EVALUATING THE ENVIRONMENTAL PAYBACK TIME OF ENERGY IMPROVEMENT MEASURES FOR SMALL OFFICE BUILDING RETROFITS IN THE NETHERLANDS

Analysing the environmental exploitation of retrofitting a small office building with energy improvement measures aimed at reducing energy consumption and carbon emissions to reach the ultimate goal of a Paris-proof building (Net-zero Energy & Carbon)

Laurens van der Laan
5942403

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First assessor: Herman van de Putte
Second assessor: Michaël Peeters
Third assessor: Jorg de Jonge (PhD)

Abstract

Introduction
The decarbonisation of the built environment is a crucial step towards meeting the Paris climate agreement. In the Netherlands, this decarbonisation is incentivised with the BENG and a mandatory minimum EPC label C for all office buildings. While energy improvement measures (EIMs) are widely adopted to reduce operational carbon, their environmental payback, meaning the time needed to offset the embodied carbon introduced during retrofitting, remains under-researched, particularly for small office buildings.

Aim and methods
This study investigates the environmental payback time of common EIMs in retrofitting small office buildings (100, 200 and 500m^2) in the Dutch context. A simulation-based experimental approach was used, modelling four scenarios: baseline, hybrid, full-electric, and full-electric with PV panels across the three building sizes. Operational energy use and emissions were calculated using Vabi Elements software, while embodied carbon was assessed through the Whole Life Carbon Assessment (WLCA) framework using the input from the Ökobaudat EPD/LCA database.

Results
Results show energy reductions between 56% and 78%, depending on retrofit depth, with smaller buildings exhibiting proportionally higher savings. However, operational carbon reductions were not always proportional in relation to the energy reduction, due to the carbon intensity of grid electricity. Embodied carbon varied greatly, especially between biobased and conventional materials, and was also significantly influenced by the PV system. Payback times ranged from less than 1 year (in the 500m^2 biobased retrofits) to over 6 years (in small 100m^2 conventional+ PV scenario).

Conclusion
This research confirms that, despite variability, all retrofits examined achieved environmental payback well within the lifespan of the implemented measures. The findings underscore the importance of material choice and highlight the growing value of biobased solutions. They also suggest that hybrid systems, in light of the payback times, can offer a better solution as long as the electricity grid is not decarbonising rapidly and there is no access to renewable energy. These insights ultimately support informed, lifecycle-based retrofit decision-making.

Keywords
Sustainability - Office buildings - Energy improvement measures (EIMs) – Environmental exploitation – Embodied Carbon – Operational Carbon – Environmental Payback Time – Building Retrofit

Preface

This thesis marks the final milestone of my master's degree in Management in the Built Environment at the TU Delft. It not only reflects the culmination of the research I have done over the past year, but also my journey that led to the result of this thesis.
Throughout this process, I have deepened my understanding of sustainability practices, with a focus on energy improvement measures, operational and embodied carbon emissions, and their net impact on the climate within the corporate real estate sector. The challenges I encountered, the insights I gained, and the support I received along the way have all contributed to shaping both the thesis and my development as a future professional in the field.

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Herman continuously challenged me with his critical perspective and steadfast opinions, which were very welcome to shape both the subject and structure of this thesis. Michaël, with his creative mind, regularly brought fresh and innovative ideas to the table, sparking new perspectives and always responding promptly to my questions. Jorg supported me with practical insights and regularly shared up-to-date developments related to my thesis topic.

I am also grateful to Vabi for granting access to their simulation software and providing expert consultation. Their support significantly helped me in understanding the technical aspects of the tool, enabling me to implement the different retrofit packages effectively and confidently.

Finally, a huge thank you to my family, girlfriend, and friends, and especially my parents, for their unconditional support, thoughtful conversations, and the encouraging words that kept me going during the more demanding moments of this long and challenging process.

Management summary

Chapter 1: introduction, literature review, problem statement

Introduction
The urgency to decarbonise the built environment is becoming bigger, driven by international climate commitments and national regulations. In the Netherlands, all office buildings are now required to meet at least EPC label C, with more ambitious standards coming up under European legislation such as the EPBD IV and the ETS 2. These developments reflect a broader shift towards net-zero operational and embodied emissions by 2050. However, while operational energy use is widely targeted through energy improvement measures (EIMs), the environmental cost of implementing these measures is often overlooked.

Literature review
Numerous studies support the efficacy of energy improvement measures (EIMs). Literature shows that light retrofits can yield energy savings of around 25%, while deep retrofits that include holistic system upgrades can achieve reductions of over 60%. Integrated approaches that combine passive and active measures are considered most effective, particularly when executed with a long-term, life-cycle perspective.

However, the climate benefits of these measures are sometimes questioned when viewed through the lens of whole life carbon. As pointed out by Hollyman et al. (2024) and Bienert (2023), reducing operational emissions often comes at the cost of increasing embodied emissions. Despite operational energy savings, the total climate benefit of a retrofit can be compromised if embodied emissions are too high or if operational reductions take too long to compensate for the initial carbon investment.

To assess this trade-off, the concept of carbon payback time is introduced. This metric quantifies the number of years it takes for operational carbon savings to offset the embodied emissions of the retrofit.

Several studies demonstrate that carbon payback times can vary significantly, from under two years for light retrofits to over ten years when high-carbon materials or systems like PV panels are involved. These variations are influenced not only by the scope and size of the intervention but also by material choices and the carbon intensity of the local energy grid.

Research gap and problem statement
Despite growing attention and knowledge about embodied carbon and payback times, the body of research specifically addressing the impacts of energy-improving retrofits is still behind. Moreover, the majority of existing studies in this field seem to rely on case studies

or simulation-based assessments of relatively large office buildings, or residential buildings outside the Dutch context.

Given the increasing regulatory and environmental pressures, there is a clear need to evaluate whether retrofitting small office buildings leads to a net environmental gain. Therefore, this study addresses that gap by assessing the carbon payback time of typical retrofit strategies in small office buildings in the Netherlands. It aims to inform future policy and retrofits by identifying which combinations of energy improvement measures offer the most efficient environmental return over time.

Chapter 3: Theoretical background

Corporate real estate (CRE) is no longer just about physical space; it has become a strategic asset in the climate transition. With growing attention to ESG performance and climate risk, CRE managers are now increasingly responsible for integrating carbon accounting into decision-making. This includes both operational and embodied emissions, especially in the context of retrofits that can either mitigate or accelerate climate-related asset risks.

To measure these emissions, it is important to have an accurate measurement of energy performance, which forms the basis for understanding operational emissions. In the Netherlands, the NTA 8800 methodology is the mandatory standard for calculating energy use and assigning EPC labels. However, this method is based on standardised assumptions and theoretical performance, which can differ significantly from real-world energy use. As an alternative, the WEii (Werkelijke Energie-intensiteit Indicator) offers a data-driven view of actual energy consumption, thereby improving transparency and comparability across assets. Nevertheless, for the purposes of this study, energy performance had to be simulated. This is done by using Vabi Elements using the NTA 8800 standards to enable a consistent comparison of retrofit scenarios.

While operational energy modelling is crucial for assessing operational emissions, a full environmental assessment must also account for the embodied carbon introduced during retrofitting. This study adopts the Whole Life Carbon assessment (WLCA) framework to calculate embodied emissions using environmental product data (EPD) from the Ökobaudat database, which provides detailed life cycle information for building materials.

Chapter 5: Research methods

For this research, an experimental approach has been chosen, centred around a developed case study model. This methodology involves creating a baseline 'standard' office building in three different sizes, 100m^2, 200m^2 and 500m^2, and simulating various retrofit scenarios to evaluate their effects.

The primary objective is to calculate the environmental payback time of the measures that are focused on improving the energy consumption of the building. The retrofit scenarios that were created are as follows:

- Scenario 1: Baseline (no improvements, gas boiler)
- Scenario 2: Hybrid (gas boiler + heat pump, with envelope upgrades including raff stores, isolation, double paned glass and mechanical ventilation with heat recovery)
- Scenario 3: Full-electric (scenario 2 + low temperature floor heating and without gas boiler)
- Scenario 3+: Full-electric + PV panels

These scenarios integrate a set of widely recognised energy improvement measures (EIMs), that were found in the literature review. To then assess the operational performance of these scenarios, building simulations were conducted using Vabi Elements. This enabled the estimation of energy demand and associated operational carbon emissions.

For the analysis of embodied carbon, the Whole Life Carbon Assessment (WLCA) methodology was adapted. The scope of this research was limited to only the WLC of the retrofit and life cycle modules A and C. The EPD data was retrieved from the Ökobaudat database, and each retrofit scenario was modelled in two material variants: one based on conventional construction materials and one incorporating biobased alternatives. This dual-modelling approach allowed for the comparative evaluation of embodied emissions based on material selection. Lastly, also material-related emissions are calculated using the calculation protocol "Paris-proof material-related emission" to express material-related emissions in kg CO_2-eq per m^2 and see if they stay beneath the Paris-proof thresholds.

Chapter 6: Results and discussion

Simulation results indicate that energy consumption was reduced by 56% to 78% across the evaluated retrofit scenarios, with the depth of intervention and building size playing a significant role. Smaller buildings showed proportionally higher energy savings than bigger buildings, most likely a result of scaling effects. Furthermore, operational CO_2 reductions did not always change proportionally with energy use, largely due to the remaining carbon intensity of the Dutch electricity grid.

Embodied carbon emissions varied substantially, primarily driven by material selection and system configuration. Scenarios incorporating biobased materials consistently showed significantly lower upfront emissions compared to conventional alternatives. The integration of PV systems also led to significantly higher embodied emissions.

In this research, carbon payback times ranged from less than 1 year, in the 500 m^2 biobased hybrid scenario, to over 6 years in the 100 m^2 full-electric + PV scenario using conventional materials. These results underline that material choice, building size, and system type are important factors in calculating the payback times.

The hybrid retrofit scenario emerged as a pragmatic middle ground, combining moderate operational savings with low embodied impact. This can be relevant in a context where the electricity grid is still partially reliant on fossil fuels. Finally, the discussion highlights the value of a phased retrofit strategy, emphasises the need for improved consistency in environmental databases, and questions the adequacy of energy labels as a sole indicator of retrofit performance. A lifecycle carbon perspective, rather than a focus on energy alone, seems essential for making climate-responsible renovation decisions.

Chapter 7: Conclusion

This research shows that retrofitting small office buildings towards net-zero energy can result in significant energy and carbon savings; However, the environmental impact seems to depend on material choice, system configuration, and building size. While energy reductions ranged from 46% to 78%, operational CO_2 savings were not always proportional, highlighting that hybrid systems can outperform full-electric solutions under current grid conditions. Embodied emissions varied widely, with biobased materials substantially lowering the carbon investment, and in some cases even achieving overall net-negative values. Despite these differences, all tested retrofit scenarios reached environmental payback well within the technical lifespan of their components, with payback times ranging from less than one to just over six years.

Chapter 8: Recommendations

- Ensure consistency in EPD databases
- Promote biobased materials with carbon storage
- Include PV capacity in full-electric assessments
- Implement a phased retrofit strategy
- Use carbon payback time in policy tools
- Account for the time value of carbon

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ABBREVIATIONS

BENG	Bijna Energie Neutrale Gebouwen (Nearly Energy Neutral Buildings)
BIM	Building Information Modelling
BPS	Building Performance Simulation
Capex	Capital Expenditure
CO_2-eq	Carbon Dioxide Equivalent
ComRE	Commercial Real Estate
CRE	Corporate Real Estate
CREM	Corporate Real Estate Management
CSRD	Corporate Sustainability Reporting Directive
DGBC	Dutch Green Building Council
EED	Energy Efficiency Directive
EIM	Energy Improvement Measure
EOL	End-of-Life
EPC	Energy Performance Coefficient / Energy Performance Certificate (context-specific)
EPBD	Energy Performance of Buildings Directive
EPD	Environmental Product Declaration
ESG	Environmental, Social, and Governance
ETS2	Emissions Trading System 2 (EU)
GFA	Gross Floor Area
GHG	Greenhouse Gas
HSB	Houtskeletbouw (Timber Frame Construction)
HVAC	Heating, Ventilation, and Air Conditioning
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
MJOP	Meerjaren Onderhoudsplan (Multi-Year Maintenance Plan)
MPG	MilieuPrestatie Gebouwen (Environmental Performance of Buildings)

nZEB	Nearly Zero Energy Building
NMD	Nationale Milieudatabase
NTA 8800	Nederlandse Technische Afspraak 8800 (Dutch Energy Performance Calculation Method)
Opex	Operational Expenditure
Ökobaudat	German environmental product declaration database
PCAF	Partnership for Carbon Accounting Financials
PV	Photovoltaic (Solar Panels)
RICS	Royal Institution of Chartered Surveyors
RVO	Rijksdienst voor Ondernemend Nederland (Netherlands Enterprise Agency)
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (Netherlands Organisation for Applied Scientific Research)
WEii	Werkelijke Energie Intensity Indicator (Actual Energy Intensity Indicator)
WENG	Werkelijk Energie Neutraal Gebouw (Truly Energy Neutral Building)
WLC	Whole Life Carbon
WLCA	Whole Life Carbon Assessment
WGBC	World Green Building Council
WWR	Window-to-Wall Ratio
ZEB	Zero Emission Building

1. INTRODUCTION

The growing emphasis on sustainability in the built environment is transforming the way construction projects are evaluated and financed (WEF, 2024). A crucial aspect of this shift is the role of Environmental, Social, and Governance (ESG) ratings and their integration in the Corporate Sustainability Reporting Directive (CSRD) (Deloitte, 2022), which increasingly influences investment decisions and financial support mechanisms (EY, 2021). One of these now mandatory investment decisions in the Netherlands is the sustainability improvement of office buildings.

Office buildings in the Netherlands must have at least energy label C as of January 1, 2023 (NOS, 2022). This means that a building must have a maximum primary fossil energy consumption of 225 kWh per m^2 or an energy label with the letter C or better (RVO, 2024a). Meanwhile, 78% of office buildings in the Netherlands meet this energy label. Therefore, some are still lagging (Ministry of Housing, 2024). To win over this last 22%, active enforcement is now being started by randomly checking for energy labels.

Since the real estate sector accounts for 30% of global energy consumption and 39% of total CO_2 emissions (IEA, 2022), no one will deny that making real estate more sustainable is essential to get closer to the Paris climate agreement. In the European Union, these Figures are slightly different, where 40% of the energy consumption and 36% of greenhouse gas emissions are accounted for by buildings (EUR-lex, 2024).

Regulatory changes and incentives for decarbonization in the built environment
To accelerate decarbonisation, the European Commission has now drawn up a new energy directive, also known as EPBD IV, that will be active from the summer of 2026. This new directive shifts the focus from nearly zero energy buildings (as described in EPBD III) to net-zero energy buildings, containing new criteria, such as including energy storage capacity, which also affects the Dutch energy label (DGBC, 2024c; RVO, 2024c). According to this directive from 1 January 2030, all new buildings must be emission-free with the overarching goal that all buildings will be emission-free by 2050. The effect of this guideline on the real estate market is not yet known exactly, but what is central is that the process of sustainability always continues and that an Energy label C of today will no longer be an energy label C in the future.

Furthermore, the introduction of the EU ETS (2) in 2026, a trading platform for carbon credits, into the built environment will create stronger incentives for improving building energy efficiency. Fossil energy suppliers to the building sector will be required to pay for their CO_2 emissions, which could significantly increase energy costs for buildings (De Tijd, 2025; EC, n.d.).

As said the EU aims to achieve fully emission-free buildings by 2050 (RVO, 2024c). This vision entails that all buildings will operate without emitting greenhouse gases, relying solely on renewable energy sources (DGBC, n.d.-b), effectively aligning with the concept of Paris-proof buildings and the Paris Climate agreements (DGBC, n.d.-a)
Achieving these ambitions requires tackling the challenges of **net-zero carbon** and **net-zero energy** building design. Net-zero energy refers to buildings where energy consumption is balanced by renewable energy generated on-site or nearby within a specified timeframe, typically one year. Net-zero carbon, on the other hand, encompasses all life-cycle emissions, ensuring that operational and embodied carbon emissions are offset through measures like renewable energy use and carbon reduction strategies (Maduta et al., 2022).

Transitioning to these standards introduces significant challenges, including the need for improved energy efficiency, large-scale integration of renewable energy sources, and addressing embodied emissions from materials and construction. Furthermore, the slow renovation rates in the EU and the complexity of accounting for life-cycle emissions present additional barriers to achieving fully decarbonised building stock (Maduta et al., 2022). This ambitious goal and previously named interventions underscore the growing importance of sustainability, and it shifts towards reducing Carbon emissions in the built environment.

1.1 Energy Improvements Measures (Systematic literature review)

The road to sustainability within the built environment starts at the core: making energy consumption more efficient and embracing technologies that use renewable energy sources (Chwieduk, 2003). The importance of energy-saving measures extends beyond just reducing costs, they contribute to a world where buildings are no longer a source of pollution, but rather contribute to a cleaner and healthier future. By switching to advanced energy solutions, such as smart heating, ventilation, and cooling (HVAC) systems, solar panels, and insulation improvements, buildings can drastically reduce their environmental impact (IEA, 2022b).

In their report Abu Dabous & Hosny, (2025), identify three possible approaches to building adjustments (Figure 2). In this research, implementing energy improvement measures will be called a retrofit, because it involves adding new components to the building, rather than only improving existing components.

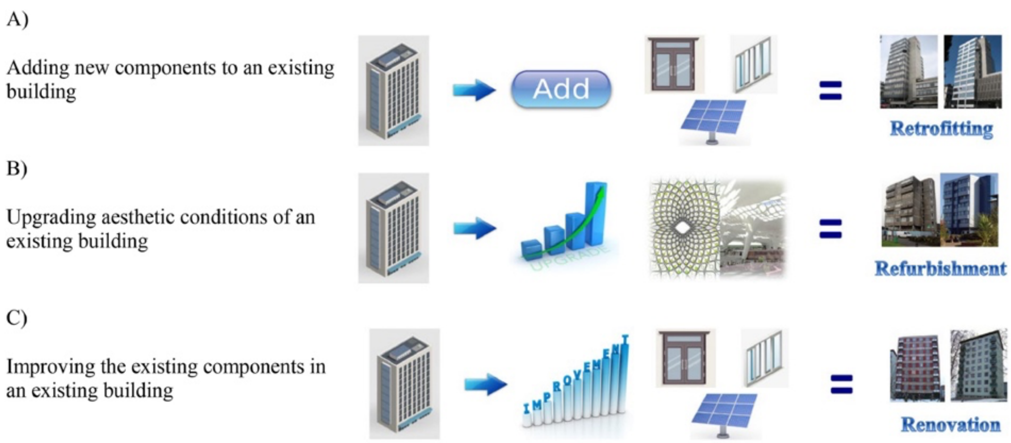

Figure 1, Retrofitting, refurbishment, renovation (source: Abu Dabous & Hosny, 2025)

Energy improvement measures (EIMs) vary in their application and effectiveness. For instance, Ferrari & Beccali, (2017) examined envelope retrofitting, HVAC upgrades, and renewable energy integration, finding that these could reduce primary energy demand by up to 40%.
In the report of the (Hollyman et al., 2024), even higher percentages are presented for different retrofit scenarios (Figure 3), they speak of 26% reduction in optimisation, meaning that after a retrofit the building controls and operational settings in response to the occupant behaviour need to be changed (Hollyman et al., 2024);
40% reduction for light retrofits, typically involving simple modifications or replacements targeting a specific building feature, such as lighting. They may also include preparatory steps that facilitate future deep retrofits, like setting up systems for the eventual integration of heat pumps (Hollyman et al., 2024);
60-65% for Deep retrofits involving extensive interventions that significantly alter a building's structure or systems. These may include multiple light retrofit measures or major changes like replacing core mechanical systems. In this stage, the building should be approached as an integrated system addressing the fabric, HVAC, and energy generation or storage holistically, something that is harder to achieve when upgrades are done incrementally (Hollyman et al., 2024).

SCOPE	RETROFIT MEASURE	WHOLE BUILDING EUI (kWh/m2(GIA)/year) Range	WHOLE BUILDING EUI (kWh/m2(GIA)/year) Mean	EUI REDUCTION (%) Mean impact	EUI REDUCTION (%) Cummulative impact
Median baseline of all datasets:		172			
OPTIMISATION	• BMS upgrade / health check. • Reduce tenant equipment loads.	106-164	127	**26%**	**26%**
LIGHT RETROFIT	• Pump motor replacement • Lighting controls • Low energy lighting	60-162	108	**15%**	**37%**
DEEP RETROFIT PATHWAY 1	• Roof insulation • Building airtightness • Wall insulation • Window replacement • Decarbonisation of heat (ASHP) • ASHP for DHW	15-146	68	**37%**	**60%**
DEEP RETROFIT PATHWAY 2	• Roof insulation • Building airtightness • Façade replacement • Decarbonisation of heat (ASHP) • MVHR • CO_2 Ventilation control • ASHP for DHW	12-138	60	**44%**	**65%**
RENEWABLES	Solar PV	n/a	n/a	**5%** of EUI supplied by Solar PV	

Figure 2, Retrofit scenarios (source: Clark et al., 2024)

These numbers are also presented in research by Bienert, (2023), who researched retrofits with similar measures. In their research, Bienert, (2023), talk about light, medium and deep retrofits (Figure 13) and the same amount of energy reduction is presented (Figure 4).

	Light	Medium	Deep	*New building*[5]
Savings	< 25% of energy consumption	25–50% of energy consumption	> 50% of energy consumption	*n/a*

Figure 3, Energy savings for commercial and residential real estate, found by Bienert, (2023).

Similar to this, in their research, Abu Dabous & Hosny, (2025) state that energy-efficient retrofitting generally consists of targeted upgrades to both the physical structure and the technical systems of a building (Abu Dabous & Hosny, 2025). A key focus is the building envelope, particularly improving the insulation, to meet or surpass the current energy standards. In buildings with a lot off glass in the facades, upgrading windows and integrating solar shading systems are among the most effective strategies for reducing solar heat gain and minimising cooling demand (Abu Dabous & Hosny, 2025). These passive design interventions not only support energy savings but also improve thermal comfort for occupants (Abu Dabous & Hosny, 2025).
They also state that improving the HVAC systems, next to these passive improvements, is essential to reach a proper synchronisation between the passive and active measures so that the maximum result is achieved (Abu Dabous & Hosny, 2025).

The importance of integrated and well-balanced retrofit strategies is further underlined by Moran et al., (2020), who evaluated triple-glazed windows, insulation, and PV panels in Irish residential buildings, emphasising their role in reducing energy demand. Ascione et al., (2017) also highlighted the combined benefits of advanced insulation, efficient lighting, and smart HVAC systems for operational efficiency, while Kneifel, (2010) also stressing the importance of integrated designs that reduce HVAC sizing to maximise energy savings.

In the Dutch context, the EIB, (2020) finds similar measures (Figure 5) to those mentioned above. Linking the measures to specific label improvements from an EPC label of G, having the worst energy performance to a label of A, having the best energy performance.

