replacement included. Investment and annual cost saving are normalised per heated floor area. Reference lines correspond to annual return rates of 5 %, 10 %, 20 %, and 30 %.

The general pattern, that ventilation measures dominate the early high-return portion of the path and that window replacement consistently drives the largest drop in package return, is generalisable across both buildings. The two paths also reach broadly comparable normalised investment levels at the final package stage. The main difference lies in the magnitude of the cumulative cost saving achievable, with Building A reaching a higher final saving of 126 SEK/(m²·yr) compared to 107 SEK/(m²·yr) for Building B, and in the shape of the path, where Building B flattens earlier and at a lower return level.

This confirms that the absolute cost-effectiveness of an integrated renovation package is not only a function of the measures applied but also of the underlying baseline condition of the building, which determines the marginal return achievable at each step.

The main cause in total cost saving between the two buildings originates from the effectiveness of ventilation measures. This difference is directly attributable to the baseline conditions of each building, which is FT system with a weighted HR efficiency of only 12 % in Building A, while in Building B the existing system already operates with a HR efficiency of 65 %. In both buildings, AHU replacement upgrades the system to 85 % HR efficiency, meaning that Building A achieves a notably larger improvement in absolute terms, while Building B operates from an already moderate baseline.

The absolute investment cost for AHU replacement is comparable between the two buildings. However, when normalised per heated floor area, the investment per m² is lower for Building B at 145 SEK/m² compared to 250 SEK/m² for Building A. Despite this lower investment per unit area, the measure delivers a higher cumulative cost saving in Building A, confirming that the baseline system condition is the dominant factor in the effectiveness of the measure, rather than the investment cost per unit area.

Also, this difference is clearly visible in the slope of the renovation paths. In Building A, the AHU replacement step shows a very steep upward shift, reflecting the large reduction in ventilation heat losses achievable when upgrading from 12 % to 85 % HR. The subsequent CAV to VAV step in this path produces a smaller marginal jump, as the system has already been improved and the additional benefit of VAV operates on top of an already efficient AHU. In Building B, both the AHU replacement and the VAV conversion steps show comparable slopes, indicating a more gradual and balanced contribution of each ventilation measure.

The pattern observed in Building A confirms a more general finding: when the initial ventilation condition is poor, the first ventilation measure applied, whether AHU replacement or VAV conversion, captures a large share of the available improvement. This was also evident in Figure 22.

In both buildings, the cumulative package is positioned above the 20 % reference line at the point where window replacement is applied, indicating that all preceding measures collectively maintain a high level of profitability.

The other main different pattern in graphs is related to windows. The investment cost of window replacement is higher in Building B than in Building A, even when normalised per heated floor area, due to the higher window-to-area ratio of 16 % in Building B compared to 10 % in Building A. The baseline window *U*-value also differs between the two buildings, at 1.3 W/(m²·K) for Building A and 2.2 W/(m²·K) for Building B, meaning that window replacement delivers a larger thermal improvement in Building B than in Building A.

This difference is reflected in the slope of the renovation path during the window step. In Building B, the slope is higher, indicating a larger marginal energy saving per unit of investment, while in Building A it shows a more flattening. Despite the higher slope in Building B, the final package settles between the 5 % and 10 % reference lines, while in Building A the final package remains above the 10 % reference line. This may be result of the higher cumulative savings of earlier measures in Building A, as well as the higher investment required for windows in Building B per heated area.

Across both buildings, the cumulative pathway analysis confirms that economic efficiency is highest at early stages of renovation, where system-level interventions provide large savings relative to investment. As additional measures are implemented, diminishing returns lead to a progressive decline in return rate.

6 Conclusions

This study was developed in the context of the EPBD recast and the introduction of MEPS for non-residential buildings, which establish binding renovation obligations for the worst-performing segments of the European building stock. As compliance becomes mandatory a portion of the Swedish non-residential stock will need to be renovated within a short timeframe. Beyond regulatory compliance, the energy performance of non-residential buildings is also increasingly recognised as a determinant of market competitiveness. This market signal reinforces the pressure introduced by the EPBD recast, strengthening the case for identifying renovation strategies that are both energy- and cost-effective for existing non-residential buildings.

Meeting these requirements demands not only technical solutions but also systematic and replicable methodologies for identifying the most effective renovation pathways applicable within the specific characteristics of each building category.

This study contributes to that challenge by developing and applying an integrated modelling and evaluation framework to two office buildings in Sweden with district heating.

Regarding the choice of non-residential building category, office buildings were identified as the most appropriate category for analysis in this study, based on their high share of total non-residential floor area in Sweden and their relatively homogeneous functional characteristics.

With respect to modelling assumptions and input parameters, the sensitivity screening demonstrated that, among the input parameters investigated, ventilation system parameters showed the strongest influence on simulated heating demand in the selected buildings, followed by envelope parameters including wall *U*-value, window *U*-value, and infiltration rate. These findings indicate that accurate representation of the ventilation system is the most impactful modelling input for this building category that shares similar characteristics.

Fitting the energy model to measured energy data revealed that initial selected inputs tended to over-predict heating demand relative to measured values, with the initial simulation dataset clustered predominantly in the over-prediction zone. Through structured sensitivity screening and parametric simulation, energy models satisfying ASHRAE Guideline 14 acceptance criteria were identified, with CVRMSE values of 12–15 % and NMBE within ±5 %. Residual uncertainty was retained and explicitly represented through three fitted energy models per building, reflecting plausible variations in envelope and ventilation system conditions that remain unknown.

Across both case-study buildings and between assessed renovation measures, ventilation measures delivered the largest energy savings. AHU replacement achieved absolute savings reaching up to 73 kWh/(m²·yr) in the building with 12 % HR efficiency at baseline, corresponding to a 37 % energy reduction, and between 17–34 kWh/(m²·yr) (8 % to 15 %) in the building where HR efficiency average was around 65%. Conversion from CAV to VAV operation ranked second, with savings of 68 kWh/(m²·yr) (35%) in the building with near-absent HR and 33 to 44 kWh/(m²·yr) (15 % to 20%) in the building with a more efficient system, with the wider range in the latter reflecting uncertainty in the assumed baseline HR efficiency. Window replacement showed the highest variability across cases for both buildings, with savings ranging from 4 % to 8 % and 5 % to 12 %. Roof insulation contributed to an average energy reduction of approximately 3 % in both cases. LED lighting contributed to an average energy reduction of approximately 1 %. Pump replacement had the smallest absolute impact, with of an average reduction of approximately 0.3 % in both cases.

Concerning the cost-effectiveness of individual renovation measures, LED lighting achieved the shortest payback period of approximately 1.3 years. Ventilation-related interventions followed, consistently delivering the highest energy savings alongside short payback times across both buildings; with AHU replacement and CAV to VAV conversion achieving payback times of 3–6 years. Pump replacement showed payback times of 7 to 22 years between the two buildings, indicating that its economic performance is case-dependent. Roof insulation offered moderate energy savings at payback times of approximately 20–25 years. Window replacement carried the longest payback times, ranging from 31 to 75 years depending on baseline conditions. Window and pump replacement were the only measures that had a payback time equal to or exceeding their expected lifespan.

When individual measures were applied in descending order from highest to lowest return on investment, LED lighting consistently appeared first, with an ROI of 73 %. Ventilation-related measures followed, with average ROIs of 27 % for AHU replacement and 40 % for CAV to VAV conversion across all cases in both buildings. Pump replacement showed an ROI of 4 % to 14 % between buildings, while roof insulation remained stable at approximately 5 % across all cases. Window replacement, the most expensive measure in both buildings, yielded the lowest ROI at 1 % to 3 %, depending on the baseline window *U*-value.

The renovation path in both buildings can be structured into three economic ranges, defined by the cumulative ROI of the package at sequential steps. The high-return on investment range, with a package ROI above 30 %, was defined in both cases by ventilation-related measures combined with LED lighting, requiring an average cumulative investment of 250 SEK/m² and delivering annual energy savings of 36–76 kWh/(m²·yr), with the higher savings achieved in the building with near-absent heat recovery at baseline. When the conversion from CAV to VAV operation was added to the package, total energy savings reached 53–93 kWh/(m²·yr), with an average additional investment of 160 SEK/m², while the package ROI remained between 25 % and 30 % across both buildings.

The further addition of roof insulation and pump replacement consistently populated the moderate-return on investment range, bringing the package ROI to approximately 20 % to 22% at a cumulative investment of 360–590 SEK/m². Window replacement marked the transition into the low-return range in both buildings, with a final package ROI of 11% and 8% respectively, at a total investment of approximately 1 100–1 200 SEK/m².

Despite the differing baseline conditions of the two case-study buildings, the profitability ranking of measures and the resulting renovation sequence followed a comparable pattern. In both cases, ventilation-related measures defined the high-return band, roof insulation populated the moderate-return range, and window replacement marked the transition into the low-return band. The consistency of this ranking across representative cases suggests that the identification of priority interventions is not strongly sensitive to the modelling uncertainty represented by the fitted cases, for the specific building characteristics studied. This means that despite the uncertainty in the initial condition of some building components, the priority renovation measures identified would have been the same regardless of which fitted parameter combination is used to represent the baseline, pointing to the potential replicability of the proposed procedure.