Maatregel	G-C	F-C	E-C	D-C	C-B	Geren. C-B	C-A	Geren. C-A	C-BENG	Geren. C-BENG	B-A+	Geren. B-A+	A-A+	Geren. A-A+	Geren. B-A	A-BENG	Geren. A-BENG
Vloerisolatie										✓							✓
Spouwmuurisolatie	✓																
Binnengevelisolatie										✓							✓
Dakisolatie										✓		✓		✓			✓
HR++ glas	✓								✓	✓							
Balansventilatie met WTW						✓		✓		✓							
HR107	✓																
Warmtepomp elektrisch (met aquifer)									✓	✓						✓	✓
HF-verlichting	✓			✓	✓		✓										
LED verlichting		✓	✓						✓		✓		✓			✓	
Veegpulsschakeling	✓	✓															
Aanwezigheidsdetectie		✓															
PV (monokristallijn)							✓	✓	✓	✓	✓	✓		✓	✓	✓	✓

Figure 4, Measure Packages and EPC Steps (source: EIB, 2020)

As most of the researches present more or less the same energy improvement measures/retrofit strategies to reduce energy demand, the measures found are displayed in Figure 6

		Action	Concequence
Passive Measures	Wall/Roof/floor Insulation	Upgrading thermal insulation of building envelope	Reduces heat loss/gain, improves thermal comfort, lowers heating/cooling loads
	High-performance Glazing	Installing double/triple glazing or low-E coatings	Reduces solar heat gain and heat loss; improves comfort
	Solar Shading Devices	Adding fixed or dynamic shading to windows	Minimises cooling demand, enhances daylight control
	Airtightness Improvements	Sealing gaps, improving joints	Reduces infiltration, enhances HVAC efficiency
	Lighting Upgrades	Replacing conventional lighting with LEDs	Reduces electricity use and internal heat gains
Active Measures	HVAC System Upgrades	Installing efficient heat pumps or hybrid systems	Matches new load profile and lowers energy demand,
	Smart HVAC Controls	Systems that adjust operation based on demand and occupancy	Optimises performance, improves comfort, reduces waste
	Mechanical Ventilation with Heat Recovery (WTW-units)	Recovers heat from exhaust air to preheat incoming air	Reduces heating needs, improves air quality
	Lighting Control Systems	Daylight or occupancy sensors, dimming controls	Enhances energy savings through intelligent use
Monitoring & Management	Smart Meters and Sub-meters	Devices that monitor consumption in real time	Informs optimisation, supports accountability and diagnostics
	Building Management Systems (BMS)	Centralised control of systems using real-time data	Enables dynamic optimisation and lifecycle management
Renewable Integration	Photovoltaic (PV) Panels	Solar electricity generation on rooftops or façades	Reduces grid dependency, lowers operational carbon emissions

Figure 5, Overview of measures found

All these energy improvement measures, however, also have a downside. As in some of these reports also mentioned, (Hollyman et al., 2024) highlights that operational energy savings often increase embodied carbon, complicating the retrofit process, as this requires an in-depth analysis. The EIB, (2020), also mentions in their report that, because of the electrification, as a result of implementing energy improvement measures such as Heat Pumps, the total amount of CO_2 emissions is not going down proportionally with the energy reduction of the buildings.

Despite the consensus on the EIMs that should be implemented to reduce the energy demand. This is only a part of the steps to become more sustainable, as it is necessary to not only reduce the energy demand but also the operational and embodied carbon to achieve national and international climate targets, as laid down in the Paris Climate Agreement.

1.2 Carbon emissions and payback times (Systematic literature review)

As outlined by the World Green Building Council (WGBC, 2019), achieving a climate-neutral built environment involves much more than simply reducing operational energy use. In line with the Paris Climate Agreement, the WGBC introduced the Net-zero Carbon Buildings Commitment, which aims to achieve net-zero operational carbon. This means that "the emissions associated with energy used to operate the building should become net-zero" (WGBC, 2019).

While operational emissions are an important focus, they represent only part of a building's total carbon footprint. The other major component is embodied carbon, defined as "carbon emissions associated with materials and construction processes throughout the whole lifecycle of a building or infrastructure" (WGBC, 2019). Long overlooked, embodied carbon accounts for approximately 11% of global carbon emissions and can represent up to 50% of a building's total carbon footprint (WGBC, 2019).

While the embodied carbon of newly constructed buildings has already got more research focus, the embodied carbon of retrofits remains behind (Bienert, 2023). This gap is critical, as a significant proportion of the 2050 building stock already exists and must be upgraded to meet climate targets. As aforementioned in research done by (Hollyman et al., 2024), Bienert, (2023) also argues that EIMs that reduce operational energy demands often lead to increases in embodied emissions, which means retrofits must not only be evaluated on their reduction in energy but also on the embodied carbon that was used to create this energy reduction.

To determine whether the embodied carbon invested in reducing a building's operational carbon emissions can be recovered, an ecological Capex vs Opex analysis can be made. In this context, the embodied carbon represents the capital expenditure (Capex), while the operational carbon corresponds to the ongoing operational expenditure (Opex).

The outcome of this analysis is the 'carbon payback period'. The concept of the 'carbon payback period' refers to the time it takes for the greenhouse gas (GHG) emissions generated during the implementation phase, known as the embodied carbon, can be offset by the reduction in emissions (operational carbon) achieved over time (Hollyman et al., 2024). The term 'carbon payback' or sometimes also referred to as 'Ecological payback' or 'Environmental payback' is commonly applied in the analysis of retrofit projects to assess whether the embodied carbon associated with building-level retrofit measures can be justified by the resulting decrease in operational energy use and carbon emissions throughout the building's lifespan (Hollyman et al., 2024).

For this research, the Whole Life Carbon method (Figure 7) will be used to analyse the payback times. This method not only looks at the embodied carbon but also includes operational carbon, essential to calculate these payback times. More elaboration can be found later in this research.

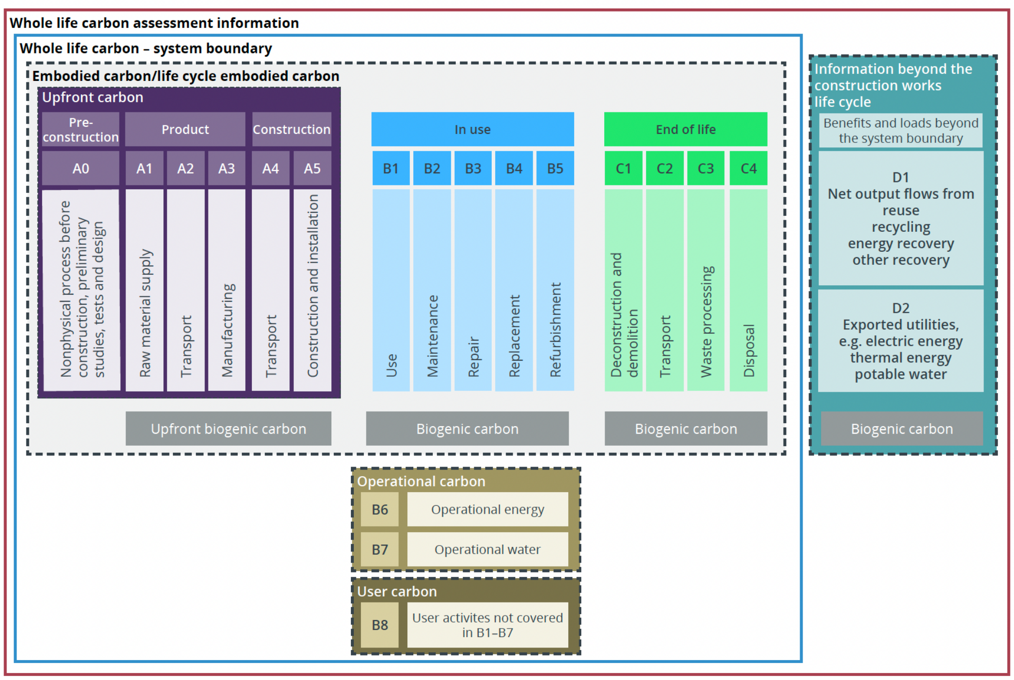

Figure 6, Schematic representation of the Whole Life Carbon principle based on the LCA methodology (EN 15978) (source: RICS, 2023)

Several studies, using different methods, have analysed this carbon payback time of retrofits aimed at reducing operational energy use and carbon emissions.

Asdrubali et al., (2019) assessed four retrofit scenarios for a case study school building in Northern Italy. The Measures included combinations of LED lighting, biomass boilers, heat pumps, PV systems, wall and roof insulation, triple-glazed windows, solar thermal systems, and ventilation improvements. In their study they used a dynamic energy

simulation model that was calibrated with actual energy bills and they applied a Life Cycle Assessment (LCA) for the environmental evaluation of the measures to calculate the payback time.
It is important to note that for the payback time that was calculated, they analysed LCA components A1 t/m A5.
The study presents an energy reduction of 40% to 75% percent depending on the retrofit scenario. The version with the least energy improvement is also the version with the lowest carbon payback time, this makes sense as this is also the version with the least amount of measurements taken. Furthermore, this research also confirms that the higher the energy reduction, the more measures are added and that this also increasing the Carbon payback time. The payback times in this research vary from 2.9 year for the smallest amount of carbon added in the cost optimal scenario (64kg CO_2-eq/m^2) up to 6,5 years for the biggest amount of carbon added in the NZEB 1(185kg CO_2-eq/m^2).

Extra materials and systems for every retrofit solution.

Component	Materials	Cost-optimal	DM 2015	NZEB 1	NZEB 2
Envelope					
Vertical walls	Rockwool	26442 kg	31630 kg	43300 kg	43300 kg
	Plaster	479675 kg	480000 kg	480000 kg	480000 kg
	Mortar glue	109017 kg	152253 kg	152253 kg	152253 kg
Transparent surfaces	PVC window frame	–	1399 m^2	1399 m^2	1399 m^2
	Flat Glass, coated	–	25741 kg	38612 kg	38612 kg
	Argon	–	19 m^3	19 m^3	19 m^3
Solar shadings	Viscose	–	730 kg	730 kg	730 kg
	Glass fibre	–	528 kg	528 kg	528 kg
	Aluminium frame	–	350 m^2	350 m^2	350 m^2
Systems					
Generator	Heat Pump	–	857 kW	857 kW	–
	Biomass Boiler	–	–	–	231 kW
	Heat Storage	–	–	–	5780 l
	Wood Collection, Production	–	–	–	53125 kg
Solar Collectors	Evacuated tube collectors	–	6 m^2	6 m^2	6 m^2
	Heat storage	–	600 l	600 l	600 l
	Pump	–	40 W	40 W	40 W
	Copper pipes	–	40 kg	40 kg	40 kg
	Polyurethane Insulation	–	25 kg	25 kg	25 kg
	Solar station	–	1	1	1
	Frame (stainless steel)	–	120 kg	120 kg	120 kg
PV	Mono-crystalline panels	267 m^2	400 m^2	533 m^2	533 m^2
	Inverter	40 kW	60 kW	80 kW	80 kW
	Electric wires	200 m	200 m	200 m	200 m
	Aluminium frame	6768 kg	10140 kg	13689 kg	13689 kg
Ventilation system	18 ventilation units with heat recovery and steel ducts	120 m^3/h	120 m^3/h	120 m^3/h	120 m^3/h
Lighting	LED lamps (30 W)	–	–	1151	1151
	Fluorescent lamps (36 W)	1151	1151	–	–

Figure 7, Retrofit scenarios (source: Asdrubali et al., 2019)

In another study by Rabani et al., (2021) in which they also conducted a Life Cycle Assessment (LCA) to evaluate various retrofit scenarios for a typical 1980s office building in Norway. The study analysed four retrofit scenarios: two based on the Norwegian Passive House (PH) standard and two based on life cycle cost (LCC) optimised scenarios.

The measures included in the retrofits were: additional envelope insulation (walls, roof, floor), replacement of windows with triple-glazed glass, installation of new exterior façades, HVAC system upgrades and, in the nearly zero-energy building (nZEB) cases, photovoltaic (PV) panels.
The study employed dynamic energy simulations via IDA-ICE software, which were based on prior calibrated models. These simulations supplied operational energy demand figures, which were then integrated into the OneClick LCA tool for an environmental impact assessment. For the calculation of payback time they used modules A, B2 (maintenance) and C.

In this study, all four scenarios resulted in more or less the same rates of energy reduction namely around 70%. The difference between the scenarios being the used heating systems (radiators vs air heating) and the amount of extra insulation for the building envelope. In this research, however, the two scenarios that had the most amount of insulation added to the building envelope didn't have a larger energy reduction than the scenarios that didn't, while they do have a higher carbon payback time. The payback time for the scenarios with more isolation added is around 5 years while for the scenarios with less insulation added, the payback time is around 4 years. Adding solar panels increased payback times to 6 years for Polycrystalline panels and up to 12 years for Monocrystalline panels.

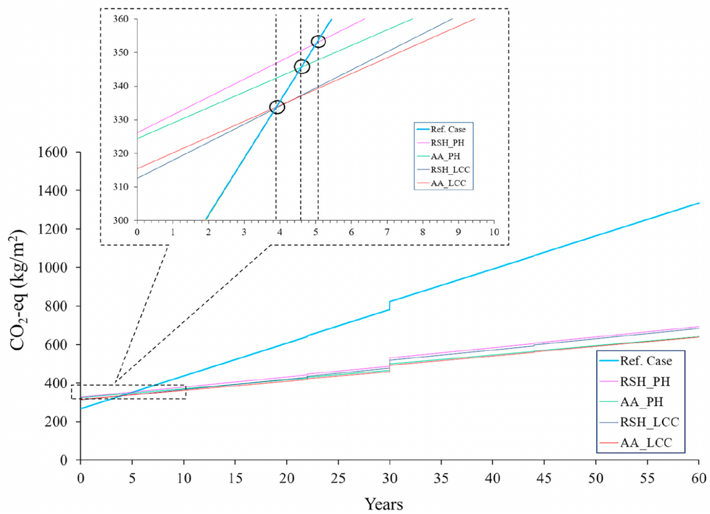

Figure 8, Payback times as found by Rabani et al., (2021)

Mohammadpourkarbasi et al., (2023) did a case study on residential buildings in the UK. The deep retrofit scenarios were designed to meet the EnerPHit standard, which is the Passivhaus certification for retrofits Mohammadpourkarbasi et al., (2023),

The measures analysed in this study included internal and external wall insulation, floor and roof insulation, triple-glazed windows, air-tightness improvements, mechanical ventilation with heat recovery (MVHR), air-to-water heat pumps, and solar PV panels. The retrofits were classified into six scenarios (Figure 10): three deep retrofits (S1–S3) and three shallow retrofits (S4–S6), differing in depth and material type (natural or petrochemical).

The retrofit scenarios.

Deep retrofit scenarios	Scenario 1 (S1)	As-built: EnerPHit Plus with natural insulation materials and PV panels
	Scenario 2 (S2)	EnerPHit Plus with 'standard' petrochemical-derived insulation materials and PV panels
	Scenario 3 (S3)	EnerPHit with 'standard' petrochemical-derived insulation materials
Shallow retrofit scenarios	Scenario 4 (S4)	Part L with 'standard' petrochemical-derived insulation materials and heat pumps
	Scenario 5 (S5)	Part L with natural insulation materials
	Scenario 6 (S6)	Conventional retrofit: Part L with 'standard' petrochemical-derived insulation materials

Figure 9, Retrofit scenarios as researched by Mohammadpourkarbasi et al., (2023)

The study used PHPP (Passive House Planning Package) to model operational energy use for all scenarios, including EnerPHit and conventional standards. For calculating the embodied carbon of the materials, OneClick LCA software was employed, following the RICS and BS EN 15978 and EN 15804 principles (Mohammadpourkarbasi et al., 2023). The LCA covered modules A1–A5 (product and construction), B1–B5 (use phase including maintenance and replacements), and B6 (operational energy use). Importantly, modules C1–C4 (end-of-life) and D (benefits beyond system boundary) were not included in the payback time calculations since the authors stress that this is only a minor part of the total amount of carbon included. Mohammadpourkarbasi et al., (2023) explicitly focused their comparative results on A1–A5, B1–B5, and B6, arguing that these stages dominate the life cycle impact, and contributions from end-of-life processes were considered to be less than 10% of total emissions, thus not central to their conclusions.

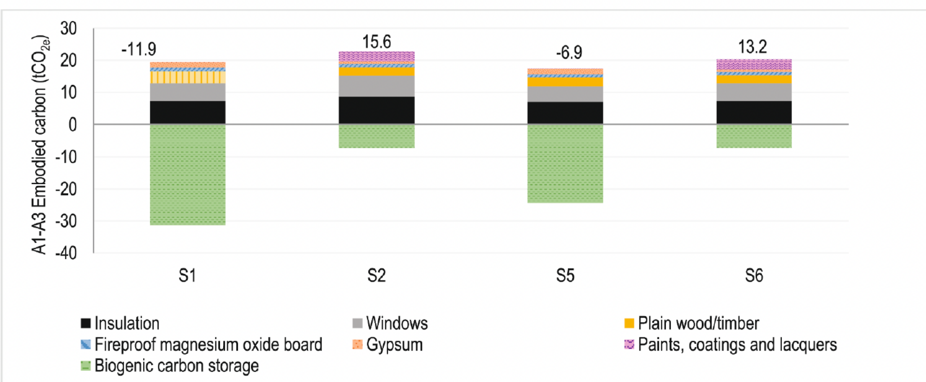

Figure 10, Embodied carbon scenarios (source: Mohammadpourkarbasi et al., 2023)

The following carbon payback time is reported for each scenario (Figure 12). When biogenic carbon storage (Figure 11) is not considered, the deep retrofit options (S1, S2, and S3) achieve the shortest payback periods, ranging from four to five years. In contrast, the shallow retrofit scenarios (S4, S5, and S6) have payback times between five and six years. Notably, by the fourth year, the cumulative carbon emissions of all shallow retrofits exceed those of the deep retrofits. This finding highlights the importance of incorporating Life Cycle Assessment (LCA) when selecting the most appropriate retrofit strategy. In general another important conclusion that can be drawn from this research is that the carbon payback time of retrofit for all scenarios is considerably lower than the lifespan of the retrofit measures, and that incorporating the biogenic carbon storage into the calculations significantly reduces the payback time for scenarios with natural materials, S1 and S5, to just one year.

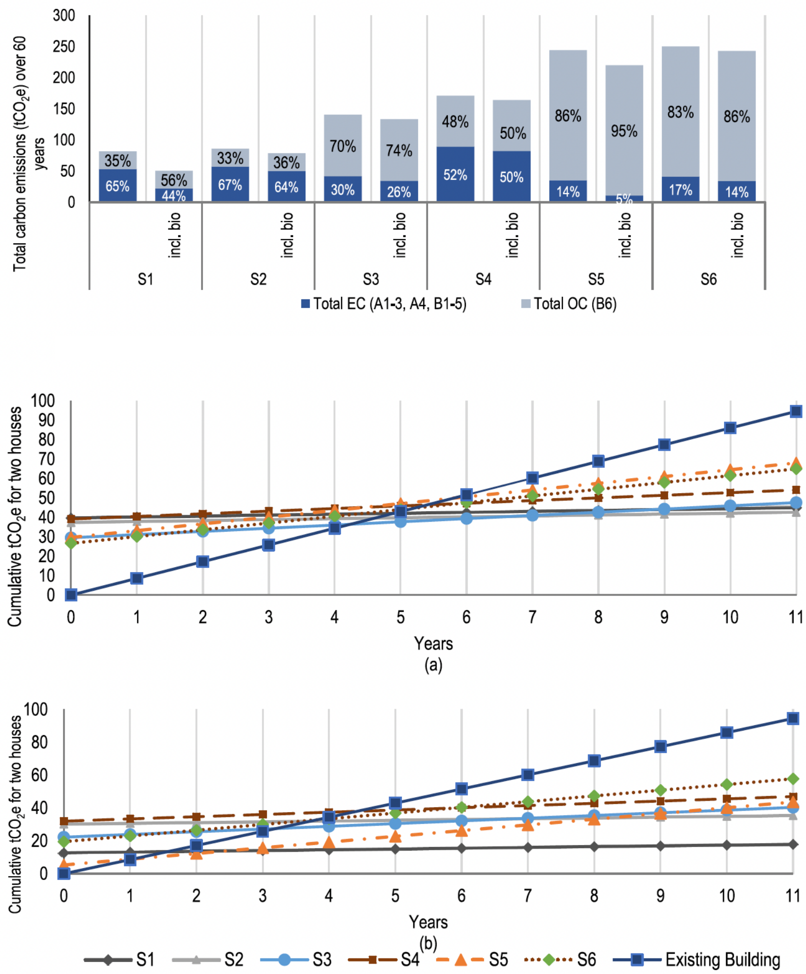

Figure 11, Payback times as found by Mohammadpourkarbasi et al., (2023)

Lastly, the research the earlier-mentioned report of Bienert, (2023), analysed 36 global energetic retrofit projects that had different user types in various regions and climate zones. In the report, Bienert, (2023), found that the embodied carbon emissions ranged between 20–140 kg CO_2eq/m^2 for the different scenarios (Figure 13) that were defined as follows:

- **"Light measures** that require minimal effort, such as replacing light bulbs with LEDs or the optimisation of the BMS (Building Management System), leading to a fast carbon payback due to low material input;
- **Medium measures,** such as facade insulation or window replacement, that significantly change the building but exclude structural interventions;

- **Deep retrofits** when an asset has reached a certain stage of its life cycle or when calculated savings greatly reduce operational consumption
They involve major equipment replacement, complete renewal of the building envelope (facade and windows), resulting in substantial reductions in net energy. Extensive retrofits often require long-term planning, e.g. they are typically undertaken during renewal events, in case of new occupancy or ownership, and for green building certifications. Deep retrofit measures should be prioritised in buildings over 35 years old." (Bienert, 2023)

In their report they also used these figures to calculate the payback time where a maximum carbon payback period up to eight years was found, with average payback years of 1,3y for the light retrofit, 4,1y for the medium retrofit and 4,4 years for the deep retrofit (Figure 13) (Bienert, 2023). Here, it is important to note that the assessment is explicitly limited to LCA modules A1–A3, covering the product stage only. Although this can go up to 2/3rd of the total carbon emissions of a building, still a part of the lifecycle is missing (Bienert, 2023).

Although the focus of the study was on retrofits using conventional materials, Additionally, as stated in their report: "switching from conventional construction material to low-carbon and bio-based solutions has the potential to reduce up to 50% of the resulting CO_2 emissions" (Bienert, 2023).

Residential real estate (Multifamily)				
	Light	Medium	Deep	*New building*[5]
Savings	< 25% of energy consumption	25–50% of energy consumption	> 50% of energy consumption	*n/a*
Embodied carbon/ m²(current market practice)	n/a	In our cases 20 to 80 kg CO_2e/m^2		*600–700 kg CO_2e/m^2*
Typical carbon payback period in years	n/a	1 up to 5 years		*n/a*
Commercial real estate				
	Light	Medium	Deep	*New building*[5]
Savings	< 25% of energy consumption	25–50% of energy consumption	> 50% of energy consumption	*n/a*
Embodied carbon/ m² (current market practice)	Up to 30 kg CO_2e/m^2	In our cases up to 140 kg CO_2e/m^2		*600–750 kg CO_2e/m^2*
Typical carbon payback period in years	Below 3 years	Up to 8 years		*n/a*

	Light	Medium	Deep
Typical carbon payback in years	~ 1,3 year	~ 4,1 years	~ 4,4 years
Typical measures	▪ Replacement of convention light bulbs with LED light bulbs ▪ Insulation attic ▪ HVAC replacement and retro-commission-ing ▪ Other electronical measures with low risk and short payback periods	Individual measures on the building envelope: ▪ Façade and roof insu-lation ▪ Basement insulation ▪ Replacement of windows ▪ Remediation of ther-mal bridges ▪ Improved building air tightness	Measures on the entire building envelope: ▪ Window replacement ▪ Combined bundle of HVAC, thermal enve-lope, and renewable power and heat supply ▪ Downsizing of HVAC system due to lower heating and cooling demands ▪ Elimination of perime-ter zone conditioning ▪ Building envelope insulation ▪ Improved airtightness
Tips for optimization	Take note of the low-hanging fruit: ▪ Review of the heating systems and power supply (Electrical / plumbing system updates) ▪ Install occupancy sensors or timers to automatically control lighting in areas with low occupancy ▪ Install smart meters	▪ Choose low carbon material (e.g. renew-able raw materials) ▪ Prioritize insulation upgrades in the build-ing envelope, particu-larly in areas with the highest heat loss or gain ▪ Address and remediate thermal bridges to improve the overall thermal performance of the building ▪ Evaluate the cost-ef-fectiveness of each measure bundle and consider the long-term benefits of energy savings and comfort improvements	▪ Choose low carbon material (e.g. renew-able raw materials) ▪ For retail: the replace-ment of old refrigera-tion systems should be accelerated ▪ Take a holistic approach by combin-ing HVAC system upgrades, thermal envelope improve-ments, and renewable power and heat supply solutions. ▪ Conduct thorough modeling and life cycle cost (LCC) analysis to determine the tech-nical characteristics and economic viability of core technology measures

Figure 12, Payback times and Scope of retrofits for commercial and residential real estate, found by Bienert, (2023)

Considering the reported energy savings from the analysed retrofit projects, the findings in Bienert, (2023) align with the general patterns observed in the previously discussed studies. Although the range of results in Bienert's research is broader, several cases demonstrate energy reductions exceeding 50% of the building's pre-retrofit consumption, reinforcing the substantial impact that well-designed energetic retrofits can achieve.

Through calculating the carbon payback time, comparing embodied carbon as an ecological investment against operational carbon savings. Multiple studies have demonstrated that although deeper retrofits tend to incur higher initial embodied emissions, they often yield significant long-term reductions. Nonetheless, payback periods still vary depending on material choices, system configurations, and contextual factors such as building type, climate, and retrofit scope. These findings underscore the importance of further investigating diverse retrofit scenarios across different contexts to develop more nuanced, data-driven strategies for achieving carbon-neutral buildings.

1.3 Problem statement

The urgent need to reduce greenhouse gas emissions from the built environment has placed energy efficiency and carbon reduction as a high priority for building policy and practice. In the Netherlands, regulatory interventions such as the mandatory energy label C for office buildings, the upcoming EPBD IV directive, and the inclusion of the built environment in the EU ETS underscore the growing pressure on building owners to improve energy performance and reduce carbon emissions.

The literature has already discovered that a wide range of retrofit strategies, ranging from light measures such as lighting upgrades and control optimisation to deep interventions involving insulation, HVAC upgrades, and renewable energy integration, can significantly reduce operational energy use and associated carbon emissions. Multiple studies, including those by Asdrubali et al., (2019); Bienert, (2023); Mohammadpourkarbasi et al., (2023); Rabani et al., (2021), confirm that while operational carbon savings are substantial, these improvements come at the cost of increased embodied carbon.
The introduction of the carbon payback time concept has helped quantify this trade-off, highlighting the time required to offset embodied emissions through operational savings.

As addressed, this time varies depending on the depth of the retrofit, the materials used, and the building context. Historically, most research has focused on reducing operational energy demand and operational carbon emissions (Bienert, 2023; WGBC, 2019). Only in recent years has embodied carbon gained more attention, though primarily in the context of new construction.

The body of research specifically addressing the embodied carbon impacts of energy-improving retrofits is still behind (Bienert, 2023). Moreover, the majority of existing studies in this field seem to rely on case studies or simulation-based assessments of relatively large office buildings, or residential buildings outside the Dutch context.

Given the increasing regulatory pressure in the Netherlands and the importance of meeting national and European climate goals, it is critical to evaluate whether the embodied carbon invested in retrofitting small office buildings can be justified through future operational carbon savings. Therefore, further research is needed to investigate the carbon payback time of such retrofit interventions and to support more sustainable and informed decision-making

1.4 Aim of the study - The environmental business case of retrofitting office buildings towards net-zero energy and carbon emissions.

This research aims to evaluate what happens with the carbon emissions when an office building is renovated towards the goal of net-zero energy. By working towards operational carbon emissions (Opex) that will be reduced to zero, in line with net-zero targets, the study focuses on the one-time impact of capital expenditures (Capex) in embodied carbon, related to energy improvement measures (EIMs). The goal is to explore how different combinations of EIMs influence the total embodied carbon, and which package has the best payback time within the life expectancy of the measures, making it the most efficient package.

This research ultimately seeks to provide for more sustainable and informed decision-making for investors, owners, and policymakers in Corporate Real Estate, supporting strategic choices around sustainable renovation with maximum environmental efficiency and long-term impact.

2. RESEARCH DESIGN

This chapter will explain the main design of the research, highlighting the key concepts that are important to understand the context of this research. Furthermore, it also explores the main question and the conceptual framework that helps answer the main question.

2.1 CONCEPTS

2.1.1 THE MAIN QUESTION

The main question for this research is:

> *"What is the environmental payback time of energy improvement measures for small office buildings retrofits in the Netherlands?"*

Two main concepts:
The concept of *energy improvement measures(EIMs)* is about the most popular measures that can be taken to improve energy performance. This involves looking at these specific measures, their energy reduction, operational- and embodied carbon, and the initial and long-term costs of these measures. Long-term costs are understood to mean a multi-year maintenance plan (MJOP). The initial cost means the purchase and installation of the measures.
The concept of *environmental exploitation (LCA)* in this study is about measuring the environmental costs as a result of implementing energy improvement measures, with the environmental costs meaning the impact of these measures on the operational and embodied carbon

2.1.2 ADDITIONAL CONCEPTS

As explained in Chapter 2.1, there are two main concepts for this research. These two concepts, which present the main focus of this research, are further explored in the literature review/theoretical background. To answer the main question, and to dive deeper in the main concepts, this research must be scoped well. Scoping also means that the context of this research is presented clearly. That is why three additional concepts were selected. These concepts will also be incorporated in the sub-questions of this research.

The first concept is Corporate Real Estate (management) (CRE & CREM). To understand the context of this research, it is essential to define Corporate Real Estate (CRE) and Corporate Real Estate Management (CREM). Exploring the current and future role of sustainability within CRE and CREM is crucial for understanding how they contribute to the decarbonisation of the built environment. This requires an understanding of their historical development over time and the regulatory frameworks that shape their evolution.

The second additional concept is *Energy Measurement*. When discussing energy improvements and their effects, it is essential to identify and compare various methods of measuring energy performance. Clear and consistent measurement approaches are crucial for assessing returns, as they ensure that data is collected and analysed within a

standardised framework. This consistency safeguards the reliability of the data, allowing it to be generalised and effectively applied in this research. By using widely used systems, the analysis of energy improvements becomes more robust and comparable across different scenarios.
The third concept is Carbon emission measurement. As an essential component of environmental exploitation, the assessment of carbon emissions plays a crucial role in this research. To evaluate the true environmental impact of energy improvement measures, it is necessary to understand how both operational and embodied carbon emissions are quantified and assessed.

2.2 Conceptual model

To answer the main question, this research is divided into several steps. These are presented below. Later in this research, the research approach can be found, presenting the sub-questions and the relation among them.

Step 1: Identify and Analyse Energy Improvement Measures
The first step involves identifying the most commonly implemented energy improvement measures (EIMs) in office buildings, such as insulation, HVAC systems, and renewable energy technologies. This includes:

- Analysing the characteristics of these measures.
- Mapping their expected impact on energy performance, operational carbon, and embodied carbon.
- Laying the groundwork for further exploration of environmental implications.

Step 2: Evaluate Energy and operational carbon impact (Opex)
This step focuses on quantifying the energy usage and carbon emissions associated with the identified EIMs:

- Energy Analysis: Comparing pre- and post-intervention energy consumption, examining the operational energy savings
- Carbon Analysis: Conducting an assessment to evaluate operational carbon impacts to asses relation with energy reduction

Step 3: Assess Embodied Carbon Impacts (Capex)
This step evaluates the embodied carbon introduced by implementing various energy improvement measures. Using life cycle assessment (LCA) methodologies, this stage involves:

- Quantifying the embodied carbon associated with the added materials
- Comparing the different materials and systems
- Establishing the embodied carbon 'investment' that must be offset through operational savings (Capex)

Step 4: Calculate Environmental Payback Time
Building on the results from Steps 2 and 3, this step calculates the environmental payback time-defined as the time required for operational carbon savings to offset the embodied carbon emissions of the retrofit. This analysis includes:

- Determining the annual operational carbon savings per scenario.
- Dividing the total embodied carbon by the annual operational savings to estimate the payback time.
- Evaluating how building size, retrofit depth, and material choice affect this offset period.

Step 5: Compare results to literature and write a discussion
Step 6: Conclusions

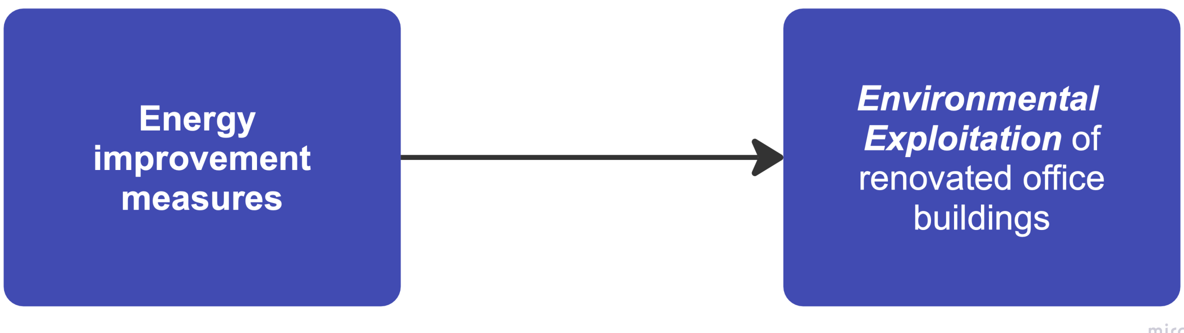

Figure 13, Conceptual model

3. Theoretical Background

3.1 Status of sustainability in Corporate Real Estate

This chapter explores the evolving landscape of corporate real estate (CRE) and its management in the context of sustainability. It begins with the definition of CRE and the evolving role of CRE throughout time. This is followed by an overview of corporate real estate management (CREM), highlighting how it integrates operational, strategic, and institutional perspectives to align real estate with sustainability goals.
Hereafter, the current regulatory and market status of Dutch office building is discussed, followed by the principles of Carbon accounting and therefore the increasing importance of embodied carbon in retrofit decisions. The chapter then finishes with introducing carbon risk management as a critical component of forward-looking CRE strategies, emphasising the need for life cycle-based assessment to prevent asset stranding and to align portfolios with Paris-proof trajectories.

3.1.1 Corporate Real Estate (throughout time)

This chapter clarifies the concept of Corporate Real Estate (CRE) to provide context for this research, which focuses on office buildings in the Netherlands. CRE refers to “the real properties that house the productive or business activities of an organisation that owns or leases and, consequently, manages real estate incidental to its primary business objectives, which are not real estate.” (CoreNet Global, Inc, 2015)

Importantly, CRE differs from Commercial Real Estate (ComRE). While ComRE treats real estate as the business itself, aiming to generate investor returns, CRE supports an organisation’s core business (Arkesteijn, 2019; CoreNet Global, Inc, 2015). Office buildings can belong to either category depending on their ownership and function, reflecting the context-dependent nature of real estate classification.

Throughout time

Historically focused on property management (Veale, 1989), CRE has become a strategic business partner involved in workplace design, space optimisation, and supply chain efficiency (Jalil Omar & A. Heywood, 2014).
Modern CRE aims to shift from a cost centre to a value driver (Amos & Boakye-Agyeman, 2023; Anker Jensen & Van Der Voordt, 2016), enabling productivity and competitiveness. This shift reflects a broader redefinition of CRE (see Appendix A), moving beyond physical space to enabling business productivity and global competitiveness. The adoption of flexible workplace strategies like hoteling, desk sharing, and remote work illustrates this transformation (CoreNet Global, Inc, 2015).

As organisations increasingly align with environmental and ESG goals, sustainability is likely to reshape the role of CRE once again, positioning it as a key driver in achieving long-term corporate resilience and climate targets.

3.1.2 Corporate real estate management

As previously explained, corporate Real Estate (CRE) is more than just physical space, it also adds strategic value to organisations. Its inclusion in the Corporate Sustainability Reporting Directive (CSRD) reflects its growing importance in supporting sustainability goals and the increasing value of sustainable practices. (Deloitte, 2022; EY, 2024).

Bon, (1994) defines CREM as the management of properties used by non-real estate organisations, while Singer et al., (2007) describe it as a strategic tool aligned with competitive business strategies via incremental, value-based, and standardised approaches (Figure 15).

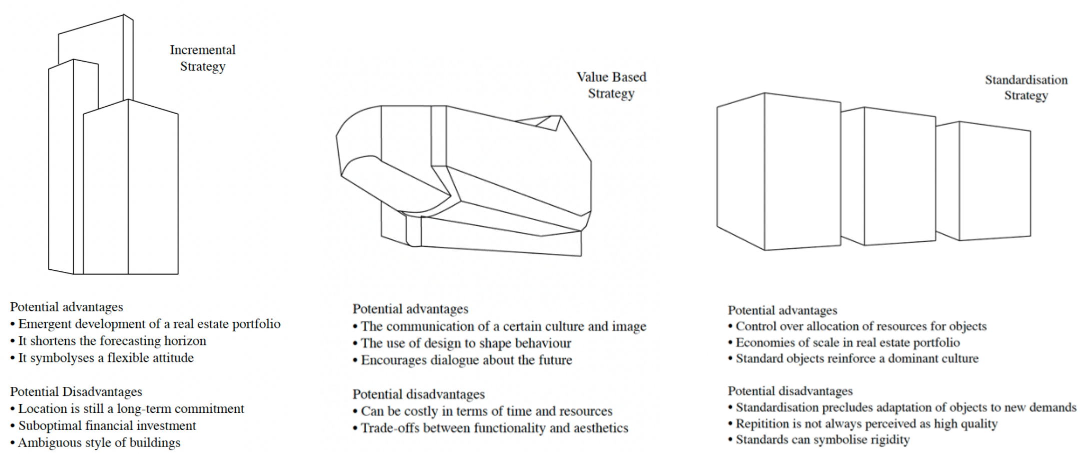

Figure 14, CREM Strategies (source: (Singer et al., 2007))

Jalil Omar & A. Heywood, (2014) go a step further than that by looking at CREM as a tool for competitive strategy. By branding CREM, which elevates its role from operational to strategic, it can become part of the strategy rather than it just being a tool (Jalil Omar & A. Heywood, 2014). This means reinforcing alignment with organisational goals, such as the increased focus on sustainability.

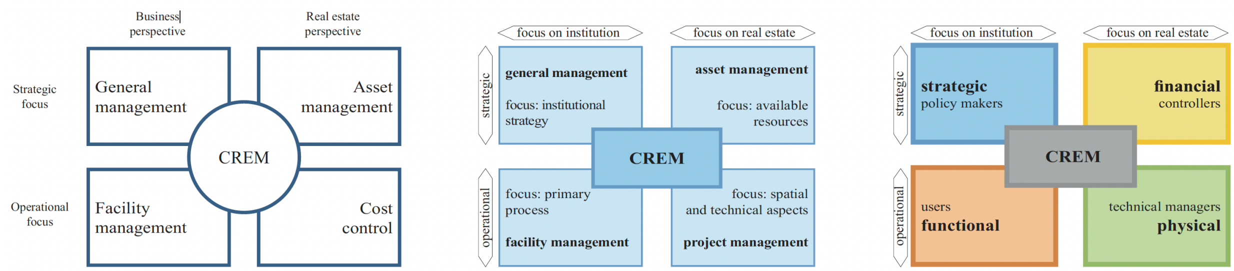

Figure 15, The evolution of Delft CREM model (source: (Vande Putte & Jylhä, (2023))

Through the Delft CREM model (Figure 16), developed at TU Delft , Vande Putte & Jylhä, (2023), builds on these ideas. Originating in the 1990s, but further developed, it integrates institutional, real estate, strategic, and operational perspectives to guide CREM alignment with business objectives. Today, the model serves both as a framework and a diagnostic tool to identify alignment gaps. Some even believe that the alignment itself is the raison d'être of CREM (Arkesteijn, 2019).

Given the rise of ESG goals, and the focus on net-zero building targets. Sustainability is expected to further redefine the role of CREM, shaping it as a central and essential enabler of corporate strategy and performance towards a sustainable and net-zero future.

3.1.3 The current status of corporate real estate and its road to becoming Paris-proof.

As already explained in the introduction of this report, Office buildings in the Netherlands must have at least energy label C as of January 1, 2023 (RVO, 2018) Currently, this goal has been reached by 82% of the m^2 office space available in the Netherlands, which still leaves room for 18% to follow this example (RVO, 2024b). Of this 18%, 4% currently has a label D or worse and 14% has no EPC Label.
Even though it is important to reach this label as soon as possible, given the fact that a fine is among the direct consequences of not having at least an EPC label C (RVO, 2024e) . New sustainability ambitions are already at the doorstep of the corporate world, looking at for example, the Paris Climate Agreement, which aims to generate all energy sustainably, this means only 1/3 of the energy that is used now would be available (DGBC, n.d.-a). Therefore, all buildings must reduce their energy consumption by an average of two-thirds compared to current levels to operate entirely on sustainable energy sources. The consequence of this is that by 2050, all office buildings should have an EPC Label which is A+++ or higher (DGBC, 2024b; Envalue, 2024a), in other words, also called the Renovatiestandaard (RVO, 2023). An analysis of the EPC labels of the current office building stock in the Netherlands, by Dutch Green Building Council (DGBC) Partner, Envalue, provides a helpful inside into the division of energy labels among office buildings. As seen in Figure 17, currently only 6% of the office building stock is Paris-proof. This means that there is much work to be done in the CRE sector.

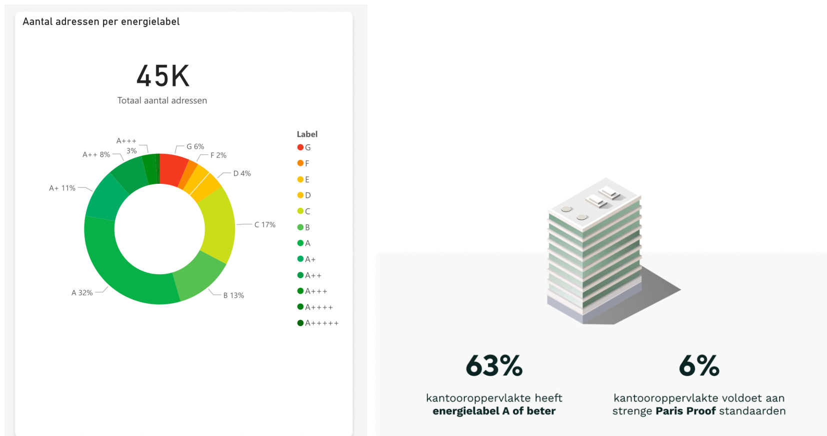

Figure 16, EPC labels and Paris-proof office building Stock (Source: Envalue, 2024b)

Looking at research from Jylhä et al., (2019), into changed paradigms in CRE, a change in the way Corporations deal with sustainability has also been affirmed. Sustainability is now considered a necessity rather than an option. Corporations perceive it as a critical risk to manage, a mandatory policy shift to comply with, and a market expectation that shapes corporate reputation and strategies. Additionally, the perspective on sustainability has evolved from focusing on short-term objectives to embracing the entire lifecycle of buildings, emphasising practices like adaptive reuse, green certifications, and long-term sustainable design (Jylhä et al., 2019).

This broader view aligns with the paradigm shift in CRE from cost minimisation to holistic value delivery. Sustainability is now integral to this value framework. Current reports from big Corporations such as EY and Deloitte also acknowledge this shift, delving from their latest reports about the CSRD and ESG, they highlight the growing importance of integrating and aligning the Real Estate portfolio to these frameworks and the Corporate Strategy (Deloitte, 2022; EY, 2024). Looking back to what was written earlier in this chapter, about using CRE as a competitive strategy and/or even Branding, it seems that this way of using CRE is gaining support. This is starting to make more and more sense since research shows that the advantages of making corporate real estate more sustainable stretch further than only the possible reduction in energy use and costs (BPIE, 2024).

3.1.4 Carbon Accounting in Corporate Real Estate

As previously introduced, the built environment accounts for a substantial share of global greenhouse gas (GHG) emissions. That is why the pressure to become less polluting becomes bigger and bigger on the corporate real estate sector. As regulatory pressure intensifies through initiatives like EU ETS (2) and directives such as the CSRD and EPBD IV, companies are increasingly compelled to address the carbon footprint of their real estate assets. This process is called Carbon accounting, or in other words, “GHG accounting”, which stands for “the processes required to measure the amount of GHGs emitted, avoided, or removed by an entity (e.g., asset or company) over a specific period"(PCAF, 2023). It enables organisations to track and disclose their emissions in a manner consistent with standard accounting practices, like financial reporting (PCAF, 2023).

This accounting also involves quantifying emissions resulting from both the operational use of buildings and from their construction, retrofits and maintenance. These emissions can be divided into operational and embodied emissions (Figure 18) (PCAF, 2023).

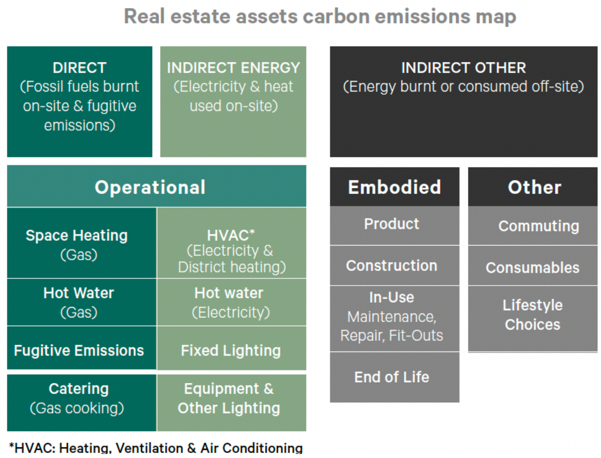

Figure 17, Real estate assets carbon emissions map (source: PCAF, 2023).

According to the EN 15978 standard, operational carbon emissions arise from the energy consumed by technical systems (Figure 18) embedded in the building during its use (PCAF, 2023). The embodied emissions/carbon refers to the total GHG emissions associated with the creation, upkeep, and end-of-life processes of a building (PCAF, 2023) . This encompasses upfront embodied carbon, which arises from the extraction, production, transport, and on-site assembly of construction materials (as defined in life cycle stages A1 to A5), and downstream embodied carbon, which stems from the materials and activities involved in maintaining the building during use, as well as its eventual demolition and waste processing (captured in stages B1 to B5 and C1 to C4 and D) (PCAF, 2023).

Notably, downstream embodied emissions do not include stages B6 and B7, as these are classified as operational energy and water use.
In the case of existing buildings, the upfront embodied carbon (A1–A5) is typically considered a sunk cost, which means the emissions that have already occurred during initial construction and are thus no longer within the scope of active reduction strategies.

As seen in Figure 18, an organisation's carbon inventory consists of both direct and indirect greenhouse gas emissions (CRREM, 2020). According to standard carbon reporting frameworks, these emissions can be categorised into three scopes: Scope 1 includes direct emissions from sources controlled by the organisation; Scope 2 covers indirect emissions from purchased electricity, heating, and cooling; and Scope 3 comprises all other indirect emissions occurring in the value chain (CRREM, 2020). While reporting Scope 3 emissions is often optional, certain components, such as energy use by tenants, are essential for evaluating the stranding risk of individual assets.

In this moment, most organisations have established good systems for collecting data related to Scope 1 and Scope 2 emissions within their corporate reporting boundaries (CRREM, 2020). The extraction of the building-related data from these categories is typically straightforward (CRREM, 2020).

However, many firms, including real estate investors and owners, lack adequate data on Scope 3 emissions associated with their buildings (CRREM, 2020). As a result, this segment of the carbon inventory is often incomplete, limiting the ability to fully assess carbon-related risks (CRREM, 2020). Additionally, access to this data is often hindered by practical barriers, such as third-party ownership of the information or misalignment in reporting requirements, which may prevent data sharing (CRREM, 2020).

3.1.5 Upfront emissions and building retrofits

Traditionally, the operational phase of a building has been the dominant contributor to its total emissions over its lifetime. However, this balance is changing rapidly in many regions, and the relative significance of embodied carbon compared to operational emissions is frequently undervalued (PCAF, 2023). Even without factoring in future decarbonisation of the energy grid, the impact of embodied emissions remains substantial (PCAF, 2023).

One of the primary environmental concerns in new construction projects lies in the significant resource consumption and the substantial volume of embodied greenhouse gas (GHG) emissions generated during the early stages. First and foremost the production, transportation, and on-site assembly of construction materials (Zimmermann et al., 2023). These so-called 'upfront emissions' pose a serious barrier to the immediate and necessary reductions in GHG emissions required to limit global warming to 1.5°C, as outlined by the IPCC,(2021). As a result, strategies that are aiming to mitigate emissions from the building and construction sector must account not only for operational impacts but also consider the Whole life cycle (Zimmermann et al., 2023).

In recent years, there has been a noticeable shift in attention from constructing new buildings towards upgrading and renovating the existing building stock. The principles of a circular economy and the ambition to reach net-zero GHG emissions have increasingly shaped the foundation of European Union sustainability policies (Zimmermann et al., 2023). Renovation is now recognised as a critical lever for achieving rapid emission reductions.

Accurately calculating and collecting data on embodied carbon emissions of these renovations is essential to ensure that the operational carbon reductions achieved through retrofitting do not lead to higher emissions in other parts of the lifecycle (CRREM, 2020).

3.1.6 Carbon risk management

The relevance of carbon accounting also extends beyond regulatory compliance and sustainability. It is increasingly recognised as a strategic tool to manage carbon-related risks and investment decisions (CRREM, 2020). In their report, they also underscore how carbon risk, particularly in the form of transitional risk[1], can directly impact asset valuation, liquidity, and long-term profitability (CRREM, 2020). Assets with high operational and embodied emissions that fail to align with future climate regulations or market expectations risk becoming "stranded[2]" (Figure 19), prematurely obsolete and financially weakened (CRREM, 2020). This places increasing importance on data transparency, lifecycle-based analysis, and scenario planning (CRREM, 2020).