Among the fitted energy models assessed, the renovation measures identified as priorities converge consistently. This convergence indicates that the fitting procedure achieves a level of accuracy adequate for its intended purpose. This is particularly meaningful given that the parameters most influencing the solution space, namely ventilation system characteristics and the thermal transmittance of windows and façade, can typically be verified by building managers through existing documentation and routine inspection. Consequently, in real renovation projects where such verification is feasible, the residual uncertainty would be further reduced, reinforcing the reliability of the methodology beyond the conditions of the present study.

The performance gap between fitted energy models had a greater influence on the estimated savings from ventilation measures than from envelope or auxiliary interventions, reflecting the stronger sensitivity of ventilation system performance to baseline HR efficiency. This implies that greater precision in documenting existing ventilation systems carries particular importance when evaluating renovation potential in office buildings of this type. Furthermore, HR efficiency was found to be a more impactful source of baseline uncertainty than envelope parameters in the buildings studied.

This study demonstrates a methodology for evaluating energy renovation measures in office buildings under data uncertainty. The framework is applicable to comparable building types and supports structured decision-making. Future work should address several aspects that fall outside the scope of the present study. Detailed investment estimates that include installation cost, demolition cost and project management cost can reduce the gap between planning-level and execution-stage cost assessments. Furthermore, a full lifecycle cost analysis incorporating discount rates, energy price trajectories and maintenance cost would enable a broader understanding of expected returns over the lifespan of renovation measures. Finally, a critical area for future improvement is the documentation accuracy of ventilation systems, which would reduce baseline uncertainty and strengthen the reliability of renovation savings prediction for the measures most sensitive to baseline assumptions.

References

Almeida, Manuela, and Marco Ferreira. 2017. *EBC Annex 56 Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation: Project Summary Report*. University of Minho.

Arbetsmiljöverket. 2023. *Utformning av arbetsplatser (AFS 2023:12)*. AFS 2023:12. https://www.av.se/globalassets/filer/publikationer/foreskrifter/utformning-av-arbetsplatser-afs2023-12.pdf.

Arghand, Taha, Saqib Javed, Anders Trüschel, and Jan-olof Dalenbäck. 2021. "Energy Renovation Strategies for Office Buildings Using Direct Ground Cooling Systems." *Science and Technology for the Built Environment* 27 (7): 874–91. https://doi.org/10.1080/23744731.2021.1890520.

ASHRAE. 2014. *Measurement of Energy, Demand, and Water Savings*. Guideline 14-2014. *ASHRAE Guideline 14-2014*. American Society of Heating, Refrigerating and Air-Conditioning Engineers. https://www.ashrae.org.

ASHRAE. 2022. *ANSI/ASHRAE/IES Standard 90.1-2022 (I-P): Energy Standard for Sites and Buildings Except Low-Rise Residential Buildings*. 90.1-2022. ASHRAE.

Bandak, Asala, Athira Sreenivasan, Akram Abdul Hamid, and Pieter de Wilde. 2025. "The Energy Performance Gap – a Swedish Perspective." *Journal of Building Performance Simulation* 0 (0): 1–22. https://doi.org/10.1080/19401493.2025.2567993.

Bell, Malcolm, Jez Wingfield, Dominic Miles-Shenton, and Jenny Seavers. n.d. *Lessons from Elm Tree Mews*.

BELOK. 2013. *Totalprojekt – Handbok (utbildningsmaterial)*. https://www.belok.se/insida/files/documents/Totalprojekt%20handbok-utbildningsmaterial.pdf.

BELOK. 2017. *Tappvarmvatten i lokaler*. https://belok.se/wp-content/uploads/2023/01/Rapport_tappvarmvatten_BELOK.pdf.

BELOK. 2026. "Totalmetodiken." Belok. https://belok.se/totalmetodiken/.

Berggren, Björn, and Maria Wall. 2013. "Calculation of Thermal Bridges in (Nordic) Building Envelopes – Risk of Performance Failure Due to Inconsistent Use of Methodology." *Energy and Buildings* 65 (October): 331–39. https://doi.org/10.1016/j.enbuild.2013.06.021.

Björk, Cecilia, Per Kallstenius, and Laila Reppen. 2021. *Så byggdes husen 1880–2020: arkitektur, konstruktion och material i våra flerbostadshus under 140 år*. 8th ed. Svensk Byggtjänst.

Boverket. 1993. *Boverkets Byggregler (BBR 94)*. BFS 1993:57. Boverket. https://rinfo.boverket.se/BFS1993-57/pdf/BFS1993-57.pdf.

Boverket. 2006. *Boverkets föreskrifter om ändring i verkets byggregler (1993:57) – föreskrifter och allmänna råd;* BFS 2006:12. Boverket.