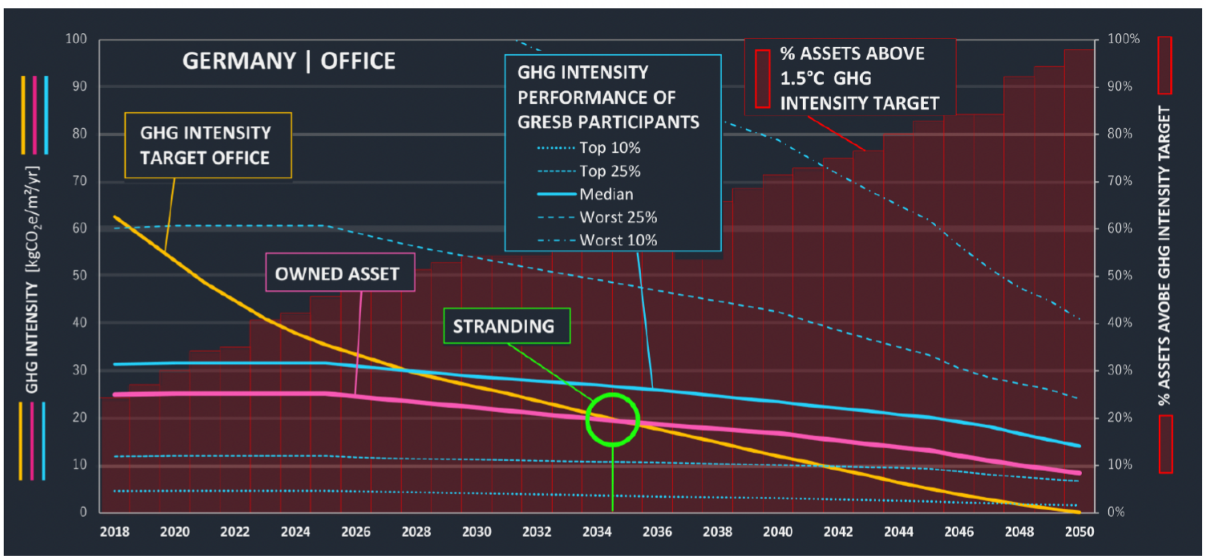

Figure 18, CRREM risk analysis concept of stranded asset (source: CRREM, 2020).

The CRREM tool, for instance, provides decarbonisation pathways and risk indicators that allow asset owners to evaluate carbon intensity, identify necessary retrofit measures, and assess associated costs and savings. In this context, carbon accounting not only facilitates compliance with instruments such as the EU Taxonomy, CSRD, or EPBD IV, but also supports evidence-based decision-making and strategic asset planning (CRREM, 2020).

[1] Transition risks are business-related risks that follow societal and economic shifts toward a low-carbon and more climate-friendly future (GRESB, n.d.).
[2] When an assets operational carbron intensity move above market avarage it becomes 'stranded' (Arup & WBCSD, 2023)

A key insight from the CRREM report is that while new buildings often perform better operationally, their high upfront embodied emissions can outweigh these benefits for many years. In contrast, “green retrofitting”, as also discussed by Zimmerman, presents an opportunity to achieve meaningful carbon reductions with considerably lower upfront emissions. This makes the evaluation of embodied carbon, particularly in renovation projects, essential to any credible carbon accounting effort.

Therefore, corporate real estate strategies must incorporate not only operational carbon data, but also embodied carbon calculations. In particular, assessing the carbon payback time of renovation packages becomes essential to determine the long-term environmental value of such investments. This approach enables organisations to prioritise retrofitting strategies that offer the most effective emission reductions within a defined period, thus aligning better with science-based targets and supporting the broader decarbonisation of the built environment.

3.1.7 Net impact on climate

The urgency of climate action is more than simply reducing emissions; it also requires a careful understanding of when emissions occur (Hawkins, 2024). In the report of Hawkins, (2024) the concept of the time value of carbon highlights that a tonne of CO_2 emitted today has a greater impact than the same tonne emitted in the future. This time sensitivity is especially relevant in the built environment, where choices about materials and energy systems can have long-lasting effects.

CO_2 accumulates in the atmosphere and continues to warm the planet for centuries, and the earlier it is emitted, the longer it contributes to global warming. Therefore, strategies that “delay” emissions can provide real benefits. This includes allowing time for technological improvements, energy grid decarbonisation, and system adaptation. For example, choosing materials that temporarily store carbon (like timber) or postponing operational emissions through efficiency gains can delay climate impacts in ways that support near-term climate goals (Hawkins, 2024).

There are three main arguments for valuing delayed emissions, as found in the report of Hawkins, (2024). The first is the buying time argument: delaying emissions creates a window to potentially avoid them altogether by using cleaner technologies in the future. Secondly, the static time-horizon argument shows that, when emissions are assessed over a fixed period (e.g. 100 years), delayed emissions result in lower cumulative warming because they have less time to exert radiative forcing. Lastly, the social time preference argument, drawn from economics, suggests we may naturally value present well-being over future well-being. In climate terms, this means that reducing emissions today is more impactful, especially if catastrophic risks increase over time (Hawkins, 2024).

These arguments are not just theoretical because various methods now exist to incorporate the time value of carbon into decision-making. These methods show that the net impact of a carbon-emitting action depends on both the quantity and the timing of emissions. For example, a retrofit that emits significant embodied carbon upfront but saves energy over time may still have a worse short-term climate impact than a less carbon-intensive alternative with moderate long-term benefits. This is especially important in the context of carbon payback periods, the time it takes for operational savings to outweigh initial embodied emissions. From a climate perspective, actions with quicker net-positive effects are more valuable, especially given the short window to limit global warming below critical thresholds.

However, incorporating the time value of carbon into standard practice introduces new challenges. Choices around time horizons, discount rates, or weighting curves often involve ethical considerations, especially in terms of intergenerational fairness. For example, valuing present generations more than future ones may justify higher emissions today, but this contradicts the principles of sustainable development (Hawkins, 2024).

Ultimately, when recognising the time value of carbon, this encourages earlier action, steering sustainable investments toward quick-impact strategies, and challenges assumptions in lifecycle thinking. It can also lead to more nuanced comparisons, for instance, favouring a material or retrofit that emits less upfront, even if long-term benefits are similar. In the face of global warming, integrating the temporal aspect of emissions seems to be essential to ensure we prioritise the actions that make the biggest difference now.

3.1.8 Conclusion

In conclusion, this chapter has shown how CRE has developed from a mainly operational role into a more strategic function or asset that supports the wider organisational objectives, including sustainability.

Modern CREM practices are no longer only about managing space and costs. Through frameworks such as the Delft CREM model, organisations are encouraged to align their real estate decisions with long-term strategies, including environmental targets. As part of this shift, the importance of sustainability and carbon reduction has grown significantly, especially with rising regulatory pressure and expectations from stakeholders.

Moreover, the introduction of carbon accounting practices, including both operational and embodied emissions, has highlighted the need to assess the full life cycle of buildings. Retrofitting, rather than new construction, is increasingly seen as a more sustainable way to reduce emissions, provided that embodied carbon is carefully considered. Most importantly, calculating carbon payback times of retrofits can help organisations make more informed decisions about which measures offer the best environmental value over time and fit to their needs.

Lastly, understanding the time value of carbon shifts the focus from simply how much we emit to also when we emit. In a climate system where early emissions cause greater harm, prioritising actions that deliver rapid net benefits is essential. Integrating this temporal lens into decision-making helps align building strategies with urgent climate goals, also ensuring that what we do now truly matters for the future.

CRE now plays a central role in reducing GHG emissions and reaching a Paris-proof climate. To meet future requirements and avoid financial and regulatory risks, companies must integrate carbon data into their real estate strategies. By doing so, they can not only contribute meaningfully to climate goals but also manage risk, enhancing the long-term performance and value of their real estate portfolios.

3.2 Energy measurement

A key factor within the WLC framework are the emissions belonging to the operational energy use under module B6. As earlier reported, buildings are responsible for 39% of global CO_2 emissions related to energy use and of this total, 28% is attributed to operational energy/emissions, while 11% stems from the energy consumed during the production of building materials and construction activities, the so-called embodied carbon (WGBC, 2019).

Measuring and understanding the operational energy is not only important for achieving sustainability goals and ensuring compliance with national and international climate agreements. It is also essential for measuring the effectiveness of retrofit measures that were or are going to be implemented in a building.

Therefore, to get a good understanding on how to measure energy performance, this chapter explores the Dutch legislation (the theoretical methodology defined by the NTA 8800) around energy measurement, the difference between real and simulation approaches energy measurement, and the use of energy simulation tools.

3.2.1 The NTA 8800, Theoretical Energy Measurement

The Dutch Technical Agreement (NTA) 8800:2024 is the standard that describes the methodology for determining the energy performance of buildings in the Netherlands. This method is used to assess the energy label of a building. The energy label, ranging from A+++++ (most energy-efficient) to G (least energy-efficient), indicates a building's energy performance. The NTA 8800 is based on the European Energy Performance of Buildings Directive (EPBD) (NEN, 2024).
The NTA 8800, however, does not set specific requirements for energy performance, but it defines the calculation method to determine whether a building meets the requirements established in other regulations, such as the **Building Decree for the Living Environment (Bbl)**. Table 1 is retrieved from the BBL and presents the Theoretical Primary Fossil Energy Consumption per EPC label. This is important regarding the energy use calculations that will be done in this research to indicate the energy performance.

EPC Label	**Primary Fossil Energy Consumption (in kWh/m^2.jr)**	**EPC Label**	**Primary Fossil Energy Consumption (in kWh/m^2.jr)**
A+++++	Smaller or equal to 0,00	C	200,01 t/m 225,00
A++++	0,01 t/m 40,00	D	225,01 t/m 250,00
A+++	40,01 t/m 80,00	E	250,01 t/m 275,00
A++	80,01 t/m 120,00	F	275,01 t/m 300,00
A+	120,01 t/m 160,00	G	Bigger than 300,00
A	160,01 t/m 180,00		
B	180,01 t/m 200,00		

Table 1, Primary Fossil Energy Consumption per EPC Label (source: IPLO, 2022)

Calculating an EPC label begins with assessing the building's energy demand, which is influenced by several key factors. The shape and orientation of the building affect how much sunlight enters and how well the building retains heat. The quality of insulation in walls, roofs, floors, and windows plays a critical role in minimising heat loss, while ventilation ensures a healthy indoor climate, albeit with potential energy losses. Additionally, airtight construction helps prevent draughts and heat leakage, and the choice of windows and doors, including glazing types and frame materials, further influences energy performance(NEN, 2024).
Beyond the building's structure, the efficiency of its systems contributes significantly to its energy performance. Heating systems, such as boilers, are evaluated for their efficiency and distribution methods, while cooling systems are examined for both active and passive cooling capabilities. The type of ventilation system, its energy recovery features, and the

efficiency of systems for domestic hot water supply are also considered. Even elements like lighting and building automation systems, which optimise energy usage, factor into the overall assessment (NEN, 2024).
The NTA 8800 also emphasises the importance of renewable energy sources, recognising their potential to reduce fossil fuel dependency. Systems like solar panels for electricity, solar collectors for heating water, and wind turbines are encouraged. Additionally, technologies such as combined heat and power (CHP) systems, biomass boilers, and geothermal energy solutions are evaluated for their ability to enhance energy efficiency (NEN, 2024).
Further considerations include the building's usable floor area, its intended function (e.g., residential, office, or retail), and standardised climate data, which reflect average Dutch weather conditions (NEN, 2024).
The NTA 8800 quantifies energy performance through three key indicators. The energy demand indicator calculates the energy needed per square metre annually. The primary fossil energy indicator measures fossil energy consumption, while the renewable energy ratio highlights the proportion of energy sourced from renewables (NEN, 2024).
To ensure accuracy, the NTA 8800 relies on standardised values for many parameters, such as material properties and equipment energy use. These can be substituted with specific values through certified quality declarations when available. For buildings with external heating or cooling supply, detailed performance declarations are required to validate energy performance claims (NEN, 2024).
While the NTA 8800 is a highly technical and detailed framework, its comprehensive approach ensures buildings are assessed fairly and consistently.

However, parties such as the DGBC are fairly critical on this current measurement framework since it only measures the theoretical amount of energy that is used (DGBC, 2024e). In their white paper, they (DGBC) argue that the theoretical energy use is sometimes far from the actual energy usage. This is underpinned by research that TNO did into the difference between theoretical vs real energy use of Office buildings. It can be seen (Figure 20) that compared to Table 1, for higher energy labels, the theoretical estimate is too high, and for lower energy labels, it is to Low (TNO, 2022). The (trend-based) average actual energy consumption for label A3+ is approximately 100 kWh/m^2 (as seen in Figure 20). This corresponds to the label category linked to the proposed BENG2 ("New construction requirements for the maximum primary fossil energy use in kWh per m^2 of usable floor area per year (kWh/m^2.year)" (RVO, n.d.)) of **55 kWh/m^2** (TNO, 2021). Currently, the real energy use isn't up to that standard, which is another reason why it would be better to measure the real energy use of buildings instead of only using the NTA for calculating the EPC label and the energy use of a building since an EPC label can give a false representation of how energy efficient the building actually is. If not known, this can lead to significant disappointments for building owners who just bought- or want to renovate a building, since the energy label is thus not always representative of the real energy use and the real operational carbon emissions.

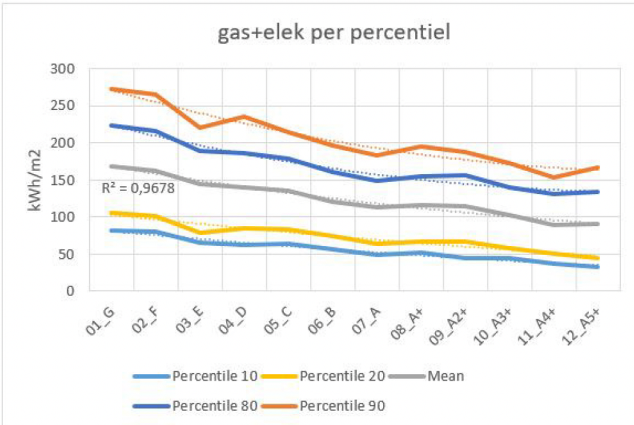

Figure 19, Real Primary Fossil Energy use (source: TNO, 2022)

3.2.2 Measuring Real Energy and Operational Carbon

Continuing from the above, the DGBC has developed the WEii (Real Energy Intensity Indicator), a tool that is becoming more popular and is highly useful for corporations under the CSRD legislation as this tool provides them with the Real energy consumption of a building, including its Operational Carbon based on the Energy Carriers (DGBC, 2024f). The WEii score is expressed in kWh/m^2 per year and is based on the total actual energy consumption of a building, including all energy supplied to the building and any energy returned to the grid (DGBC, 2024g).
This tool (Which also has an API available) is used with the EPC label to form the position of an organisation on the Energy compass. This Energy compass is another tool, developed by DGBC, and it aims to guide organisations in the transition to Paris-proof buildings by presenting them with steps they can undertake to become more sustainable and reach a Paris-proof building (DGBC, 2024e).
However, to date, this tool only presents suggestions on what measures to take, and it doesn't present the consequences of these measures in terms of energy reduction, their operational CO_2, and their possible influence on the future environmental exploitation costs of the building. Therefore, these measures need to be tested on the forehand.

3.2.3 Measuring Energy Usage without a real building

In situations where a building has not yet been constructed or renovated, measuring actual energy use is impossible. Instead, Building performance simulations (BPS) are employed to estimate energy performance in a virtual model (Di Biccari et al., 2022).

These simulations can be used when evaluating the impact of EIMS and forecasting operational energy use after a retrofit. By creating a virtual model of a building, in other

words, a BIM model[3]. Various physical and environmental parameters can be manipulated to predict energy demand, system efficiency, and occupant comfort, long before real-world data becomes available.
This BIM-based approach can enhance both the energy efficiency and performance of buildings by ensuring the use of accurate and up-to-date building data, which leads to more precise energy performance predictions (Di Biccari et al., 2022). Moreover, it makes creating and evaluating multiple design options more effective than traditional methods, thus contributing to better-informed and higher-quality decision-making (Di Biccari et al., 2022).
The Building Information Model (BIM) can then be integrated into simulation software to support performance analysis. Evaluating the energy and environmental behaviour of buildings has long posed a major challenge for designers. To address this complexity, a range of building energy performance simulation tools has been developed to facilitate more accurate and efficient assessments (Di Biccari et al., 2022).

Energy simulation tools typically rely on dynamic building physics models that incorporate climate data, thermal properties of materials, HVAC systems, occupancy patterns, and usage profiles. The advantage of simulation software is its flexibility in scenario testing, allowing stakeholders to compare alternative design strategies and their influence on energy use, operational carbon emissions, and comfort levels(Clarke, 2007).
The selection of a particular simulation platform is often influenced by the user's preferences and level of technical expertise (Abu Dabous & Hosny, 2025).
Among these platforms, some of the most widely used internationally are, Trnsys, EnergyPlus, DesignBuilder, and IESVE (Abu Dabous & Hosny, 2025; Di Biccari et al., 2022).

In the Dutch context, Vabi Elements is one of the most common simulation tools, used in 9 out of 10 non-residential buildings (Vabi, n.d.). It is specifically developed to comply with national legislation, including the NTA 8800 methodology (as described before), and is regularly used for EPC calculations and sustainability assessments. Vabi Elements supports direct integration with Building Information Modelling (BIM) platforms, enabling scenario testing for various energy-saving measures such as insulation upgrades, HVAC optimisation, and renewable energy implementation. Due to its alignment with Dutch standards and its intuitive user interface, Vabi is considered a standard for building energy simulations in the Netherlands (Vabi, n.d.)

For this research, Vabi is considered the most convenient one of these tools because it is already calibrated to Dutch regulations and widely used in this context, it is relatively easy to use and there are a lot of instruction manuals available. In addition, Vabi also offered

[3] BIM is an approach that involves the "construction of a model that contains the information about a building from all phases of the building life cycle" and the Building Information Model is a "shared digital representation of physical and functional characteristics of a building asset" (Di Biccari et al., 2022).

validation checks so the input in the model can be validated by an expert. In appendix D, the signed validation document can be found.

Creating an energy simulation in BPS software, including Vabi, typically requires several key inputs, including location-specific weather data, building geometry, material specifications, space typologies, thermal zoning, internal loads from occupants, appliances, and lighting, HVAC system details, and other relevant simulation parameters (Di Biccari et al., 2022). These input parameters need to be gathered in advance so the simulation can be executed as detailed/realistic as possible.

This also leads to a critical side note considering energy simulations. They are only as accurate as the assumptions and input data used. Differences (As also presented above) between simulated and real-life performance are often referred to as the "performance gap", and they can arise due to oversimplified user behaviour, inaccurate assumptions regarding building operations, or deviations from the planned design during construction (De Wilde, 2014). This issue is further explored in the work of van Van Den Brom, (2020), who conducted a comprehensive comparison between theoretical and actual energy consumption in Dutch buildings. Their research highlights the challenges in aligning simulated predictions with real-world energy use. This means that although simulations are great for upfront decision making, their results must be interpreted with care as they are not 100% accurate.

3.2.4 Conclusion

Understanding and accurately measuring operational energy use is essential within the Whole Life Carbon (WLC) framework, particularly given its significant share of total building-related emissions. While the NTA 8800 provides a detailed and standardised methodology to assess theoretical energy performance in the Netherlands, it remains a calculation framework based on standardised and theoretical inputs, which may not fully reflect real-world energy consumption. Furthermore, the research from TNO highlights a consistent performance gap between theoretical estimates and actual energy use, raising concerns about the reliability of EPC labels as indicators of true energy efficiency.

To address this limitation, real energy use measurement tools such as the WEii have been developed to offer a more accurate representation of operational performance. These tools are increasingly important because of regulatory developments such as the CSRD and the aim for Paris-proof buildings. However, real performance data can only be captured post-construction or post-renovation, making them unsuitable to predict future outcomes.

In cases where a building is still in the design or planning phase, energy simulations remain crucial. By leveraging BIM-integrated simulation software, such as Vabi Elements in the Dutch context, various retrofit scenarios can be tested to estimate energy use and operational carbon emissions. These simulations provide critical insights for early-stage decision making, though their reliability is dependent on the accuracy of input data and underlying assumptions.
Therefore, a combined approach, following regulatory compliance, real performance monitoring, and validated simulations, offers the most comprehensive understanding of a building's operational energy performance.

3.3 Carbon emission measurement

Following the focus on operational energy use and carbon emissions, this chapter shifts attention to the second major contributor to a building's environmental footprint, embodied carbon. As the urgency to stay within global carbon budgets increases, embodied carbon becomes an essential consideration, particularly in renovation projects where material reuse can offer significant benefits.

This chapter explores the what and the why behind embodied carbon, introduces key methodologies such as the WLC(A) to asses embodied carbon, outlines the dutch regulatory context including the MPG calculation and Paris-proof benchmarks for material-related emissions and finally highlights the importance of reliable LCA/EPD databases.

3.3.1 Understanding and addressing embodied carbon in Buildings

In the previous section, the focus was placed on operational energy use and the associated carbon emissions. However, to fully understand the environmental impact of buildings, it is essential to consider the other major contributor, embodied carbon which is defined as "carbon emissions associated with materials and construction processes throughout the whole lifecycle of a building or infrastructure" (WGBC, 2019). These emissions are primarily released during the production, transport, and installation of materials, as well as during maintenance, renovation, and end-of-life stages such as demolition and disposal (WGBC, 2019).

The urgency to measure and reduce embodied carbon comes from its growing share in total emissions. According to the 'Roadmap Whole Life Carbon' by DGBC, (2024a), the global carbon budget for limiting warming to 1.5°C, estimated at 400 gigatons of CO_2 in 2020 (Figure 21), is being depleted at an alarming rate. Most projections suggest this limit will be surpassed between 2030 and 2035. The Intergovernmental Panel on Climate Change (IPCC) confirms that human-induced emissions are accelerating climate change, which is already causing more frequent and severe weather events in the Netherlands, including heatwaves, heavy rainfall, and droughts (DGBC, 2024a). The science is clear: every tonne of CO_2 emitted contributes to global warming, and even a marginal temperature increase of 0.1°C can have significant consequences (DGBC, 2024a).

Figure 20, CO_2 budget (source: DGBC, 2024a)

Furthermore, under the EU's Fit for 55 initiative, the buildings sector will be integrated into the EU Emissions Trading Scheme starting in 2026 (ETS2). This integration aims to establish emission caps and achieve a targeted 43% reduction in emissions compared to 2005 levels. The initiative will also involve revisions to the Energy Efficiency Directive (EED) and the Energy Performance of Buildings Directive (EPBD) (Arup & WBCSD, 2023). Under this ETS 2 trading scheme, organisations can expect a higher bill for their fossil energy use, since energy suppliers will have to pay for CO_2 allowances (De Tijd, 2025; EC, n.d.). This is another reason why it is important to reduce the amount of carbon produced while using a building. Lastly, as mentioned earlier in this report in chapter 3.1, measuring the operational carbon (and maybe embodied in the future) is also needed for organisations included in the CSRD.

3.3.2 Measuring embodied carbon emissions

Accurate measurement of embodied carbon is a critical step in the transition towards a low-carbon built environment. To calculate this, an LCA assessment needs to be done. An LCA, or Life Cycle Assessment, evaluates the environmental impact of all processes and raw materials required for a product throughout its lifecycle (WGBC, 2019). Within the built environment, an LCA is used to assess the carbon footprint of materials, building elements, or entire buildings. It supports informed decision-making by allowing stakeholders to compare different design or material choices based on environmental performance (WorldGBC, 2019).

To ensure consistency, international standards such as EN 15978 and ISO 14044 define the procedures for conducting an LCA's, on which all LCA assessments are based.
A key input for these assessments, on the building-level, is the Environmental Product Declaration (EPD), which provides third-party verified environmental data for construction products (WorldGBC, 2019). EPDs are also based on standardised Product Category Rules according to EN 15804 and allow for credible comparisons between similar products. Their adoption has expanded rapidly in recent years, with more and more databases that present these EPDs (on which later more). Since July 2022 there is also an update from the

old EN 15804+A1 standardisation called the EN15804+a2 which is more accurate and provides more impact indicators (OneClick LCA, n.d.).

A growing number of tools and platforms now facilitate the application of these LCAs in the early stages of building design. Software such as One Click LCA (Finland), Tally (USA), and eToolLCD (Australia) integrates environmental databases (filled with EPDs) and building information modelling (BIM) systems to simplify carbon accounting during the design process (WorldGBC, 2019). Using these tools makes it possible to receive real time feedback on the impact of materials on the embodied carbon of a construction project (WorldGBC, 2019).

Within the built environment, a new principle called Whole Life Carbon (WLC), which is Embodied- + Operational Carbon (DGBC, 2024a), is developed. This is an assessment framework based on the LCA methodology presented above.
While the two terms are closely related, WLC and LCA are not interchangeable. The key distinction lies in their scope. Where an LCA focuses solely on the embodied carbon of (building) elements, the WLC framework (Figure 22) also incorporates the emissions produced during the operational phase DGBC, 2024a).

This framework is divided into several modules, and is usually reported in modules A1 to C4, with module D reported separately (WGBC, 2019). In module A, sometimes referred to as 'upfront carbon', are "the emissions caused in the materials production and construction phases (A1-5) of the lifecycle before the building or infrastructure begins to be used. In contrast to other categories of emissions listed here, these emissions have already been released into the atmosphere before the building is occupied or the infrastructure begins operation" (WGBC, 2019); Module B, sometimes referred to as 'Used stage embodied carbon' are "all emissions associated with materials and processes needed to maintain the building or infrastructure during use such as for refurbishments (B1-5). These are additional to operational carbon which are the emissions associated with energy used (B6) to operate the building or in the operation of infrastructure" (WGBC, 2019); Module C, sometimes referred to as 'end of life carbon', are "the carbon emissions associated with deconstruction/demolition (C1), transport from site (C2), waste processing (C3) and disposal (C4) phases of a building or infrastructure's lifecycle which occur after its use." (WGBC, 2019); Module D, sometimes referred to as 'Beyond the lifecycle' "encompasses all carbon emissions or emissions savings incurred due to reuse or recycling of materials or emissions avoided due to using waste as a fuel source for another process" (WorldGBC, 2019).

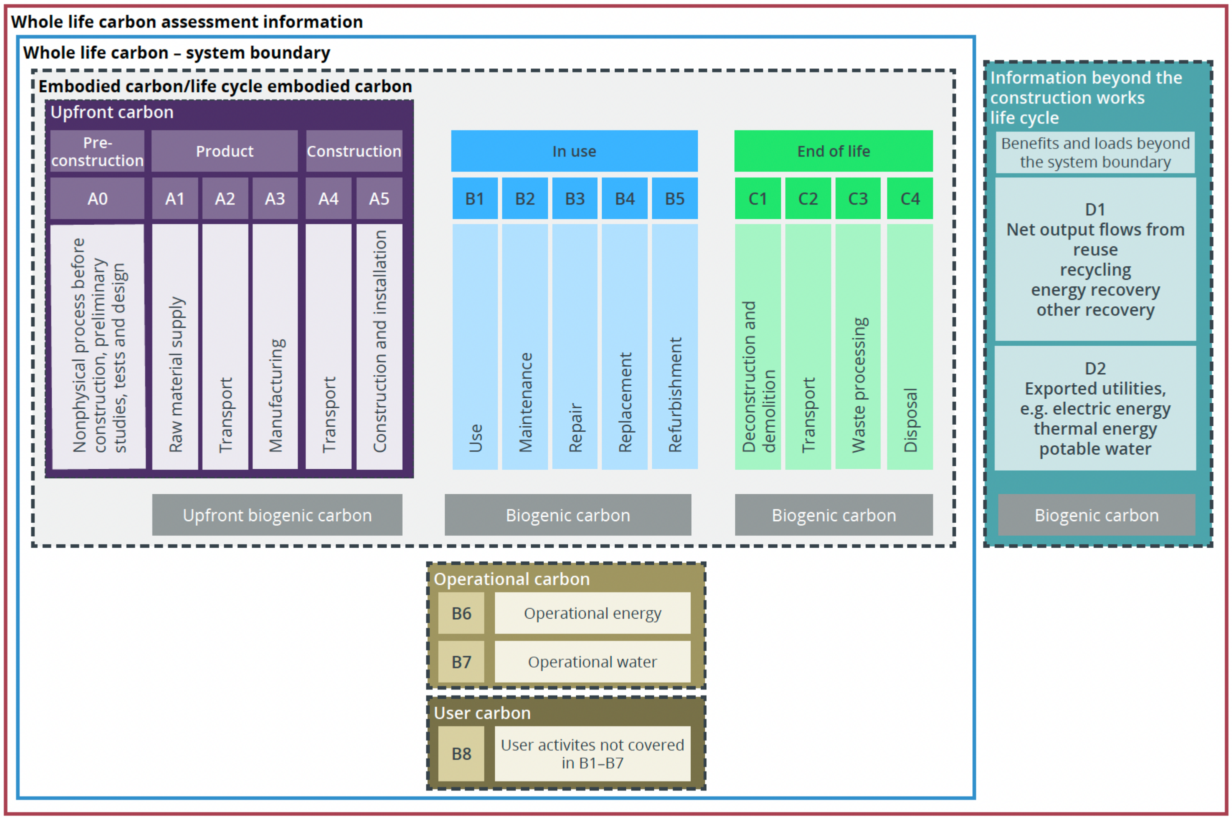

Figure 21, Schematic representation of the Whole Life Carbon principle based on the LCA methodology (EN 15978) (source: RICS, 2023)

To enable consistent decision-making in retrofit projects and minimise errors, it is essential to define clear protocols for standardised data collection practices. Therefore, the WLCA (Whole life carbon assessment) was developed by the RICS[4]. The WLCA for the built environment provides guidance and clarifies how the previously named standards, such as EN 15804, EN 15978 should be applied to ensure a consistent and uniform Life Cycle Assessment (Bienert, 2023).

3.3.3 Dutch regulatory context and Paris-proof material related emissions

For current **operational carbon** emissions in the Netherlands, the BENG[5] applies. The BENG requirements for operational emissions primarily apply to new construction projects, meaning these emissions are already extensively considered. Additionally, the DGBC (Dutch Green Building Council) aims to achieve Truly Energy Neutral Buildings (WENG), where the focus is on the actual energy consumption of a building. A WENG is

[4] *Royal Institution of Chartered Surveyors*
[5] "Eisen voor Bijna Energieneutrale Gebouwen (BENG). Deze eisen vloeien voort uit het Energieakkoord voor duurzame groei en uit de Europese Energy Performance of Buildings Directive (EPBD)"(RVO, n.d.).

characterised by a WEii (Actual Energy Intensity indicator) of 0 kWh, aligning with the Paris-proof approach. As described earlier, these operational carbon emissions can be measured using the WEii (DGBC, 2024a). However, for this research Vabi is deployed since it is only based on building simulation.

For the **embodied carbon** emissions, the Environmental Performance of Buildings (MPG) calculation is a mandatory requirement for all environmental permit applications for office buildings larger than 100 m^2 and for new residential buildings. The MPG measures the environmental impact of materials used in construction by summing their shadow costs. It is a key instrument used by the Dutch government to reduce the environmental footprint of new buildings and, more recently, also of renovation and transformation projects (RVO, 2024d).

The MPG can be used to identify direct CO_2 emissions from construction materials and set specific reduction targets. These targets can be established at the level of individual projects, companies, or portfolios, enabling structured actions to remain within allocated carbon budgets. Immediate emission reductions are necessary, as delaying action is not an option (DGBC, 2024a).
The MPG calculation is conducted at the building level, as outlined in the methodology described in Bepalingsmethode Milieuprestatie Bouwwerken (Chapter 3) and the Gids Milieuprestatie-berekeningen (RVO, 2024d). This calculation must be performed using one of the tools recognised by the Stichting Nationale Milieudatabase (NMD) (available at www.milieudatabase.nl). The latest version of the NMD must be used for the calculation, and the date on which the calculation was conducted must be included in the results (DGBC, 2024d).
The MPG calculation, which serves as the foundation for determining material-related CO_2-equivalents, must account for all components of the building, as realised upon completion or as designed, including all energy generation systems and insulation materials (DGBC, 2024d).

To set a first step towards the Paris-proof buildings, DGBC has developed the Paris-proof material-related emission benchmarks (Figure 23). These are based on the DGBC background report developed in collaboration with NIBE. This report uses global CO_2-budget calculations as presented in in the rapport of the IPCC,(2021). From the worldwide budget of 400 Gt CO_2-equivalents (for the 1.5°C scenario with a 67% probability), a national budget was derived based on population share, from which a "fair" share was allocated to the Dutch construction sector (DGBC, 2024d; Nibe, 2021).
This was then translated into a maximum allowable embodied carbon per m^2 for both new construction and renovation. These values, as presented in Figure 23 are for the retrofit scenario's. Important to note is that the values are based on modules A1-5 and do not include the other WLC modules. The goal is to ensure that the total construction output in

the Netherlands between 2021 and 2050 remains within the limits of the Paris climate targets.

Paris Proof grenswaarden	materiaalgebonden kg CO_2-eq. per m²			
	2021	2030	2040	2050
Woning (eengezinswoning)	100	63	38	23
Woning (meergezinswoning)	100	63	38	23
Kantoor	125	79	47	28
Retail vastgoed	125	79	47	28
Industrie	100	63	38	23

Figure 22, Paris-proof limit values Embodied CO_2 for construction (source: DGBC, 2024d)

3.3.4 Carbon databases

To calculate embodied carbon, LCA data is required for all implemented energy improvement measures. Renovations that aim to enhance energy performance often keep the original structural framework of a building and keep the embodied carbon from its initial construction (Bienert, 2023). As a result, upgraded buildings can sometimes demonstrate better overall environmental performance over their full lifecycle compared to new constructions. This advantage is largely due to the reduced need for resource-intensive materials such as concrete, steel, and metals, which are frequently reused in retrofit projects (Bienert, 2023).

However, significant retrofit interventions, such as the addition of insulation, replacement of windows, or modernisation of heating systems, can still make a big impact on the environmental footprint of retrofit. In this context, the selection of materials becomes a critical factor influencing embodied emissions. That is why materials and systems should be carefully reviewed. The use of biobased materials that store CO_2 for example, can lead to negative embodied carbon, and thus have a positive impact on the environmental footprint of the retrofit. Furthermore, research by (Mohebbi et al., 2021) has shown that using databases with the right amount of detail can reduce embodied carbon with 35,2%, stating that using only the same database can even reduce it up to 40,7%. This also means that using multiple databases or very general EPDs can up the amount of embodied carbon by the same percentage.

To evaluate these embodied carbon emissions associated with building materials, data is collected and consolidated in various environmental product declaration (EPD) databases, which may be either commercial or open-access public resources. These databases, used internationally, offer insights and reference values regarding the environmental burden of construction materials, see Figure 24 for the most known databases as found by Bienert, (2023).

Provider of database	Name of database	Number of included datasets	Geographical coverage	Life cycle stages covered	Cost/ Access	Data origin	Type of tool	Latest Update
University of Bath	ICE Database	> 200	UK	A1–A3	Free	LCI Data, Reports, Journals, Literature	Excel-based	2019
Federal Ministry for Housing, Urban Development and Building	Ökobaudat	>1,400	Germany	A1–D	Free	EPD, generic data	Online Application	2023
HQE-GBC Alliance	INIES	> 7,000	France	A1–A5	Free	EPD, generic data	Online Application	-
Carbon Leadership Forum/ Building Transparency	EC3	> 90,000	US	A1–A5	Free	EPD	Cloud-based	2023
Sphera	GaBi	> 15,000	EU	A1–C4	Fee required	-	Desktop software application	-
Athena Sustainable Materials Institute	Athena Impact Estimator	> 200,000	US & Canada	A1–C4	Free	TRACI v2.1 Database, Athena LCI Database	Desktop software application	2020
Melbourne School of Desing	Epic Database	> 850	Australia	A1–A3	Free	EPD	Online Application	2019
Nationale Milieudatabase	NMD	> 3.000	Netherlands	n/a	Fee required	EPD, generic data	Online Application	2020
Climate Earth	Climate Earth	> 25,000	US	A1–A3	Fee required	EPD, generic data	Cloud-based	-
ASTM International	ASTM International	> 15.000	US	A1–A3	Free	EPD	Online Application	-

Figure 23, EPD database as found by Bienert, (2023)

The databases differ in several aspects, including: (1) how many materials they cover, (2) which regions they pertain to, (3) the phases of the building life cycle they account for, (4) the reliability and origin of their data, (5) how frequently the data is updated, and (6) whether the information is freely accessible. Some software tools, now include these databases (such as some official MPG tools include the NMD), enabling users to estimate the embodied carbon associated with materials more efficiently Bienert, 2023).

As found by inspection of the different databases, the Ökobaudat seems the most convenient and up-to-date database considering the materials and systems presented. Other databases, such as the NMD, are less convenient to use. The NMD database still only publishes data according to the old EN 15804+A1, the new +A2 set is available but only as a plugin for officially rated software none of which is freely accessible (NMD, 2025). The other databases only report on a limited amount of LCA data or are difficult to use.

3.3.5 Conclusion

Calculating embodied carbon requires detailed LCA data for all energy improvement measures applied during retrofit projects. While retaining structural elements can significantly reduce embodied emissions compared to new construction, the environmental impact of the newly added materials, such as envelope- or HVAC upgrades remains substantial. Furthermore, the difference between 'normal' and biobased can be big, and so the right choice of materials can further improve the environmental performance of a renovation. Accurate assessment depends heavily on reliable LCA/EPD databases, which vary in quality, coverage, and accessibility. Among the available databases, the Ökobaudat appears to be the most comprehensive and user-friendly, whereas databases like the NMD still face limitations due to outdated standards and restricted accessibility.

3.4 Conclusion and discussion:

This chapter has shown that addressing embodied carbon is essential to work towards a Paris-proof building, as operational energy becomes increasingly regulated and reduced, the share of embodied emissions becomes more significant, particularly in the context of renovation projects where material reuse can offer a substantial advantage over new construction. To assess and manage these emissions, frameworks such as the Whole Life Carbon Assessment (WLCA) have been introduced, underpinned by international standards like EN 15978 and ISO 14044 in order to a ensure a consistent and uniform Life Cycle Assessment

Within the Dutch regulatory context, the MPG (Milieuprestatie Gebouwen) calculation provides a mandatory and structured method to quantify embodied emissions for new buildings and major renovations. Next to that, Paris-proof material-related emission benchmarks have been introduced to align the construction sector with international climate targets by setting maximum allowable embodied emissions per square metre.

Lastly, the selection and use of EPD databases play a critical role in ensuring reliable carbon estimates. While tools like Ökobaudat offer comprehensive and up-to-date datasets, others, such as the NMD, still rely on older standards and have limited accessibility, which may hinder broad application in early-stage design and decision-making.

4. Research Approach

This chapter will give a concise overview on the Main question and sub-questions in this report. It will not go into further depth, since the main question is already explained earlier and the sub-questions will be explained in further detail in chapter 5, about the methodology this research will use.
The following **main question** will be explored**:** *“What is the environmental payback time of energy improvement measures for small office buildings retrofits in the Netherlands?”*
To answer this question, the following sub-questions were formulated as a result of the literature review that was done before. For schematic representation, see Figure 25

Sub-questions:
1.What energy improvement measures are commonly implemented in office buildings, and what are their key characteristics?

Understanding which energy improvement measures are most commonly applied provides a foundational basis for the research. By identifying their characteristics (e.g., Energy use, Embodied carbon impact, Thermal conductivity) the study ensures that the measures evaluated are relevant to the Dutch context and fit the Net-zero energy and Net-zero carbon focus.

2.How do these energy improvement measures impact energy usage and operational carbon emissions (Opex)?

This sub-question evaluates the environmental impact of EIMs, focusing on reductions in operational energy usage and carbon emissions.
Understanding these impacts allows for an assessment to which degree the EIMs truly contribute to operational energy and carbon emission reduction or if unintended trade-offs arise.

3. What is the amount of CO_2 that is invested as a result of implementing the energy improvement measures (Capex)?

This question synthesises the findings from the previous sub-questions and researches the invested embodied carbon (Capex) that was implemented as a consequence of the Eims packages that were assembled in sub-question 1. Eventually, the answer to this question will also lead to the step that gives answer to the main question. The Opex (found in sub-question 2) can now be compared to the Capex found in this question. This will result in the Payback time of the Embodied carbon.

Systematic research approach:

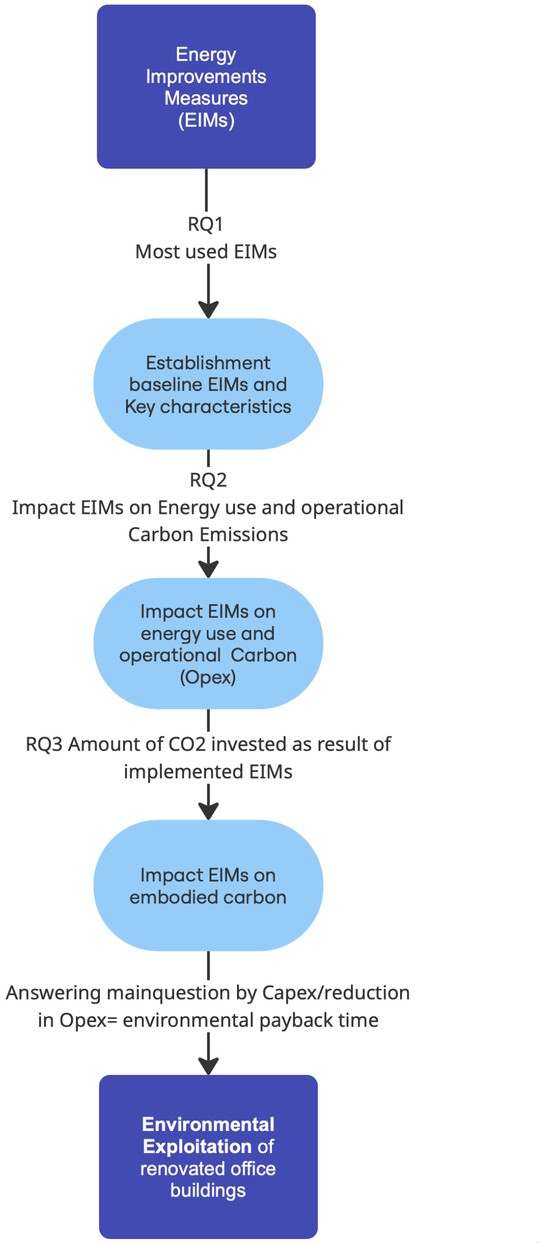

Figure 24, Schematic research approach

5. RESEARCH METHODS, EXPERIMENT

This chapter outlines the research methodology adopted to assess the environmental payback time of energy improvement measures for small office building retrofits in the Netherlands. An experimental approach has been chosen, centred around a developed case study model. This methodology involves creating a baseline 'standard' office building in three different sizes, 100m^2, 200m^2 and 500m^2, and simulating various retrofit scenarios to evaluate their effects.

The primary objective is to calculate the environmental payback time of the measures that are focused on improving the energy consumption of the building.
The subsequent sections of this chapter detail the approach taken to address each of the research sub-questions systematically. For each sub-question, the methodological steps, data requirements, and analysis techniques are described, providing a structured overview of the research process. Additionally, the methods of data collection are explained to ensure transparency and reproducibility of the study.

In this study, an experiment will be held to evaluate the performance of a hypothetical office building retrofitted with significant energy improvement measures (EIMs). The case study will start with modelling a building with relatively bad Rd values (of floor, façade and roof) and an high energy use, after which an experiment with certain retrofit scenarios will be held to work towards a net-zero energy building, aligning with the research aim to investigate the payback time of measures that move a building towards net-zero energy. The objective is to assess the impact of the various retrofit scenarios on the building's energy use, operational and embodied carbon. This simulated approach ensures a systematic investigation of energy improvement strategies without real-world data for this research.

5.1 SUB-QUESTION 1: "WHAT ENERGY IMPROVEMENT MEASURES (EIMS) ARE COMMONLY IMPLEMENTED IN OFFICE BUILDINGS, AND WHAT ARE THEIR KEY CHARACTERISTICS?"

To identify effective strategies for energy improvement in office buildings, this sub-question explores commonly implemented EIMS in Dutch office buildings that are renovated towards Paris-proof standards. This means net-zero energy. It aims to categorise these measures and categorise their characteristics.

Methodology:
Step 1: Conduct a literature review and desk research to identify commonly implemented EIMs in office buildings that are retrofitted towards net-zero energy goals (typically around EPC label A+++, Paris-proof building).

Step 2: Compile a list of these EIMs typically associated with energy efficiency improvements, categorising them by type (e.g., insulation, HVAC upgrades, renewable energy systems) and noting their key characteristics such as energy-saving potential, costs, and material requirements. This includes reviewing industry reports,

5.1.1 Energy improvement measures commonly found in office buildings.

The first step for this research question was to identify the most commonly taken energy improvement measures so that retrofit scenarios could be created. To do this, desk research was used to gather information on this topic. This research was already conducted during the literature review on the energy improvement measures in the introduction of this thesis. In this method section, part of this research comes back along with some of the extra refinements, focusing on retrofit scenarios.

Likewise to the research of Bienert, (2023), who found 3 different retrofit scenarios. In the research done by the EIB, (2020), different scenarios were identified for reducing the energy use of office buildings in the Netherlands. Each scenario incorporates different assumptions regarding building envelope upgrades, technical installations and renewable energy integration (Figure 26).

Scenario 4: naar 45-55% besparing in 2050 vanaf:	C	B	A	A+	A++
Dakisolatie Rc 3,5	✓				
Vloerisolatie Rc 3,5	✓				
Gevelisolatie Rc 3,5	✓				
HR++ glas	✓	✓			
Lucht/water warmtepomp	✓	✓	✓	✓	✓
Water/water warmtepomp					
Zon PV					

Scenario 5: naar 75-85% besparing vanaf:	C	B	A	A+	A++
Met water/water warmtepomp (wko-oplossing)					
Dakisolatie Rc 7,5	✓	✓	✓	✓	✓
Vloerisolatie Rc 5	✓	✓	✓	✓	✓
Gevelisolatie Rc 6	✓	✓	✓	✓	✓
Triple glas	✓	✓	✓	✓	✓
Lucht/water warmtepomp					
Wko (i.c.m. water/water warmtepomp)	✓	✓	✓	✓	✓
Zon PV	✓	✓	✓	✓	✓
Met lucht/water warmtepomp					
Dakisolatie Rc 7,5	✓	✓	✓	✓	✓
Vloerisolatie Rc 5	✓	✓	✓	✓	✓
Gevelisolatie Rc 6	✓	✓	✓	✓	✓
Triple glas	✓	✓	✓	✓	✓
Lucht/water warmtepomp	✓	✓	✓	✓	✓
Water/water warmtepomp					
Zon PV	✓	✓	✓	✓	✓

Scenario 6: hybride oplossing vanaf:	C	B	A	A+	A++
Dakisolatie rc 3,5/HR++	✓				
Lucht/water warmtepomp	✓	✓	✓	✓	✓

Figure 25, Measure Packages for different scenario's (source: EIB, 2020)

Among the scenarios, the "hybride oplossing" (hybrid solution) stands out as a particularly efficient and practical solution for many existing office buildings at this moment. It combines partial electrification (primarily through heat pumps) with the continued use of gas-fired installations as a backup, while also implementing insulation and ventilation upgrades where needed (EIB, 2020).
However, in their report, the EIB also acknowledges the fact that this scenario isn't fully up to Paris-proof standards. Therefore, an alternative to the hybrid solution is a fully electric retrofit scenario, which replaces the gas-fired boiler entirely with a larger heat pump system. This scenario assumes that the building envelope is upgraded by adding Insulation, at least double-paned glass, integration of balanced ventilation systems with heat recovery, the addition of low heating distribution systems and the addition of renewable energy sources.