Boverket. 2016. *Boverkets föreskrifter och allmänna råd om fastställande av byggnadens energianvändning vid normalt brukande och ett normalår*. BFS 2017:6. https://rinfo.boverket.se/BFS2016-12/pdf/BFS2017-6.pdf.

Boverket. 2018. *Boverket's Mandatory Provisions and General Recommendations, BBR (BFS 2011:6 with Amendments up to BFS 2018:4)*. Boverket.

Boverket. 2024. *Preliminära beräkningar av gränsvärden för energiprestanda i befintliga lokalbyggnader*. Dnr: 3894/2024. Boverket. https://www.boverket.se/globalassets/publikationer/dokument/2024/preliminara-berakningar-av-gransvarden-for-energiprestanda-i-befintliga-lokalbyggnader.pdf.

Boverket. 2025. "Tidplan och hållpunkter för energiprestandadirektivet, EPBD." October 13. https://www.boverket.se/sv/byggande/uppdrag/direktiv-for-byggnaders-energiprestanda/tidplan-energiprestandadirektivet/.

Boverket. 2026a. "Direktiv för byggnaders energiprestanda, EPBD." March 18. https://www.boverket.se/sv/byggande/uppdrag/direktiv-for-byggnaders-energiprestanda/.

Boverket. 2026b. "Energiguiden." March 19. https://www.boverket.se/sv/energiguiden/.

Boverket. 2026c. "Klimatdatabas." https://klimatdatabasen.boverket.se/navigera/7.

Boverket. 2026d. "Räkna På Lönsamhet." 2026. Boverket. https://www.boverket.se/sv/energiguiden/energieffektivisera-flerbostadshus/energirenovera/byggide/valja-atgarder/rakna-pa-lonsamhet/.

Boverkets Allmänna Råd Om Funktionskontroll Av Ventilationssystem, BFS 2012:7 Boverkets författningssamling (BFS) (2012).

Boverkets byggregler (BBR 29): föreskrifter och allmänna råd, med ändringar t.o.m. BFS 2020:4 BFS 2011:6 (2011). https://rinfo.boverket.se/BFS2011-6/dok/BFS2020-4_Konsolidering.pdf.

Boverkets Föreskrifter Om Ändring i Verkets Byggregler (BBR), BFS 1998:38, BFS 1998:38 Boverkets författningssamling (1998).

CEN; SIS. 2021. *SS-EN 12464-1:2021*. SS-EN 12464-1:2021. Light and lighting — Lighting of work places — Part 1: Indoor work places. CEN (European Committee for Standardization); SIS (Swedish Institute for Standards).

Coakley, Daniel, Paul Raftery, and Marcus Keane. 2014. "A Review of Methods to Match Building Energy Simulation Models to Measured Data." *Renewable and Sustainable Energy Reviews* 37 (September): 123–41. https://doi.org/10.1016/j.rser.2014.05.007.

Commission Delegated Regulation (EU) No 244/2012. 2012. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32012R0244.

Cuerda, Elena, Olivia Guerra-Santin, Juan José Sendra, and Fco. Javier Neila. 2020. "Understanding the Performance Gap in Energy Retrofitting: Measured Input Data for Adjusting Building Simulation Models." *Energy and Buildings* 209 (February): 109688. https://doi.org/10.1016/j.enbuild.2019.109688.

De Wilde, Pieter. 2014. "The Gap between Predicted and Measured Energy Performance of Buildings: A Framework for Investigation." *Automation in Construction* 41 (May): 40–49. https://doi.org/10.1016/j.autcon.2014.02.009.

Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the Energy Performance of Buildings, Directive 2002/91/EC 65 (2002). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32002L0091.

Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (Recast), Directive 2010/31/EU (2010). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32010L0031.

Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 Amending Directive 2010/31/EU on the Energy Performance of Buildings and Directive 2012/27/EU on Energy Efficiency, Directive (EU) 2018/844 75 (2018). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32018L0844.

Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the Energy Performance of Buildings (Recast), Directive (EU) 2024/1275 (2024). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202401275.

Dronkelaar, Chris van, Mark Dowson, E. Burman, Catalina Spataru, and Dejan Mumovic. 2016. "A Review of the Energy Performance Gap and Its Underlying Causes in Non-Domestic Buildings." *Frontiers in Mechanical Engineering* 1 (January). https://doi.org/10.3389/fmech.2015.00017.

Dronkelaar, Chris van, Mark Dowson, Catalina Spataru, Esfand Burman, and Dejan Mumovic. 2019. "Quantifying the Underlying Causes of a Discrepancy Between Predicted and Measured Energy Use." *Frontiers in Mechanical Engineering* 5 (May). https://doi.org/10.3389/fmech.2019.00020.