		Action	Concequence
Passive Measures	Wall/Roof/floor Insulation	Upgrading thermal insulation of building envelope	Reduces heat loss/gain, improves thermal comfort, lowers heating/cooling loads
	High-performance Glazing	Installing double/triple glazing or low-E coatings	Reduces solar heat gain and heat loss; improves comfort
	Solar Shading Devices	Adding fixed or dynamic shading to windows	Minimises cooling demand, enhances daylight control
	Airtightness Improvements	Sealing gaps, improving joints	Reduces infiltration, enhances HVAC efficiency
	Lighting Upgrades	Replacing conventional lighting with LEDs	Reduces electricity use and internal heat gains
Active Measures	HVAC System Upgrades	Installing efficient heat pumps or hybrid systems	Matches new load profile and lowers energy demand,
	Smart HVAC Controls	Systems that adjust operation based on demand and occupancy	Optimises performance, improves comfort, reduces waste
	Mechanical Ventilation with Heat Recovery (WTW-units)	Recovers heat from exhaust air to preheat incoming air	Reduces heating needs, improves air quality
	Lighting Control Systems	Daylight or occupancy sensors, dimming controls	Enhances energy savings through intelligent use
Monitoring & Management	Smart Meters and Sub-meters	Devices that monitor consumption in real time	Informs optimisation, supports accountability and diagnostics
	Building Management Systems (BMS)	Centralised control of systems using real-time data	Enables dynamic optimisation and lifecycle management
Renewable Integration	Photovoltaic (PV) Panels	Solar electricity generation on rooftops or façades	Reduces grid dependency, lowers operational carbon emissions

Figure 26, Overview of measures found

Using these findings it and the measures that were found in the literature review (Figure 27), it was chosen to create two scenarios (Figure 28), a hybrid scenario and a fully electric scenario, as these are most implemented in the road to net-zero buildings. For the selection of the materials used for isolation and shading, a list from the Nibe milieu[6] classifications was used to determine the right materials per category, based on the milieu classification of the materials commonly used according to Nibe. Important to note is that this data was not used for the EPDs but nor as a systematic overview of common implemented systems. For the insulation of the façade, wood fibre insulation in a timber frame (HSB, houtskeletbouw) inner wall construction was chosen, as Bienert, (2023) stated that these biobased materials can significantly reduce embodied carbon. In addition, the results also include a variant of this approach, using another commonly selected option, a metal stud construction filled with mineral wool. This was done to compare the results of a 'normal' material in comparison to a biobased material.

[6] https://www.nibe.info/nl

		Scenario 2 (Hybrid)			Scenario 3 (Fully electric)	
		Rc value (m2 K/W)			Rc value (m2 K/W)	
		Facade	5,6		Facade	5,6
		Glass	1,1		Glass	1,1
		Roof	7		Roof	7
		Floor	3,3		Floor	3,3
		Thickness (MM)			Thickness (MM)	
External wall type	Outside	Masonry brick	90	Outside	Masonry brick	90
		Mineral wool	80		Mineral wool	80
		Brick	140		Brick	140
		Flexible woodfiber + Timber framework and board material	163		Flexible woodfiber + Timber framework	163
	Inside	Plaster	2	Inside	Plaster	2
Roof type	Outside	EPDM	20	Outside	EPDM	20
		PUR Isolation	100		PUR Isolation	100
		PUR Isolation	80		PUR Isolation	80
	Inside	Concrete floor	180	Inside	Concrete floor	180
Floor type	Outside	PUR Isolation	80	Outside	PUR Isolation	80
		Concrete floor	300		Concrete floor	300
		Chape (sand cemen	70		Chape (sand cemei	70
	Inside	Floortiles	20	Inside	Floortiles	20
Window type		Wooden frame & HR++ Glass			Wooden frame & HR++ Glass	
Internal Walls		Not included in this study			Not included in this study	
Space Conditioning		Hybrid setup Natural gass boiler (HR107) + Air-Water Heatpump Ventilation type D -Balance ventilation -WTW unit Multisplit Cooling			Heatpump Air-Water xKW - COP 4 Ventilation type D -Balance ventilation -WTW unit Multisplit Cooling	
Heat and Air distribution system		Radiators (Low temperature) Airducts for ventilation			Floorheating 200mm (Low temperature) Airducts for heating	
Reneweble Energy (Scenario 3+)		Absent			PV panels Monocrystalline silicon 1650x1000 mm Power: WP 400	
Lighting		500LUX 100% TL&LED Power 4W/m2			500LUX 100% TL&LED Power 4W/m2	
Solar shading		Raffstores on all windows			Raffstores on all windows	

Figure 27, Scenario hybrid and full electric

For the systems, it was chosen to implement a simple balanced ventilation system, because it concerns small office buildings, and there is no special need for bigger air handling units. For the heatpump was chosen to implement an air-to-water heatpump. These are simpler to install, suited for smaller buildings and are more commonly used in renovations (Daikin, n.d.). The technical details of these systems and materials will be displayed in the next chapter.

5.1.2 Baseline definition

The experiment starts with a 'Baseline Office building'. Therefore, it also needs to be explored which starting point should be taken from a baseline office building perspective. As seen in Figure 29, 72% of the office stock was built before 2000. As this is a significant portion of the total building stock, and it involves buildings that need to improve significantly, for this research, it will be assumed that the baseline model will be an office building built before 2000.

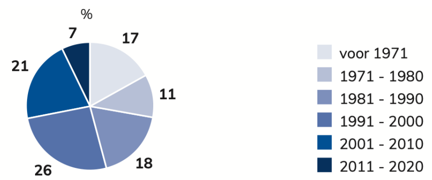

Figure 28, Stock office space divided by construction year (source: NVM, 2021)

For this research, it was important that, from the base scenario, relatively big improvements could be made to simulate a retrofit of buildings with a bad EPC label. The baseline scenario (Figure 30) was built using the specifications that were found by the EIB, (2016) and is a mix of office buildings built before 2000. For this scenario, the same applies as the previous ones; the technical details will be displayed in the follow-up chapter.

	Baseline scenario 1
	Rc value (m2 K/W)
Facade	2.9
Glass	0,5
Roof	3.3
Floor	0,3
Temperature Heat supply	HT
Central heating	HR 107
Distribution system	Radiators
Cooling	Multisplit system
Ventilation	Natural Ventilation (System type A)
Window type	Wooden frame & HR Glass
Lighting	500LUX 50/50 TL&LED Power 9,5W/m2

Figure 29, Specifications baseline scenario (source: self-made, based on EIB, 2016)

5.1.3 Databases

To evaluate the embodied carbon emissions associated with building materials, data is collected and consolidated in various environmental product declaration (EPD) databases, which may be either commercial or open-access public resources. These databases, used internationally, offer insights and reference values regarding the environmental burden of construction materials, see Figure 31 for the most well-known databases as found by Bienert, (2023).

Provider of database	Name of database	Number of included datasets	Geographical coverage	Life cycle stages covered	Cost/ Access	Data origin	Type of tool	Latest Update
University of Bath	ICE Database	> 200	UK	A1–A3	Free	LCI Data, Reports, Journals, Literature	Excel-based	2019
Federal Ministry for Housing, Urban Development and Building	Ökobaudat	>1,400	Germany	A1–D	Free	EPD, generic data	Online Application	2023
HQE-GBC Alliance	INIES	> 7,000	France	A1–A5	Free	EPD, generic data	Online Application	-
Carbon Leadership Forum/ Building Transparency	EC3	> 90,000	US	A1–A5	Free	EPD	Cloud-based	2023
Sphera	GaBi	> 15,000	EU	A1–C4	Fee required	-	Desktop software application	-
Athena Sustainable Materials Institute	Athena Impact Estimator	> 200,000	US & Canada	A1–C4	Free	TRACI v2.1 Database, Athena LCI Database	Desktop software application	2020
Melbourne School of Desing	Epic Database	> 850	Australia	A1–A3	Free	EPD	Online Application	2019
Nationale Milieudatabase	NMD	> 3.000	Netherlands	n/a	Fee required	EPD, generic data	Online Application	2020
Climate Earth	Climate Earth	> 25,000	US	A1–A3	Fee required	EPD, generic data	Cloud-based	-
ASTM International	ASTM International	> 15.000	US	A1–A3	Free	EPD	Online Application	-

Figure 30, EPD database as found by Bienert, (2023)

For the analysis conducted in this research, the ÖKOBAUDAT database was selected. This database was chosen for its accessibility, comprehensive data coverage, and its inclusion of advanced life cycle information. A key advantage of the ÖKOBAUDAT over the Dutch NMD is that it already EN 15804+A2 data, which is crucial for a more accurate and current representation of embodied emissions. In contrast, the NMD currently only provides access to this level of data within a limited number of official calculation tools, making ÖKOBAUDAT a more up-to-date resource for independent academic research.

The specific embodied carbon data points used in this study can be found in appendix C

5.2 SUB-QUESTION 2: "HOW DO THESE ENERGY IMPROVEMENT MEASURES IMPACT ENERGY USAGE AND OPERATIONAL CARBON?"

To assess the impact of the energy improvement measures identified in sub-question 1, this section investigates how different retrofit packages affect the operational energy demand and associated carbon emissions of an office building. The analysis was conducted using Vabi Elements, a Dutch energy simulation tool provided for this study, which enables detailed modelling of energy performance based on various building configurations and technical installations.

This section describes how the most important parameters considering the systems where filled in. This will be done by dividing the parameters in to different categories and within each category the details per scenario will be displayed.

5.2.1 PRE-CONDITIONS AND SIMULATION ASSUMPTIONS

In this chapter, the preconditions will be explained. For equal results, it is important that for every scenario and building size, the parameters are filled in equally so that the outcomes are comparable.

This research focuses on small office buildings; for this research, this means office buildings up to 500m^2. That is why 3 different sizes were chosen: 100m^2, 200m^2 and 500m^2. Researching three different sizes allows to compare the effects of building size on energy use and carbon emissions.

The following pre-conditions were established:

- The comfort level must remain the same (this means approximately the same indoor climate)
- The window-to-wall ratio must be consistent for each building size.
- The building envelope stays the same for each building size.
- For each building size, no changes will be made to the type of installations used within the different scenarios.
- The building orientation remains consistent across the scenarios.
- The same user behaviour assumptions will be made (e.g. occupancy schedules, internal heat gains)
- The PV panels will have the same orientation per scenario and building size

5.2.2 TEST PARAMETERS AND SYSTEM INPUTS

This chapter will delve further into the chosen measures from chapter 5.1 and explains in detail how certain parameters are filled in considering the conditioning of the buildings in Vabi. Note that this is only done for the parameters that weren't already displayed in the scenario overview. Adding to this, also one of the Vabi Reports will be added to the appendices, in this report some of the consistent parameters (e.g. the number of people per m^2, location and orientation, amount of solar panels) in all building scenarios can be found back. It can be assumed that, except for the specific capacities of the heating, cooling and ventilation installations (these are also mentioned below), all parameters are filled in consistently.

Space conditioning

For each scenario, the required heating and cooling capacities were determined using the Adaptieve Temperatuur Grenswaarden (ATG) method. This adaptive temperature guideline, as outlined in ISSO Publication 74, allows for a dynamic assessment of indoor comfort based on outdoor conditions and perceived user satisfaction. As explained in the previous chapter, all scenarios and all building sizes had to reach a comparable level of comfort. In Figure 32 the specific parameters considering the amount of ventilation, heating capacity, and cooling capacity can be found. The ventilation capacities are based on the BBL (besluit bouwwerken leefomgeving) article 4.122.

Scenario baseline			100 m2	200m2	500m2
	Space Conditioning	Power Natural gass boiler (HR107) in KW	14	17	28
		Vantilation amount, natural ventilation	n/a	n/a	n/a
		Power Multisplit Cooling in KW	3	4	6
Scenario 2					
	Space Conditioning	Hybrid setup Natural gass boiler (HR107) + Air-Water Heatpump in KW	14 + 3	17 + 5	28 + 8
		Ventilation amount type D in M3/h	300	600	1500
		Power Multisplit Cooling in KW	3	4	6
Scenario 3					
	Space Conditioning	Power Air-Water Heatpump in KW	4	5	8
		Ventilation amound type D in M3/h	300	600	1500
		Power Multisplit Cooling in KW	3	4	6

Figure 31, Parameters space conditioning

Materials

For all material specifications, such as construction details, lambda values and the density that was used, the Vabi rapport in appendix B can be used. Here is an overview of all the constructions that were used. All lambda values and densities are based on the previously mentioned 'millieudatabase' from Nibe.

Percentage Glas:

For this research the selection of window-to-wall ratios (WWRs) was based on the findings of Yeom et al., (2020) who conducted a combined cognitive and energy performance analysis using virtual reality and simulation tools. In Their study, they identified optimal WWRs per façade orientation: 44.47% for the East, 50.58% for the South, 44.37% for the

West, and 40.95% for the North façade. These values were therefore adopted in this study to ensure a balance between thermal performance, energy efficiency, and occupant well-being in small office buildings.

Energy emission factors

For the calculation of the operational carbon, the emission factors as determined by the RVO are used. These are displayed in kg CO_2 eq/unit(eenheid) in Figure 33

	WTW	*TTW*	*WTT*	*Biogene Emissies*	*Eenheid*
Aardgas (G-gas)	**2,134**	1,779	0,355	0	Nm3

	Totaal (WTW)	*Directe emissies (TTW)*	*Ketenemissies (WTT)*	*Infrastructuur*	*Eenheid*
Grijze Stroom	**0,536**	0,448	0,088	0,001	kWh
Stroom (onbekend) gridmix	**0,328**	0,270	0,058	0,013	kWh
Windkracht	**0**	0	0	0,016	kWh
Zonne-energie	**0**	0	0	0,062	kWh
Waterkracht	**0**	0	0	0,004	kWh
Biomassa	**0,071**	0	0,071	0,002	kWh
Stroometiket	**Variabel**	-	0,058	-	kWh

Figure 32, Emissie factoren voor Gas en Electriciteit (source: RVO, 2025)

To calculate the energy factor of gas, from m^3 to kWh, the recalculation factors (Figure 34) from the WEii 3.0 protocol are used (DGBC, 2024g). This leads to an emission factor of 0,22 kg CO_2 eq / kWh

Energiedrager	energiefactor $f_{conversie}$ [kWh/eenheid]	weegfactor f_{weeg}
Aardgas	9,77 (kWh/m³)	1
Elektriciteit	1 (kWh/kWh)	1
Warmte	278 (kWh/GJ)	0,33
Koude	278 (kWh/GJ)	0,10
Biomassa vast	4,19 (kWh/kg)	1
Waterstof	3,0 (kWh/m³)	1
Olie (stookolie, huisbrandolie)	11,7 (kWh/ltr)	1
Propaangas	7,058 (kWh/ltr)	1

Figure 33, Energyfactors (source: (DGBC, 2024g)

5.3 Sub-question 3: " What is the amount of CO_2 that is emitted as a result of implementing the energy improvement measures (Capex)?"

This question synthesises the findings from the previous sub-questions and researches the invested embodied carbon (Capex) that was implemented as a consequence of the EIMs packages that were assembled in sub-question 1. Eventually, the answer to this question will also lead to the step that answers the main question. The Opex (found in sub-question 2) can now be compared to the Capex found in this question. This will result in the payback time for the embodied carbon.

5.3.1 Assessment methodology and limitations

As shown in the theoretical background (chapter 3), there are several methodologies available for conducting environmental impact assessments. However, this study only focuses on the embodied carbon impact of the implemented EIMs.
In the Netherlands, the MPG (MilieuPrestatie Gebouwen) method is commonly used for environmental performance calculations (see chapter 3). However, since MPG software was not available for this research, the WLCA framework, as outlined in Chapter 3, is applied.

This approach is internationally recognised, which enhances the interpretability and comparability of the results for a global audience. For this study, the WLCA methodology (Figure 35) is used to determine the carbon payback time of the selected retrofit measures. As Bienert, (2023) states "It is important to distinguish between the life cycle of the building and the products used for the retrofit". This research focuses on the products used for the retrofit, and therefore, the following assumptions and limitations apply to this analysis:

- If the carbon payback time is shorter than the minimum lifespan of the newly added materials or systems, no further calculations will be made regarding potential replacements within the remaining lifetime of the building.

- The baseline scenario assumes the presence of a high-efficiency (HR) gas boiler, which is either retained alongside the addition of a heat pump (in a hybrid system) or replaced entirely by a heat pump. It is assumed that the HR boiler has recently been replaced or, in the case of full substitution, is due for replacement. Therefore, the embodied carbon of the HR boiler is excluded from the calculations.

- The WLCA methodology states that life cycle stages A1 to A5 for retained materials or systems can be excluded from the assessment. However, for life cycle stages B,C and D of the retained materials, reporting is mandatory. However, since this research only aims to evaluate the impact of newly added measures, the embodied emissions of existing elements are not considered. These emissions would occur regardless and are thus irrelevant for this specific payback calculation. In this respect, the study partially deviates from the full WLCA methodology.

- Although WLCA also prescribes that removed materials or systems should be included in sub-stage A5.1, this is excluded from the analysis due to the complexity and uncertainty in estimating those values.

- The End-of-Life (EOL) stage (module D) is included in the assessment as described in the WLCA methodology. However, Module D is excluded from the carbon payback time calculation, as it concerns emissions or savings beyond the building's operational phase. Instead, module D will be reported separately. In the payback time modules, A t/m C will be included.

In addition to WLCA, this research uses the calculation protocol "Paris-proof material related emission" as described by the DGBC, (2024d) to express material-related emissions in kg CO_2-eq per m^2 Gross Floor Area (GFA). These benchmarks (Figure 36), as also referenced in Chapter 3, are derived from life cycle assessments, normally conducted using MPG software and include life cycle stages A1 to A5. Although MPG software was not available for this research, the WLCA calculations follow the same LCA modules. Therefore, it is assumed that the results obtained using the WLCA framework are compatible with the DGBC benchmark comparison.

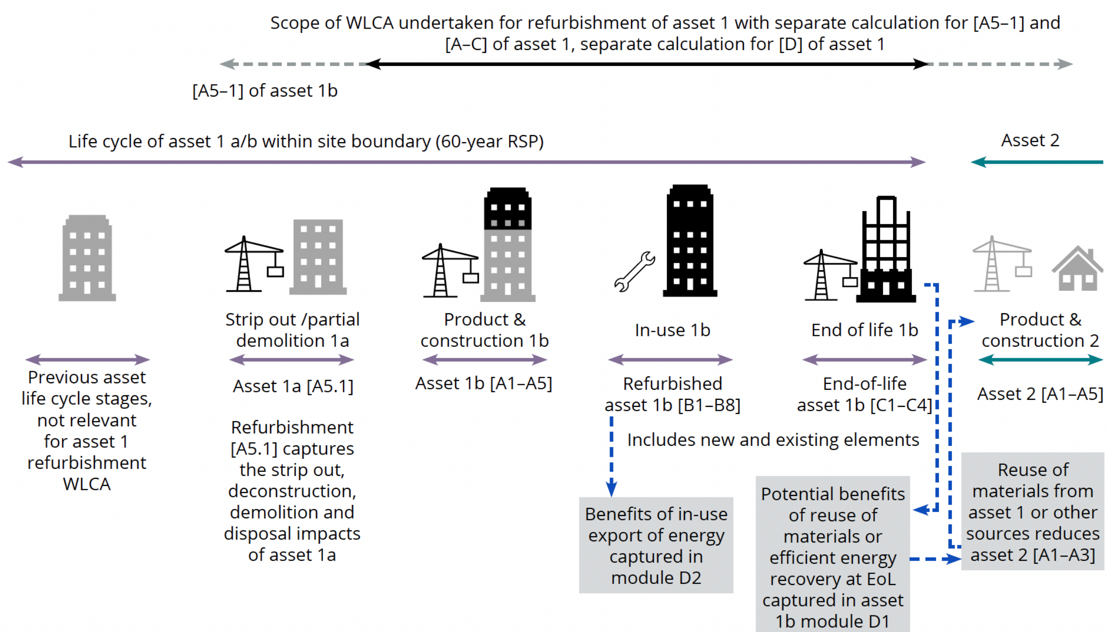

Figure 34, Scope of the WLCA applied in this retrofit analysis (source: RICS, 2023)

Paris Proof grenswaarden	materiaalgebonden kg CO₂-eq. per m²			
	2021	2030	2040	2050
Woning (eengezinswoning)	100	63	38	23
Woning (meergezinswoning)	100	63	38	23
Kantoor	125	79	47	28
Retail vastgoed	125	79	47	28
Industrie	100	63	38	23

Figure 35, Paris-proof limit values Embodied CO_2/m^2 renovation (source: DGBC, 2024d)

5.3.2 Processing the results

This section above quantifies the embodied carbon introduced by the retrofit measures. Now the answer to the main question can be formulated.
In this last step, the result section will compare the results of the various retrofit packages. Determining the effectiveness of each package in reducing energy and carbon emissions and concluding whether the retrofit packages approach net-zero energy and carbon emissions. To determine the carbon payback period, the analysis compares the reduction in operational carbon emissions against the additional embodied carbon introduced by the retrofits. This comparison provides an estimate of the time required for the operational savings to offset the initial carbon investment (see Figure 37).
In addition to that, the embodied carbon will also be calculated per square meter to analyse if it is within or outside the previously presented Paris-proof limit values.

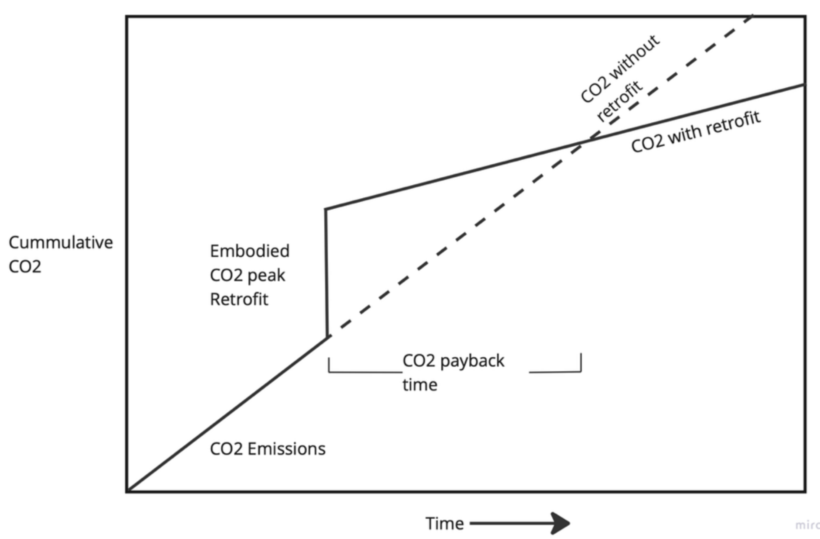

Figure 36, Schematic representation of CO_2 payback time

6. Results and Discussion

In this section, the results of this research will be displayed. The results will be divided per sub-question to present all the information found in systematic order.

6.1 Energy improvement measure scenarios

In this chapter, the retrofit scenarios, which consist out of the EIMs that were found by the literature research, are displayed. The scenarios apply to each building size variant (100,200 and 500 m^2), and in general, there are 3 scenarios. The base scenario, scenario 2 (hybrid variant) and scenario 3 (full electric variant). As explained in the method section of this research, these scenarios were also split into two general variants, one that used biobased materials for the insulation of the façade (HSB) and one that used conventional, non-biobased materials (Metalstud).