Economidou, M., V. Todeschi, P. Bertoldi, D. D'Agostino, P. Zangheri, and L. Castellazzi. 2020. "Review of 50 Years of EU Energy Efficiency Policies for Buildings." *Energy and Buildings* 225 (October): 110322. https://doi.org/10.1016/j.enbuild.2020.110322.

Ekberg, Lars. 2006. *R1 – Riktlinjer för specifikation av inneklimatkrav*. Energi- och Miljötekniska Föreningen.

Ekström, Tomas, Stephen Burke, Magnus Wiktorsson, Samer Hassanie, Lars-Erik Harderup, and Jesper Arfvidsson. 2021. "Evaluating the Impact of Data Quality on the Accuracy of the Predicted Energy Performance for a Fixed Building Design Using Probabilistic Energy Performance Simulations and Uncertainty Analysis." *Energy and Buildings* 249 (0). https://doi.org/10.1016/j.enbuild.2021.111205.

Energi i bebyggelsen – tekniska egenskaper och beräkningar – resultat från projektet BETSI. 2010. Boverket. https://www.boverket.se/globalassets/publikationer/dokument/2011/betsi-energi-i-bebyggelsen.pdf.

Energimarknadsinspektionen (Ei). 2021. "Ekonomiska uppgifter - fjärrvärme." Text. Energimarknadsinspektionen (Ei). https://ei.se/om-oss/statistik-och-oppna-data/ekonomiska-uppgifter---fjarrvarme.

European Commission. 2012. *Commission Regulation (EU) No 622/2012 of 11 July 2012 Amending Regulation (EC) No 641/2009 with Regard to Ecodesign Requirements for Glandless Standalone Circulators and Glandless Circulators Integrated in productsText with EEA Relevance*. Official Journal of the European Union L 108. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32012R0622.

European Commission. 2020. *A Renovation Wave for Europe – Greening Our Buildings, Creating Jobs, Improving Lives*. COM(2020) 662 final. European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0662.

Flodberg, Kajsa, Åke Blomsterberg, and Marie-Claude Dubois. 2012. “Low-Energy Office Buildings Using Existing Technology: Simulations with Low Internal Heat Gains.” *International Journal of Energy and Environmental Engineering* 3 (1): 19. https://doi.org/10.1186/2251-6832-3-19.

Gangolells, Marta, Katia Gaspar, Miquel Casals, Jaume Ferré-Bigorra, Nuria Forcada, and Marcel Macarulla. 2020. “Life-Cycle Environmental and Cost-Effective Energy Retrofitting Solutions for Office Stock.” *Sustainable Cities and Society* 61: 102319. https://doi.org/10.1016/j.scs.2020.102319.

Grundfos. 2026. “Grundfos.” https://www.grundfos.com/se.

Grundfos Product Center. 2026. “Grundfos Product Center | Sizing and Selection of Pumps and Pump Solutions.” https://product-selection.grundfos.com/.

Hesaraki, Arefeh, and Sture Holmberg. 2015. “Demand-Controlled Ventilation in New Residential Buildings: Consequences on Indoor Air Quality and Energy Savings.” *Indoor and Built Environment* 24 (2): 162–73. https://doi.org/10.1177/1420326X13508565.

Ilomets, Simo, Kalle Kuusk, Leena Paap, Endrik Arumägi, and Targo Kalamees. 2016. “IMPACT OF LINEAR THERMAL BRIDGES ON THERMAL TRANSMITTANCE OF RENOVATED APARTMENT BUILDINGS.” *JOURNAL OF CIVIL ENGINEERING AND MANAGEMENT* 23 (June): 96–104. https://doi.org/10.3846/13923730.2014.976259.

Johansson, D. 2023. *Supply and Exhaust Ventilation with Heat and Moisture Recovery*. Lund University.

Johansson, Pär, Paula Wahlgren, and Petra Eriksson. 2020. *Interior Super Insulation in Heritage Buildings: Challenges and Possibilities to Conserve Heritage Values and Increase Energy Performance*. Report ACE 2020:2. Chalmers University of Technology, Department of Architecture and Civil Engineering, Division of Building Technology, Research Group Building Physics Modelling.

Kalaycioglu, E., and A. Z. Yilmaz. 2018. “A New Approach Proposed to Evaluate the Cost Optimal and Nearly Zero Energy Levels of Buildings and District Energy Systems Together in Settlements.” Paper presented at uSIM18 Urban Energy Simulation. *Proceedings of uSim Conference 2018*, November 30. https://publications.ibpsa.org/proceedings/usim/2018/papers/usim2018_022.pdf?utm_source=chatgpt.com.