Baseline variant:

		Baseline scenario 1	
		Rc value (m2 K/W)	
Facade		2.9	
Glass		0,5	
Roof		3.3	
Floor		0,3	
			Thickness (MM)
External wall type	Outside	Masonry brick	90
		Mineral wool	80
		Brick	140
	Inside	Plaster	2
Roof type	Outside	EPDM	20
		PUR Isolation	80
	Inside	Concrete floor	180
Floor type	Outside	Concrete floor	300
		Chape (sand cemer	70
	Inside	Floortiles	20
Window type		Wooden frame & HR Glass	
Internal Walls		Not included in this study	
Space Conditioning		Natural gass boiler (HR107)	
		Multisplit Cooling	
Heat and Air distribution system		Radiators	
		Natural ventilation System A	
Reneweble Energy		Absent	
Lighting		500LUX	
		50/50 TL&LED	
		Power 9,5W/m2	
Solar shading		Absent	

Figure 37, Baseline scenario

Scenario 2 and 3(+) for the HSB variant:

		Scenario 2 (Hybrid)			Scenario 3 (Fully electric)	
		Rc value (m2 K/W)			Rc value (m2 K/W)	
		Facade	5,6		Facade	5,6
		Glass	1,1		Glass	1,1
		Roof	7		Roof	7
		Floor	3,3		Floor	3,3
		Thickness (MM)			Thickness (MM)	
External wall type	Outside	Masonry brick	90	Outside	Masonry brick	90
		Mineral wool	80		Mineral wool	80
		Brick	140		Brick	140
		Flexible woodfiber + Timber framework and board material	163		Flexible woodfiber + Timber framework	163
	Inside	Plaster	2	Inside	Plaster	2
Roof type	Outside	EPDM	20	Outside	EPDM	20
		PUR Isolation	100		PUR Isolation	100
		PUR Isolation	80		PUR Isolation	80
	Inside	Concrete floor	180	Inside	Concrete floor	180
Floor type	Outside	PUR Isolation	80	Outside	PUR Isolation	80
		Concrete floor	300		Concrete floor	300
		Chape (sand cemen	70		Chape (sand ceme	70
	Inside	Floortiles	20	Inside	Floortiles	20
Window type		Wooden frame & HR++ Glass			Wooden frame & HR++ Glass	
Internal Walls		Not included in this study			Not included in this study	
Space Conditioning		Hybrid setup Natural gass boiler (HR107) + Air-Water Heatpump Ventilation type D -Balance ventilation -WTW unit Multisplit Cooling			Heatpump Air-Water xKW - COP 4 Ventilation type D -Balance ventilation -WTW unit Multisplit Cooling	
Heat and Air distribution system		Radiators (Low temperature) Airducts for ventilation			Floorheating 200mm (Low temperature) Airducts for heating	
Reneweble Energy (Scenario 3+)		Absent			PV panels Monocrystalline silicon 1650x1000 mm Power: WP 400	
Lighting		500LUX 100% TL&LED Power 4W/m2			500LUX 100% TL&LED Power 4W/m2	
Solar shading		Raffstores on all windows			Raffstores on all windows	

Figure 38, Scenario 2 and 3(+) for the HSB variant

Scenario 2 and 3(+) for the Metalstud variant:

		Scenario 2 (Hybrid)		Scenario 3 (Fully electric)		
		Rc value (m2 K/W)			Rc value (m2 K/W)	
		Facade	5,6		Facade	5,6
		Glass	1,1		Glass	1,1
		Roof	7		Roof	7
		Floor	3,3		Floor	3,3
		Thickness (MM)			Thickness (MM)	
External wall type	Outside	Masonry brick	90	Outside	Masonry brick	90
		Mineral wool	80		Mineral wool	80
		Brick	140		Brick	140
		Metal stud profile CW100 + Mineral Wool and board material	125		Metal stud profile CW100 + Mineral Wool and board material	125
	Inside	Plaster	2	Inside	Plaster	2
Roof type	Outside	EPDM	20	Outside	EPDM	20
		PUR Isolation	100		PUR Isolation	100
		PUR Isolation	80		PUR Isolation	80
	Inside	Concrete floor	180	Inside	Concrete floor	180
Floor type	Outside	PUR Isolation	80	Outside	PUR Isolation	80
		Concrete floor	300		Concrete floor	300
		Chape (sand ce	70		Chape (sand ceme	70
	Inside	Floortiles	20	Inside	Floortiles	20
Window type		Wooden frame & HR++ Glass			Wooden frame & HR++ Glass	
Internal Walls		Not included in this study			Not included in this study	
Space Conditioning		Hybrid setup Natural gass boiler (HR107) + Air-Water Heatpump Ventilation type D -Balance ventilation -WTW unit Multisplit Cooling			Heatpump Air-Water xKW - COP 4 Ventilation type D -Balance ventilation -WTW unit Multisplit Cooling	
Heat and Air distribution system		Radiators Airducts for heating			Floorheating (Low temperature) Airducts for heating	
Reneweble Energy (Scenario 3+)		Absent			PV panels Monocrystalline silicon 1650x1000 mm Power: WP 400	
Lighting		500LUX 100% TL&LED Power 4W/m2			500LUX 100% TL&LED Power 4W/m2	
Solar shading		Raffstores on all windows			Raffstores on all windows	

Figure 39, Scenario 2 and 3(+) for the Metalstud variant

6.2 ENERGY PERFORMANCE AND OPERATIONAL EMISSIONS

The building simulations were conducted for three office buildings of 100 m^2, 200 m^2 and 500 m^2. In each case, four scenarios were analysed: starting with a conventional baseline (Scenario 1), followed by improvements in insulation and a hybrid heating setup (Scenario 2), than followed by full electrification trough the use of a heatpump (scenario 3), and finally integration of renewable energy (Scenario 3+). This comparison shows how energy performance and carbon emissions scale with building size and how consistent each step is in delivering reductions.

As a consequence of the envelope improvements, the heat loss and cooling load decreased by 50–60% across all building sizes, from 50% for the big building (500m^2), up to 60% for the small building (100m^2). This slight difference in percentage could be the consequence of a higher exterior surface area per m^3 of indoor space for the small building as this makes it more exposed to external temperature fluctuations and thus more responsive to thermal envelope upgrades.

Across all building sizes, the simulations have shown that the stepwise implementation of the retrofits, through the 3 different retrofit scenarios, have led to a strong reduction in energy use.

In the **100 m^2** building (Figure 42), baseline energy use is 216.5 kWh/m^2. Scenario 2 reduces this to 63.9 kWh/m^2 (–70.5%). Full electrification in Scenario 3 lowers it further to 48.2 kWh/m^2 (–24.6% compared to Scenario 2 and 78% compared to Scenario 1), and in Scenario 3+, renewable generation offsets usage entirely, resulting in a net energy surplus of 99.1 kWh/m^2.

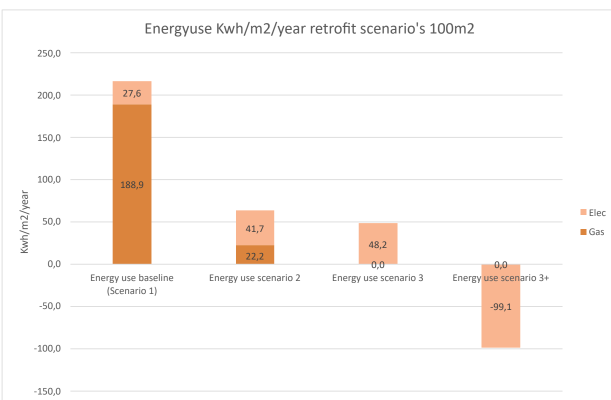

Figure 41, Energy use kWh/m^2/year retrofits 100m^2 building

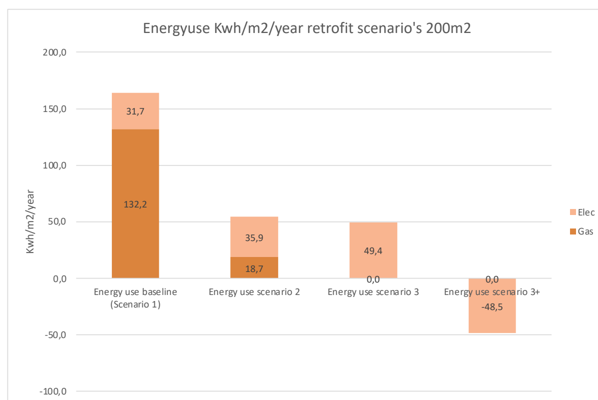

Figure 40, Energy use kWh/m^2/year retrofits 200m^2 building

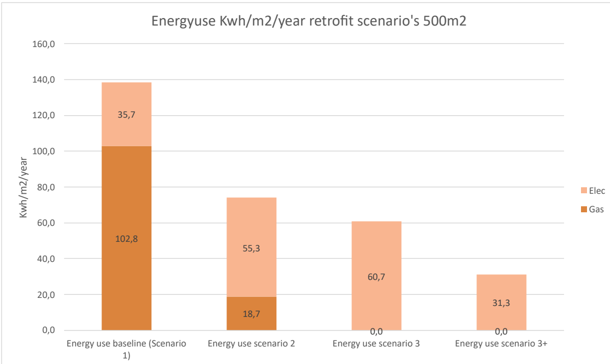

Figure 42, Energy use kWh/m^2/year retrofits 500m^2 building

The **200 m^2** building (fiure 41) starts at 163.9 kWh/m^2. Scenario 2 lowers this to 54.6 kWh/m^2 (–66.7%). Scenario 3 achieves 49.4 kWh/m^2 (–9.5% compared to Scenario 2 and 70% compared to Scenario 1), and in Scenario 3+, the building again becomes net energy-positive with –48.5 kWh/m^2.

And lastly, the **500 m^2** building (Figure 43) begins at 138.5 kWh/m^2. Scenario 2 reduces this to 74.0 kWh/m^2 (–46.6%). Scenario 3 lowers usage to 60.7 kWh/m^2 (–18.0% compared to Scenario 2 and 56% compared to scenario 1), and although Scenario 3+ includes renewable energy, the building still consumes 31.3 kWh/m^2 (–48.4% compared to Scenario 3).

The above scenarios show an energy reduction between 56% and 78%, without considering the renewable energy. These results exceed the energy-saving ranges identified by Bienert, (2023); Clark et al., (2024); EIB, (2016); Ferrari & Beccali, (2017) who all cite 40–65% energy reductions, depending on retrofit depth. However, the percentages seem to be similar. A difference to this research is that these studies all analysed bigger buildings, and the observation that can be made from this research is that, for the smallest building, the highest energy reduction is reached and for the biggest building, the lowest. This is in line with the heat loss and cooling load reduction, and it could confirm that for bigger buildings the savings are a bit lower compared to a small building. Looking at the energy use per m^2, the retrofits are in scenario 3+ all below the A+++ label (55kWh/m^2 and Paris-proof building), meaning the retrofits in this scenario reach the adequate future-proof standards.

Furthermore, in scenario 3+ the impact of renewable energy can be seen, where the two smaller buildings have enough space for the adequate amount of solar panels needed to provide enough energy to become at least net-zero energy, the bigger building (500m^2) has a much smaller roof in proportion to the m^2 office floor and is therefore not able to produce the required amount of energy, meaning this building is not a net-zero energy or better building.

Operational emissions

In terms of operational emissions, the results initially mirror energy consumption trends. With significant reductions in Scenario 2 (up to –63.2%, Figure 44), and with smaller improvements in Scenario 3, and big reductions in Scenario 3+ due to renewable offsets. However, a closer look, especially in the 200 m^2 case, reveals an emissions increase between Scenarios 2 and 3 (+2.3%), despite lower energy use (Figure 45). This finding aligns directly with the warning presented by the EIB (2020), that electrification alone does not guarantee CO_2 reductions, particularly when electricity grids still rely on carbon-intensive sources. This is also new compared to the identified literature, which doesn't seem to investigate the relation between energy reduction and operational emission reduction.

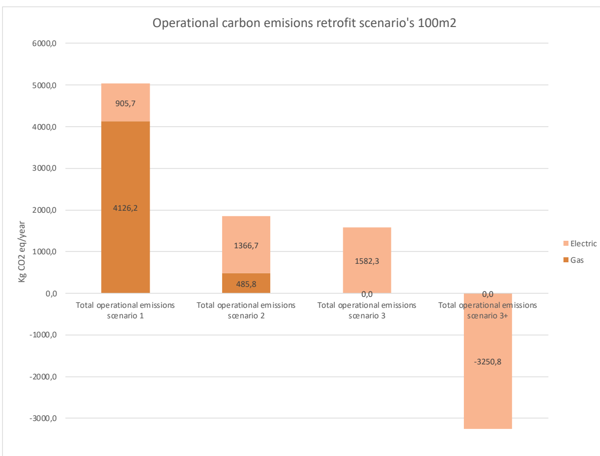

Figure 43, Operational carbon emissions 100m² building

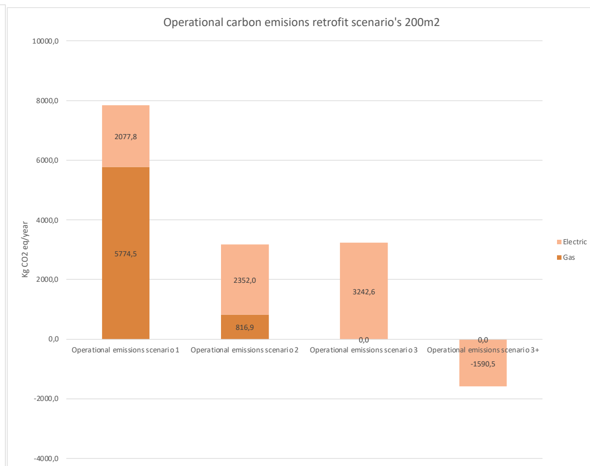

Figure 44, Operational carbon emissions 200m² building

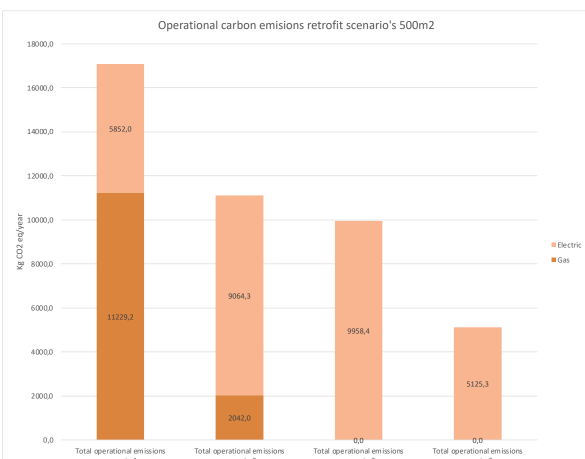

Figure 45, Operational carbon emissions 500m² building

In line with the former findings on scenario 3+ in building 500m² (Figure 46), this scenario is not able to reach zero operational carbon, which means that the renewable energy has to come from off-site renewables to become energy neutral.

6.3 EMBODIED CARBON EMISSIONS AND PAYBACK TIMES

In addition to reducing operational energy and emissions, retrofit strategies introduce new embodied carbon through the addition of new materials and systems. Evaluating whether and how quickly this embodied carbon is compensated for through operational savings is essential to determine the true sustainability impact of retrofit choices. This section explores and compares the embodied carbon payback time of the different scenarios implemented in three building sizes (100 m^2, 200 m^2, and 500 m^2) using two variants on the façade isolation, timber frame lining wall (HSB) and metal stud lining wall façade isolation, to investigate the impact of biobased vs non biobased materials as suggested in Bienert, (2023). It is assumed that in all scenarios where 'negative green emissions' arise, these offset non-green emissions, meaning that PV panels can have not only 0 operational carbon but also can have negative operational carbon, meaning offsetting emissions generated by non-renewable energy sources. That is why in most 3+ scenarios, the green line is moving downwards, meaning negative carbon emissions.

For the small building **100m^2**, Scenario 2 offers the shortest payback periods for both construction types (Figures 47, 48). HSB achieves a payback in 3.12 years, while Metalstud requires 4.19 years. These differences are due to the higher embodied carbon in the Metalstud variant (13,300 vs. 9,930 kg CO_2-eq). In Scenario 3, which introduces full electrification, payback times increase to 4.36 years (HSB) and 5.35 years (Metalstud), driven by both higher material input and diminishing returns in annual operational savings

In Scenario 3+, renewables are added, increasing embodied carbon even more, up to 45,600 kg CO_2-eq for HSB (303% more than sc3) and 49,000 kg CO_2-eq for Metalstud (265% more than sc3). Payback time now stretches to 5.51 years and 5.92 years, respectively, which is only 110% and 126% more than the scenario without renewables, although more than 2,65 and 3,03 times the amount of embodied carbon was added.

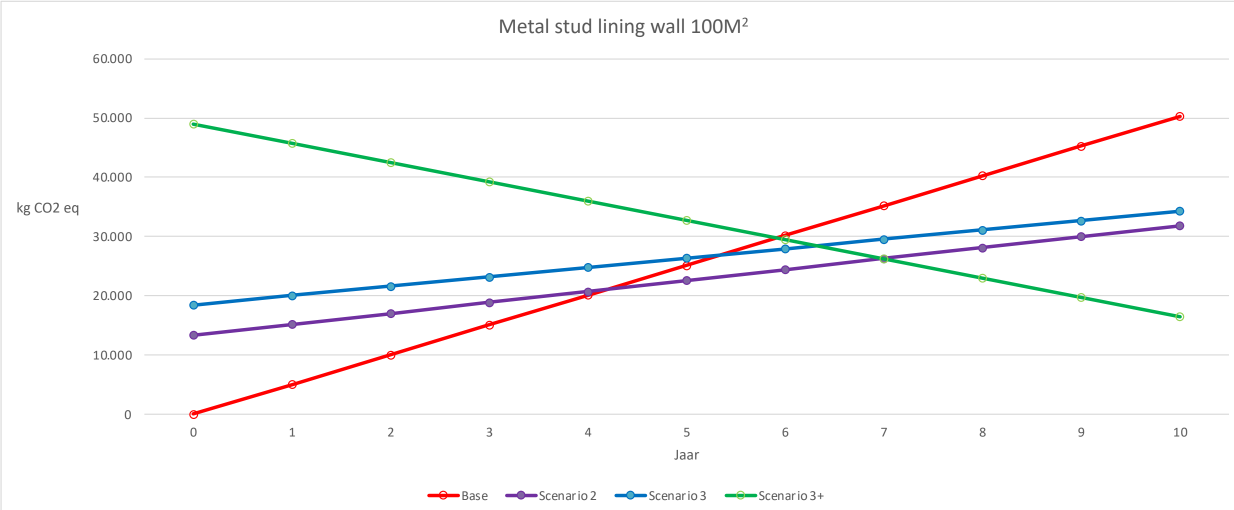

Figure 46, Carbon payback time metal stud lining wall

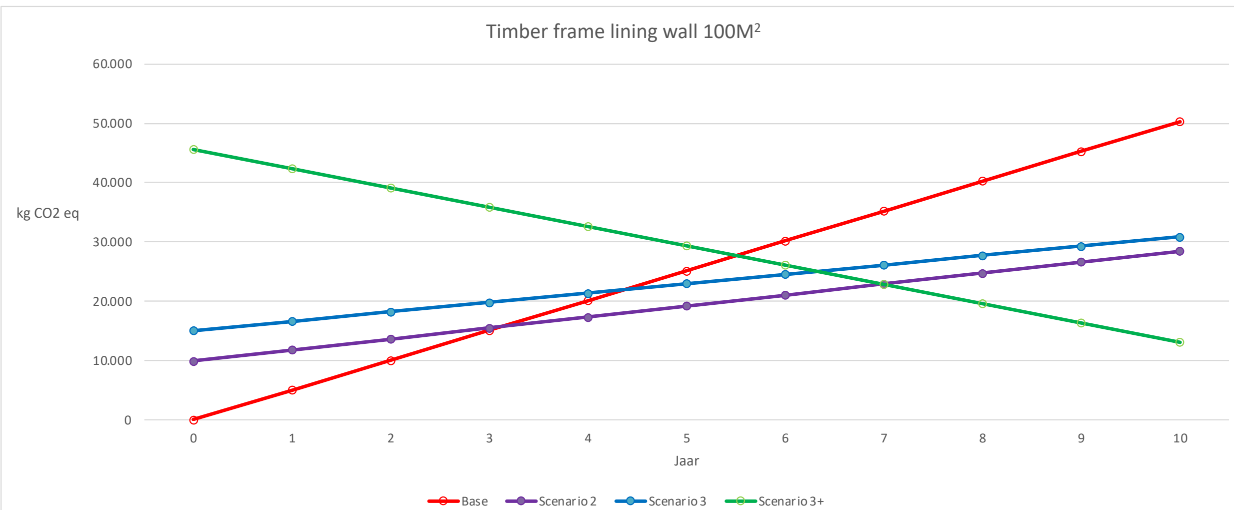

Figure 47, Carbon payback time timber frame lining wall

For the mid-sized 200 m^2 building, Scenario 2 again offers the shortest carbon payback periods for both construction types (Figure 49, 50). HSB achieves a payback in 3.03 years, while Metalstud requires 4.54 years. The difference is due to the higher embodied carbon of the Metalstud construction (21,300 vs. 14,200 kg CO_2-eq). In Scenario 3 payback times increase to 4.69 years for HSB and 6.22 years for Metalstud.

In Scenario 3+, renewables raise the embodied carbon sharply to 52,100 kg CO_2-eq for HSB (a 241% increase over Scenario 3) and 59,200 kg CO_2-eq for Metalstud (a 206% increase). Despite this large material input, the payback time increases relatively modestly: to 5.52 years for HSB (117% of Scenario 3) and 6.27 years for Metalstud (101% of Scenario 3). This reveals a similar pattern as in the small building, while embodied carbon grows steeply, the added operational savings from renewables limit the growth in payback time.

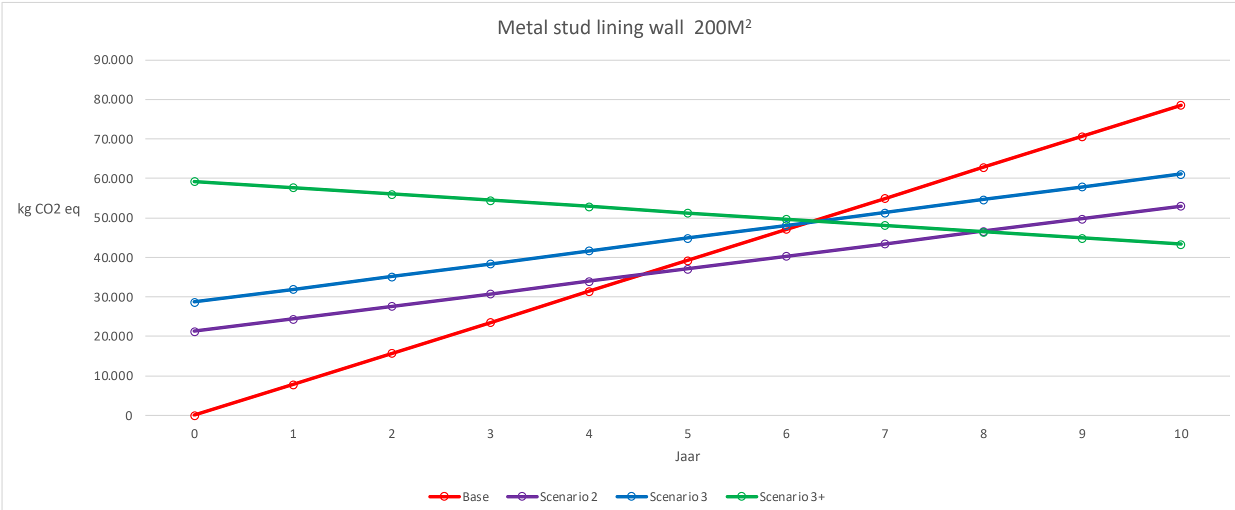

Figure 48, Carbon payback time metal stud lining wall

Figure 49, Carbon payback time timber frame lining wall

In the largest building of 500 m^2 (Figure 51, 52)., the results diverge more significantly. For HSB, Scenario 2 achieves a negative embodied carbon balance of –3490 kg CO_2-eq, resulting in a theoretical payback of –0.58 years. This case reflects that carbon-storing (biogenic) materials can have a big impact on payback time. Metalstud in Scenario 2 shows a more typical result, with 22,800 kg CO_2-eq and a payback time of 3.82 years.

In Scenario 3, electrification leads to a substantial increase in embodied carbon: up to 5730 kg CO_2-eq for HSB and 32,000 kg CO_2-eq for Metalstud. Payback times increase to 0.80 years (HSB) and 4.50 years (Metalstud), indicating high energy savings relative to the added carbon cost, especially for the timber-based structure.

In Scenario 3+, the addition of renewables results in a major rise in embodied carbon: up to 36,300 kg CO_2-eq for HSB, which is 533% more than in Scenario 3, and 62,600 kg CO_2-eq for Metalstud, a 96% increase. However, the payback times rise to only 3.03 years for HSB (379% increase) and 5.24 years for Metalstud (116% increase). This means that even though more than five times the embodied carbon was added for HSB, the resulting operational reductions still earn back the embodied carbon within a relatively short return period.