Karlsson Hjorth, Hans-Olof, Linda Lagnerö, Emma Svensson, Lin Liljefors, Mikael Näslund, and Roger Antonsson. 2021. *Implementation of the EPBD in Sweden: Status in 2021*. Concerted Action EPBD. https://www.ca-epbd.eu/outputs-archive/2021/sweden-incl-kiandds-2020.

Kempe, Per. 2025. “Reducing the Energy Performance Gap through Stepwise Verification of Building and System Functions.” *Journal of Building Performance Simulation* 18 (5–6): 611–30. https://doi.org/10.1080/19401493.2024.2416684.

“Ladybug Tools | Honeybee.” 2025. https://www.ladybug.tools/honeybee.html.

Lag (2006:985) Om Energideklaration För Byggnader, 2006:985 (2006). https://rkrattsbaser.gov.se/sfst?bet=2006:985.

Lång, Lukas, and Efraim Sandgren. 2016. “Renovation of Brick Buildings Constructed 1870-1930: Investigation of the Thermal Envelope in Renovated and Re-Renovated Dwellings.” Chalmers University of Technology, Department of Civil and Environmental Engineering, Division of Building Technology, Building Physics.

Larsson, Tomas, and Björn Berggren. 2015. *Undvik fel och fällor med köldbryggor*. Svenska Byggbranschens Utvecklingsfond (SBUF).

Lassen, N., G. Chaudhary, T. H. Dokka, P. B. Nordahl, and K. Dokka. 2024. "Closing the Gap between Theoretical Models and Real-Time Measurements - The SmartTune Initiative." 562: 10006. https://doi.org/10.1051/e3sconf/202456210006.

Li, Jie, Lisa Domenica Iulo, and Ute Poerschke. 2023. "A Review of the Energy Performance Gap between Predicted and Actual Use in Buildings." Paper presented at 2023 Building Simulation Conference. September 4. https://doi.org/10.26868/25222708.2023.1430.

Liang, Xin, Tianzhen Hong, and Geoffrey Qiping Shen. 2016. "Occupancy Data Analytics and Prediction: A Case Study." *Building and Environment* 102 (June): 179–92. https://doi.org/10.1016/j.buildenv.2016.03.027.

Liébana-Durán, María Esther, Begoña Serrano-Lanzarote, and Leticia Ortega-Madrigal. 2021. "Identification of Cost-Optimal Measures for Energy Renovation of Thermal Envelopes in Different Types of Public School Buildings in the City of Valencia." *Applied Sciences* 11 (11): 5108. https://doi.org/10.3390/app11115108.

Liu, Pei, Borong Lin, Xiaoying Wu, and Hao Zhou. 2019. "Bridging Energy Performance Gaps of Green Office Buildings via More Targeted Operations Management: A System Dynamics Approach." *Journal of Environmental Management* 238 (May): 64–71. https://doi.org/10.1016/j.jenvman.2019.02.111.

Maripuu, Mari-Liis, and Lennart Jagemar. 2005. "Energy Savings by Changing Constant Air Volume Systems (CAV) to Variable Air Volume Systems (VAV) in Existing Office Buildings."

Markusson, Caroline. 2011. "Efficiency of Building Related Pump and Fan Operation." PhD, Chalmers University of Technology.

Martín-Garín, Alexander, José Millán-García, Juan Maria Hidalgo-Betanzos, Rufino Hernández, and Abderrahmane Baïri. 2020. "Airtightness Analysis of the Built Heritage–Field Measurements of Nineteenth Century Buildings through Blower Door Tests." *Energies* 13 (December). https://doi.org/10.3390/en13246727.

Masonry and Masonry Products - Methods for Determining Thermal Properties (2026).

Menezes, Anna Carolina, Andrew Cripps, Dino Bouchlaghem, and Richard Buswell. 2012. "Predicted vs. Actual Energy Performance of Non-Domestic Buildings: Using Post-Occupancy Evaluation Data to Reduce the Performance Gap." *Applied Energy*, Energy Solutions for a Sustainable World - Proceedings of the Third International Conference on Applied Energy, May 16-18, 2011 - Perugia, Italy, vol. 97 (September): 355–64. https://doi.org/10.1016/j.apenergy.2011.11.075.

Moshfegh, B., P. Rohdin, V. Milic, A. Donarelli, P. Eriksson, and T. Broström. 2018. "A Method to Assess the Potential for and Consequences of Energy Retrofits in Swedish Historic Districts." *Energy Efficiency in Historic Buildings 2018*, 302–10.

Newsham, Guy R., Sandra Mancini, and Benjamin J. Birt. 2009. "Do LEED-Certified Buildings Save Energy? Yes, But…." *Energy and Buildings* 41 (8): 897–905. https://doi.org/10.1016/j.enbuild.2009.03.014.

Nils Holgersson-gruppen. 2024. *Nils Holgersson | Fjärrvärme 2024*. Nils Holgersson-gruppen. https://nilsholgersson.nu/rapporter/rapport-2024/fjarrvarme-2024/.

Nilsson, Lars J. 1995. "Air-Handling Energy Efficiency and Design Practices." *Energy and Buildings* 22 (1): 1–13. https://doi.org/10.1016/0378-7788(94)00882-K.

Persson, Agneta, Egil Öfverholm, Krister Mars, Kristina Landfors, Anders Göransson, and Magnus Stjerndahl. 2025. *Detaljerad energistatistik för kontor – En del av den tredje undersökningen av statistik i lokaler (STIL3)*. ER 2025:25. Statens energimyndighet. https://energimyndigheten.a-w2m.se/System/TemplateView.aspx?p=Arkitektkopia&id=1872b02eb4334b0ca3f88c8d03d41eb3&l=t&view=672&cat=%2FResurseffektiva%20byggnader.

Pettersen, Ida Nilstad, Elli Verhulst, Roberto Valle Kinloch, Antje Junghans, and Thomas Berker. 2017. "Ambitions at Work: Professional Practices and the Energy Performance of Non-Residential Buildings in Norway." *Energy Research & Social Science*, Energy Consumption in Buildings:, vol. 32 (October): 112–20. https://doi.org/10.1016/j.erss.2017.02.013.

Plan- Och Byggförordning, SFS 2011:338 Svensk författningssamling (SFS) § 5 kap. 2–6 §§ (2011).

Pombo, Olatz, Karen Allacker, Beatriz Rivela, and Javier Neila. 2016. "Sustainability Assessment of Energy Saving Measures: A Multi-Criteria Approach for Residential Buildings Retrofitting—A Case Study of the Spanish Housing Stock." *Energy and Buildings* 116 (March): 384–94. https://doi.org/10.1016/j.enbuild.2016.01.019.

Robert McNeel & Associates. 2025. "Rhinoceros 3D." Www.Rhino3d.Com. https://www.rhino3d.com/en/emea/.

Roulet, C. A., F. D. Heidt, F. Foradini, and M. C. Pibiri. 2001. "Real Heat Recovery with Air Handling Units." *Energy and Buildings* 33 (5): 495–502.

SCB. 2024. "Electricity Prices for Households and Non-Residential Premises." Statistics Sweden (SCB). Statistikdatabasen. https://www.statistikdatabasen.scb.se:443/pxweb/en/ssd/START_EN_EN0301_EN0301A/SSDHalvarElHus/.

Shaikh, P. H., F. Shaikh, A. A. Sahito, M. A. Uqaili, and Z. Umrani. 2017. "An Overview of the Challenges for Cost-Effective and Energy-Efficient Retrofits of the Existing Building Stock." In *Cost-Effective Energy-Efficient Building Retrofitting*. Elsevier. https://doi.org/10.1016/B978-0-08-101128-7.00009-5.

Signify N.V. 2024. *Environmental Product Declaration: MASTER UltraEfficient LED Bulb A Shape — COMF-8932020*. COMF-8932020. EPD Hub.

Simanic, Branko, Birgitta Nordquist, Hans Bagge, and Dennis Johansson. 2020. "Predicted and Measured User-Related Energy Usage in Newly Built Low-Energy Schools in Sweden." *Journal of Building Engineering* 29 (May): 101142. https://doi.org/10.1016/j.jobe.2019.101142.

SINTEF Building and Infrastructure. 2016. *Heat Recovery in Ventilation Systems: Field Performance and Measurement Uncertainty*.

Statens planverk. 1980. *Svensk Byggnorm 1980 (SBN 1980)*. ISSN 0348-1441. LiberFörlag / Allmänna förlaget.

Stockholms stad. 2026. "Ärenden - Ritningar Och Handlingar - Bygg- Och Plantjänsten." https://etjanster.stockholm.se/Byggochplantjansten/arendeochhandlingar.

Summary of Linear (T8) LED Lamp Testing. 2014. PNNL-SA-103319. Pacific Northwest National Laboratory. https://www.energy.gov/eere/ssl/led-linear-lamps-and-troffer-lighting.

Sundlöf, Klara. 2022. "Status and Risk Assessment as Decision Support for Energy Efficiency Measures in Historical Buildings: Testing and Development of the '3B' Method." University of Gothenburg, Department of Conservation.

Sveby. 2012. *Brukarindata kontor – Version 1.1*. Sveby. https://www.sveby.org/wp-content/uploads/2013/06/Brukarindata-kontor-version-1.1.pdf.

Sveby. 2026. "Sveby | Branschstandard för energi i byggnader." https://www.sveby.org/.

Svensson, Yvonne. n.d. *Boverkets författningssamling*.

Sweden Green Building Council. 2020. *Miljöbyggnad 3.1 – Nybyggnad*. Sweden Green Building Council. https://www.sgbc.se/app/uploads/2020/05/Milj%C3%B6byggnad-3.1-Nybyggnad.pdf.

Swedish Institute for Standards. 2017. *Energy Performance of Buildings – Economic Evaluation Procedure for Energy Systems in Buildings – Part 1: Calculation Procedures*. SS-EN 15459-1:2017(E). SIS Förlag AB.

Swegon A/S. 2026. "Prisliste 2026: Armaturer, Spjæld, Lyddæmpere, Brandkomponenter Og Kølebafler." Brøndby, Denmark. https://www.swegon.com/globalassets/digizuite/13696-en-roomunits_pricelist_da.pdf.

Swegon Group AB. 2025. "AHU Design: Air Handling Unit Selection Software." Version 4.7.0. Västra Frölunda, Sweden. https://sds.swegon.com/.

Tian, Wei, Pieter De Wilde, Zhanyong Li, Jitian Song, and Baoquan Yin. 2018. "Uncertainty and Sensitivity Analysis of Energy Assessment for Office Buildings Based on Dempster-Shafer Theory." *Energy Conversion and Management* 174 (October): 705–18. https://doi.org/10.1016/j.enconman.2018.08.086.

Tian, Wei, Yeonsook Heo, Pieter De Wilde, et al. 2018. "A Review of Uncertainty Analysis in Building Energy Assessment." *Renewable and Sustainable Energy Reviews* 93 (October): 285–301. https://doi.org/10.1016/j.rser.2018.05.029.

Turner, Cathy. 2008. "Turner: Energy Performance of LEED for New Construction... - Google Scholar." https://scholar.google.com/scholar_lookup?title=Energy%20performance%20of%20LEED%20for%20new%20construction%20buildings%20(Final%20Report)&author=C.%20Turner&publication_year=2008.

Valdiserri, Paolo, and Cesare Biserni. 2016. "Energy Performance of an Existing Office Building in the Northern Part of Italy: Retrofitting Actions and Economic Assessment." *Sustainable Cities and Society* 27 (November): 65–72. https://doi.org/10.1016/j.scs.2016.07.009.

Wahlgren, Paula, and Eva Sikander. 2010. "Methods and Materials for an Airtight Building." *ASHRAE Transactions* 116 (Part 2).

Wahlström, Åsa. 2008. "Trade Introduction of a New Building Code with Requirements for Energy Performance."

Wikells Byggberäkningar AB. 2026. "Wikells Byggberäkningar." Wikells. https://wikells.se/.

Yan, Da, William O'Brien, Tianzhen Hong, et al. 2015. "Occupant Behavior Modeling for Building Performance Simulation: Current State and Future Challenges." *Energy and Buildings* 107 (November): 264–78. https://doi.org/10.1016/j.enbuild.2015.08.032.

Yang, Zheng, and Burcin Becerik-Gerber. 2015. "A Model Calibration Framework for Simultaneous Multi-Level Building Energy Simulation." *Applied Energy* 149 (July): 415–31. https://doi.org/10.1016/j.apenergy.2015.03.048.

"Zerotude." 2026. Zerotude. https://www.zerotude.io/.

Zhang, Xueqing, and Hui Gao. 2010. "Optimal Performance-Based Building Facility Management." *Computer-Aided Civil and Infrastructure Engineering* 25 (4): 269–84. https://doi.org/10.1111/j.1467-8667.2009.00633.x.

Zheng, Zhihang, Jin Zhou, Zhu Jiaqin, Ying Yang, Feng Xu, and Hongcheng Liu. 2024. "Review of the Building Energy Performance Gap from Simulation and Building Lifecycle Perspectives: Magnitude, Causes and Solutions." *Developments in the Built Environment* 17 (March): 100345. https://doi.org/10.1016/j.dibe.2024.100345.

Zou, Patrick X. W., Xiaoxiao Xu, Jay Sanjayan, and Jiayuan Wang. 2018. "Review of 10 Years Research on Building Energy Performance Gap: Life-Cycle and Stakeholder Perspectives." *Energy and Buildings* 178 (November): 165–81. https://doi.org/10.1016/j.enbuild.2018.08.040.

Zou, Yanke. 2010. "Classification of Buildings with Regard to Airtightness." Master's Thesis, Chalmers University of Technology. https://hdl.handle.net/20.500.12380/139940.

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