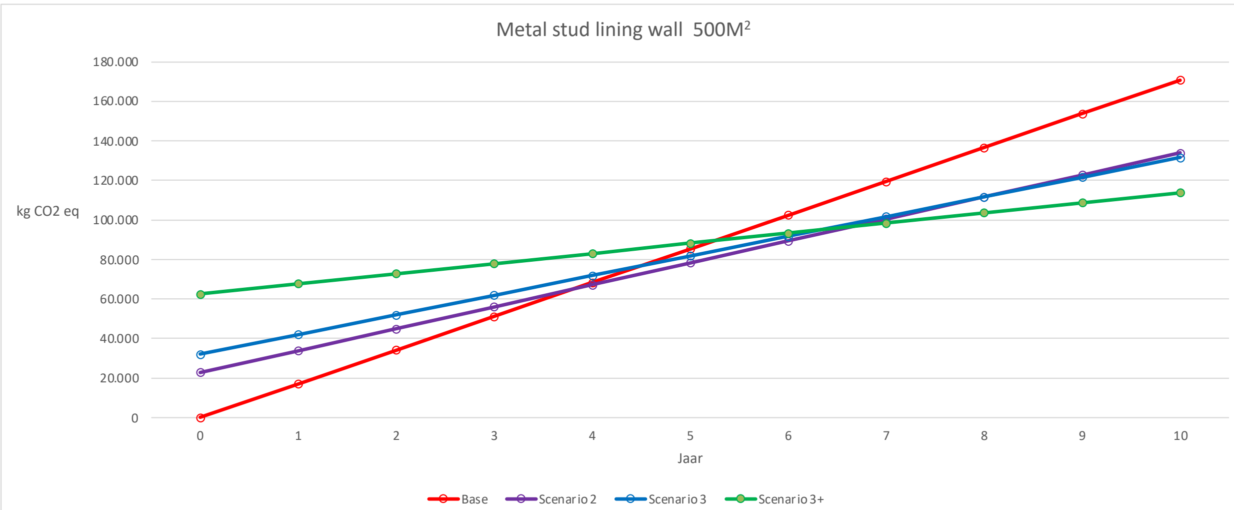

Figure 50, Carbon payback time metal stud lining wall

Figure 51, Carbon payback time timber frame lining wall

The studies earlier reviewed show that carbon payback times generally vary between 2.9 and 8 years, depending on retrofit depth, system choice, and material use. The results of this study appear to confirm these findings. However, it must be noted that not all studies use the same LCA modules or analytical methods in their calculations. For example, Bienert includes only modules A1 to A3 in his calculation, which is based on case studies. Even though it is stated that this can account for up to two-thirds of the total emissions (Bienert, 2023; Mohammadpourkarbasi et al., 2023), this means that the payback time calculated should theoretically be somewhat lower than the payback time in this study. This seems to be the case when looking at the payback times of the non-biobased variant, but the biobased variant clearly deviates from this. This can be explained by the fact that the total emissions in module C of this variant are also negative due to biogenic storage. This phenomenon is also confirmed in the study by Mohammadpourkarbasi et al., (2023), who state that biogenic storage can reduce payback times by several years.

Moreover, there seems to be a clear pattern visible: the deeper the retrofit and the more technologies or systems are added, the higher the embodied carbon and the longer the payback time. At the same time, multiple studies (see chapter 1), including this research confirm that these payback times are in all cases significantly shorter than the lifespan of the implemented measures, which underlines the long-term effectiveness of energetic retrofits.

It also seems that the use of biobased materials leads to a greater effect as building size increases, which makes sense because increasing amounts of biobased material are used compared to the non-biobased materials and systems. As a result, the difference also increases with larger building sizes. This confirms the findings of Mohammadpourkarbasi et al., (2023) and Bienert, (2023), who report reductions of 50 per cent or more, and even cases where large quantities of biobased materials result in negative embodied carbon, meaning that under the line CO_2 is stored and therefore compensates for more polluting projects.

Interestingly, there does not appear to be a direct correlation between building size and payback times in this study. However, it can be noted that in both variants (biobased vs. non-biobased), the 500 m^2 building has shorter payback times. Possible explanations for this include scale effects, the m^3-to-surface ratio, and a relatively larger share of fixed components (such as systems) in small buildings compared to floor area.

Finally, the distinction between case studies and building simulations appears to have little impact on the overall results. The outcomes of this study, despite being based on simulations, align closely with those of other studies from the literature review, such as Bienert (2023), which relies on case study data, suggesting no big differentiations across the different research approaches.

6.4 Material-related emissions

To investigate the impact of the retrofit scenarios on material-related emissions (modules A1–A5, displayed in Figure 53) per square metre, values were calculated and compared to the Paris-proof thresholds established earlier in this study.

The following observations were made:
The results show a strong dependency on building size due to the relative share of photovoltaic (PV) systems in the total material use. This is particularly influenced by the surface-to-volume ratio, as smaller buildings require proportionally more PV material per square metre of gross floor area;
Material choice significantly affects the overall embodied emissions. The differences between metal stud constructions and timber frame (HSB) variants are clearly reflected in the calculated emission values. In Figure 53 can also be seen that for the biobased variant, even negative values are presented, originating from the biogenic storage of the used materials.

For buildings of 100 m^2 and 200 m^2, the Scenario 3+ variant using metal stud construction exceeds the Paris-proof threshold. The same is true for the Scenario 3+ variant using HSB for both the 100 m^2 and 200 m^2 cases. This can be attributed largely to the high embodied carbon associated with the PV panels, which accounts for a significant portion of the total A1–A5 emissions in these scenarios.

When compared to the benchmark values reported by Bienert (2023), the Scenario 3+ variants for both material types (HSB and metal stud) exceed the referenced thresholds for smaller buildings (100 m^2 and 200 m^2). An exception is the 500 m^2 case, where both material variants remain below the 140 kg CO_2-eq/m^2 threshold set in Bienert (2023).

These findings raise the question of whether it is realistically feasible for smaller buildings to remain within the Paris-proof embodied carbon limits for renovation, as outlined in chapter 3.

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Paris proof renovation values in kg CO_2 eq for A1-A5	HSB				Metalstud		
	Scenario 2	Scenario 3	Scenario 3+	100 m2	Scenario 2	Scenario 3	Scenario 3+
	3,7001555	26,6667555	323,566755		78,9358522	101,902452	398,802452
	Scenario 2	Scenario 3	Scenario 3+	200m2	Scenario 2	Scenario 3	Scenario 3+
	-11,762385	2,84081463	151,290815		66,7230895	81,3262895	229,77629
	Scenario 2	Scenario 3	Scenario 3+	500m2	Scenario 2	Scenario 3	Scenario 3+
	-12,741791	-3,9012714	55,4787286		62,4939053	71,3344253	130,714425

Figure 52, Paris-proof renovation values

6.5 DISCUSSION

This chapter looks back at the results and critically reviews the outcomes and methods used in a systematic way.

Material and scope selection

The choice of materials and the scope of retrofit interventions, such as whether to include non-essential elements like ceiling tiles, substantially influence the embodied carbon calculation. For consistency and comparability, it is recommended to include only those measures deemed essential to achieving operational energy goals.

Given the vast array of available construction materials, each with varying environmental profiles, material selection becomes a critical determinant of the total carbon impact, as also seen in Figure 54. Glass wool insulation, for example, has a value that is twice as high as the same amount of Wood fibre insulation boards. That means by an implementation of 100m^2 roughly 300kg CO_2 eq is polluted while 100m^2 of wood fibre insulation boards would mean that 300kg is stored (=-82*0,034*100)

Material EPD label	Approx. kg CO2e (GWP) | A1- A3	Unit	Embodied Carbon (in kg / unit)
Straw insulation	-127	m³	
Hemp fibre insulation 10 cm	-2	m²	
Cork panel 6 cm	-0,34	m²	
Cork panel 1 cm	0,03	m²	
Aerogel 1 cm	12	m²	
Wood fibre insulation boards	-82	m³	
Flexible wood fibre panels	-28	m³	
Glass wool insulation 3,4 cm	3	m²	

Figure 53, Example of biobased vs normal materials kg CO_2 eq (source: Bienert, 2023)

Furthermore, the geographical origin of building products plays a significant role in determining their embodied emissions. For example, photovoltaic panels manufactured in China tend to have higher embodied carbon due to the more carbon-intensive electricity grid. Given that over 80 per cent of global panel production occurs in China (IEA, 2022a) , this factor must be carefully weighed in environmental assessments. This is, however, not always the case as not all EPD databases incorporate these statistics, such as also for this research it is also not known on which data de EPD of the used PV system is based.

Reliability of material (EPD) data

This also leads to the next point. The accuracy and consistency of embodied carbon values remain a challenge. Variations in data sources, methodological boundaries, or assumptions, such as the life cycle stages included, can lead to considerable differences in outcomes, questioning the comparability of carbon assessments across studies. As found by the research of Mohebbi et al., (2021), presented in chapter 3, using the right databases and as little as possible, can decrease the embodied carbon of projects by

40,7%. This is a considerable amount and therefore, it is essential to be transparent and critical of the WLC modules used in the payback calculations. The Ökobaudat database, used in this research, can therefore be questioned. It does display data according to the newest regulatory framework (EN15804+A2), however, for some systems, it uses relatively general data. It also doesn't always display the data across all modules for each material or system, which can lead to the assumption that it is 0 or that there is simply no data available.

Energy measurement, use and grid mix
Future shifts in the energy mix can substantially alter the operational carbon balance. For instance, if the national grid transitions more rapidly to renewable energy sources, the operational emissions associated with conventional systems may decline, affecting the relative performance and payback times of current energy improvement measures. As also proven in this research a large share from the embodied carbon emissions, especially for smaller buildings, is coming from the renewable energy created by PV systems. Depending on the grid mix the measures are compared to this can lead to long or very short off-set times

As explained in chapter 3, there can be a big difference in theoretical energy used that is based on simulations and the practical energy use when the building is in operation. This is therefore also one of the liabilities of a simulation model. It should be carefully considered that the energy use of theoretical models is often more positive than in the actual real-world operation. On the contrary, the experts at Vabi stated that, because of the quick developments made within the sector, the simulation models are getting very close to approaching the real-life energy use. This should ensure that the discrepancies between simulation and real-life scenarios are nowadays minimised.

Renewable energy and hybrid vs electrification
As the simulation results have shown, rooftop solar alone may be insufficient to meet a building's full energy demand, especially in spatially constrained urban environments. Off-site renewable generation may therefore be necessary to approach net-zero targets. Furthermore, Large-scale electrification through the adoption of heat pumps, as explained in chapter 1, will increase electricity demand considerably. The grid must be adapted accordingly to accommodate this shift, highlighting the systemic implications of decarbonising building systems, which should also be researched. As also mentioned by the EIB, (2020), presented in chapter 1,the total amount of CO_2 emissions is also not going down proportionally with the energy reduction of the buildings of this electrification. Something that this research also proves. This comes down to the still more disadvantageous CO_2 emissions of electricity compared to gas (0,328 kg CO_2/kWh for electricity and 0,22 for gas).This also again proves that Grid decarbonisation can impact the outcome of the payback times, as lower emission factors for electricity would significantly favour scenario 3

Continuing on the above, the results show that the Hybrid scenarios offer shorter carbon payback periods, but do not achieve net-zero operational emissions. However, in contexts lacking access to renewable electricity, their comparatively lower upfront carbon footprint may make them a more sustainable option. This is because when comparing the operational emissions of scenario 2 and 3, it can be seen that the difference in operational emissions is very minimal, meaning that with the current grid-mix for electricity and without access to renewable energy, the hybrid option (as also identified by EIB, 2020), seems a more logical option. The payback graphics from the two scenarios (Hybrid and full electric) also confirm this statement across all building sizes and variants.

Building size and effectiveness of Interventions
The results indicate a potential relationship between building size and the relative effectiveness of energy reduction measures. Smaller buildings exhibited greater proportional reductions in energy demand, compared to the literature, which researches bigger buildings; this would suggest a possible tipping point beyond which the impact of interventions stays relatively equal. Further research is needed to determine the extent and implications of this relationship.

Net impact on climate
Finally, as ascribed in chapter 3.1.8, an important sidenote to these results is that of the time value of carbon. While traditional assessments focus on total carbon emissions over a building's life cycle, recent insights, such as those from Hawkins (2024), highlight the importance of when emissions occur, not just how much is emitted.

Retrofit scenarios with longer payback times were, in this research, the options with the most embodied carbon, but also the highest operational reductions. However, looking at the insights from Hawkins (2024), this higher operational reduction doesn't necessarily mean that it is the right option in this moment, even though this higher reduction earns back the high embodied carbon investment.

The reason lies in the fact that emissions released today seem to exert more cumulative warming over time than those released later. Therefore, investing in high upfront carbon measures now, despite their eventual payback, may worsen long-term climate trajectories and could delay the progress of reaching climate goals. In contrast, retrofit strategies with lower embodied carbon and shorter payback periods, even if they result in slightly less total emission reduction over a certain number of years, may offer a more favourable net impact on the climate in the crucial upcoming decade.

7. CONCLUSION

This research aimed to evaluate what happens with the carbon emissions of a small office building in the Netherlands when retrofitted towards net-zero energy. The goal was to determine if the operational carbon savings resulting from these retrofits could offset the initial investment in embodied carbon within the life expectancy of these measures, in other words, the environmental payback time, and to what extent different materials/systems and building sizes influenced this so-called payback time.

7.1 SUB-QUESTION 1: WHAT ENERGY IMPROVEMENT MEASURES ARE COMMONLY IMPLEMENTED IN OFFICE BUILDINGS, AND WHAT ARE THEIR KEY CHARACTERISTICS?

Among the EIMs this research found the most relevant and widely implemented are: Envelope insulation (façade, roof and floor), at least double-pained or even triple-pained glazing, solar shading, balanced ventilation with heat recovery, HVAC upgrades in the form of (Hybrid) heat pumps and low temperature heating (in the form of floor heating), combined with PV panels to create renewable on-site energy.

Furthermore, this research identified two different logical scenarios that work towards the identified goal of net-zero. Namely, the hybrid scenario (named scenario 2), involving the addition of Envelope insulation in two variants (biobased and normal), solar shading in the form of raffstores, and a hybrid heating system (gas boiler and air-water heat pump).

The second, full electric scenario, also including renewable energy in the form of PV panels (scenario 3 and 3+), was based on scenario two but involved the addition of a heat pump instead of a hybrid system and low temperature floor heating.

7.2 SUB-QUESTION 2: HOW DO THESE ENERGY IMPROVEMENT MEASURES IMPACT ENERGY USAGE AND OPERATIONAL CARBON EMISSIONS (OPEX)?

The results from the energy simulations that were conducted in Vabi Elements show that energy improvement measures (EIMs) have a substantial impact on reducing both energy usage and operational carbon emissions, but that the relationship between operational energy and carbon is not always linear. The reduction in primary energy use across all three building sizes, 100, 200, and 500 m^2, ranged from approximately 46% to 78%, depending on the retrofit scenario and thus the depth of intervention. However, while the energy reductions were relatively consistent, the operational carbon, as said, did not decrease at the same rate. It was in one case (scenario 3, 200m^2 building) even higher than scenario 2 for that same building size. This implies that full electrification may not always be the right choice because the carbon intensity of electricity is higher than the carbon intensity of gas. This means that if the energy reduction between the hybrid and full electric scenario isn't big enough, the full electric scenario can, in some cases, lead to more operational carbon if there is no access to renewable energy sources. Therefore, it looks like the hybrid scenario can, in some cases, be the better choice if the grid mix stays as it is and doesn't decarbonise any further.

7.3 Sub-question 3: What is the amount of CO_2 that is invested as a result of implementing the energy improvement measures (Capex)?

The results display a significant variance in embodied carbon depending on material selection, retrofit depth, and building size. For instance, scenarios using timber frame façade insulation (HSB) consistently resulted in lower embodied carbon values than those using conventional metal stud construction with mineral wool. In some of the cases, HSB scenarios even achieved negative carbon values due to biogenic carbon storage, particularly in the larger 500 m^2 building.
The amount of CO_2 that was invested for the modules A1-5 ultimately varied from -12,74 kg CO_2 eq/m^2 for the scenario 2 (HSB variant) in the 500m^2 building, to 398 kg CO_2 eq/m^2 for the scenario 3+ (metalstud variant) in the 100m^2 building. The difference can be appointed to three major factors, building size (envelope/system to volume/surface ratio), biobased vs normal material and PV panels.

7.4 Conclusion on the main question

This research suggests that the environmental payback time, the period required for operational carbon savings to offset the embodied carbon introduced during retrofitting, varies significantly depending on the retrofit strategy, material selection, and building size. However, across all tested scenarios and building sizes, the payback time remains well within the technical lifespan of the implemented measures. The calculated payback times in this research vary from under one year (in large-scale retrofits with biobased materials) to just over six years (in smaller buildings using conventional materials and PV systems).

8. Recommendations

Ensure greater continuity and homogeneity in EPD databases
To make Whole Life Carbon (WLC) assessments more reliable and to support better decision-making, consistency in environmental data is essential. This can be achieved through stricter quality controls on Environmental Product Declarations (EPDs) and improved alignment at the European level.

Promote the use of biobased materials with biogenic carbon storage
Materials such as timber, flax, or hemp can temporarily store CO_2, thereby reducing embodied carbon and delaying emissions. In addition, they often have a lower environmental impact during production. This makes them particularly attractive for shortening the ecological payback time

Include required solar PV capacity in full electric retrofit assessments, regardless of actual integration, as energy is not net-zero
The effectiveness of electric systems such as heat pumps in reducing carbon emissions is directly tied to the emission intensity of the electricity grid. Further decarbonisation increases operational emission reductions, but this can only be achieved if electricity production itself becomes more sustainable. Therefore, retrofit evaluations should account for the necessary solar PV capacity, even when not physically included, as long as the grid is not yet fully net-zero.

Pursue a phased sustainability strategy with a clear roadmap
Instead of attempting to decarbonise all at once—which often leads to high peaks in embodied emissions—a structured approach with staggered investments over several years allows for a better balance. This helps avoid embodied carbon spikes and creates a gradual pathway toward net climate benefits.

Adopt carbon payback time as a steering instrument in subsidies and performance requirements
By using CO_2 payback time as a criterion in policy instruments, it becomes easier to prioritise measures that are not only effective but also deliver impact at the right time. This enables better alignment with short-term climate goals.

Integrate the 'time value of carbon' into policy frameworks and design standards
Current environmental performance indicators often overlook the timing of emissions. By considering the timing of emission reductions, measures with immediate impact become more attractive, while long-term environmental burdens can be avoided.

9. Reflection

Looking back on the entire process over the past year, I can say that I have learned an incredible amount. To begin with, i significantly underestimated how difficult it would be to choose a topic. In particular, the scoping proved to be a major challenge. I initially wanted to cover far too much. Next tot hat, in the early phase, it also seemed likely that i would graduate in collaboration with external organisations such as Skaal, CBRE, or the Dutch Police, but all three options eventually fell through. Skaal felt the topic was not a good fit, CBRE lacked capacity in the appropriate department, and with the Police, the opportunity simply vanished without clear explanation.

As a result, my topic and scope shifted quite a bit throughout the process, especially from case study to experiment was a big step. From the first topic, which was investigating the influence of ESG criteria on financing models, to my second big shift, the impact of energy improvement measures on the operational (use and maintenance) costs of office buildings, to my last and current topic. This idea actually emerged from personal frustration during the renovation of a small family-owned office building, and I am ultimately glad I stayed close to that original spark all was the original focus on the financial part and i now shifted to the environmental part, which i think is far more interesting because should be the reason to retrofit (altough it not always is).

Arriving at the P2 milestone, I believed my research direction was clear. However, it later became evident that there were still many uncertainties in my proposed methodology. Once again, I was reminded of the importance of careful scoping. My intended approach was relatively straightforward. It began by identifying the most common energy-saving measures and their properties. Establishing these properties went fairly smoothly, as much has already been published on this topic and the available reports were largely aligned. A greater challenge, however, lay in identifying the right database to extract these properties from. Although many options are available, some proved to be incomplete or extremely difficult to interpret. Some databases only reported on to little LCA modules where other reported in loose materials, making it very difficult to gather the materials and combine them into one system. Therefore, it was important to gather as much data from one database in order to keep consistency in the results.

Complicating matters further was the use of for example the Dutch NMD (Nationale Milieu Database), which was harder to access due to updates being made available only through certain proprietary software. After comparing several alternatives, I ultimately settled on the German Ökobaudat database, which offered the most complete and user-friendly format for my purposes.

Parallel to this part of the research, I also worked on energy simulations. To familiarise myself with the topic, I first created static energy calculations in Excel, based on a basic heat loss model. I combined this with data from a technical report from TNO[7] outlining the average energy usage of various systems in Dutch office buildings (such as lighting, ventilation, and water usage, in addition to heating and cooling loads). While these calculations turned out to be far from realistic, due to limitations in the 2005 excel model to calculate the heatloss and the outdated data from the NIBE database, they helped me develop a better understanding of the impact of different retrofit measures on the payback time.

Once those calculations were complete, I started looking for suitable simulation software. I initially considered TRNSYS, but ultimately gained access to Vabi Elements, which proved to be the right choice as this program also works according to dutch regulatory guidlines. I am grateful for this opportunity, as gaining access to professional software like Vabi is not always easy. However, learning to use the software proficiently took much longer than expected. At first glance, Vabi seems straightforward, but the deeper I delved into the technical parameters, the more complex it became. Fortunately, I received support from the Vabi team, and as a result, I can confidently state that my simulations were properly validated (a signed confirmation of correct use is included in appendix D)

From the start, I received feedback stressing the importance of staying critically aware of the impact of the measures I entered into the simulation software. I believe that transitioning from Excel to Vabi helped me develop a stronger intuitive grasp of the results. Interestingly, those results challenged my initial hypothesis that payback times would generally be long. While many nuances remain, the findings do align well with existing literature, though with the important side note that not all studies apply the same LCA modules or methods. This also become one of the key challenges of the thesis, ensuring meaningful comparisons without "comparing apples and pears." As was often discussed during supervision meetings, LCA/EPD data vary widely across databases. The same applies to how such data is integrated into carbon payback time calculations, where there is little consensus on which modules to include. By clearly and transparently stating the assumptions and methods used in this study, I believe the results remain comparable to the literature and can be used as a foundation for future research.

Another challenge was defining the retrofit scenarios. Given the wide range of options available, I had to narrow the scope to keep the scenarios clear and applicable to the Dutch office market. Here, I followed the advice of my supervisors not to overcomplicate the scenarios, allowing for better comparison and practical relevance.

A recurring piece of feedback since P2 was to improve the clarity of my writing. I tried to address this by thoroughly reviewing the entire thesis and improving the overall readability. As mentioned in the report, I used ChatGPT to help improve the flow of the text. This

[7] Het energieverbruik naar energiefuncties voor Nederlandse kantoren (TNO, 2024)

support was helpful, especially given the technical nature of the topic, which sometimes made it difficult to express ideas exactly as intended.

All in all, this has been an extremely instructive process with a steep learning curve. One of the most important lessons for me has been learning to let go of certain ideas and make clear choices. This remains a challenge for me, as I prefer to fully understand a topic before deciding whether or not to include it, which can take a lot of time in my case. Next to that, i have taught myself a wide range of new skills since P2, from working with environmental databases and EPDs, to setting up simplified LCA/WLC analyses, to using Vabi software. Much time was invested in mastering the technical research methods, and ultimately, it was equally important to effectively communicate and interpret the results, something that was challenging, yet also rewarding given the complexity of the input required for this type of research. In the end I can say that im proud of my self because I learned a lot of new things, such as the principles of carbon accounting, the use of the WLC framework and energy simulation programs and the analysis of the eventual results. I don't know, however, if I'm fully satisfied with the results since I have the feeling that the amount of effort that was in the input didn't fully reflect the outcome of the report. However, this is also an inherent part of the thesis journey, where the greatest learning for me did not necessarily come from the final outcome, but from the extensive process of getting there.

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DECLARATION USE OF AI

I, Laurens van der Laan, hereby declare that artificial intelligence (AI) tools have been utilised during the preparation of this master thesis to use as inspiration and to assist in text editing. I take full responsibility for the content, analysis, and conclusions presented in this thesis, regardless of the tools or technologies used during its development. The use of AI was intended solely as a means to enhance productivity and quality of the text and did not compromise the rigour or authenticity of the academic work.

Signed,

Laurens van der Laan

Date: 17 Juni 2025

APPENDICES

APPENDIX A (DEFINITIONS OF CRE)

Definition of Corporate Real Estate (CRE)

Year	Authors	Defenition of CRE
1983	Zeckhauser & Silverman	The land and buildings owned by companies not primarily in the real estate business
1988	Dresdow & Tryce	Real estate leased and controlled by the corporation
1990	Nourse	The management of real property assets for use in business other than real estate
1992	Joroff	The land and buildings used for work space, infrastructure and investment.
1993	Brown et al.	Corporate real estate management (CREM) is the optimum use of all real estate assets utilised by a corporation in pursuit of its primary business mission
1993	Brown et al.	Real properties that house productive activities of a company whose primary corporate purpose involves producing goods and services, but that incidentally owns and/ or leases and manages real estate to achieve corporate productions and objectives
1999	O'Mara	CRE – encompass all aspects of the physical settings of the organizations
1999	Nelson, Potter, & Wilder	Real estate assets which represent a significant proportion of firm value.
1999	Roulac	CRE is real property that house productive activities of a traditional corporation
1999	Booth	CRE is the quickest and most direct solution for companies looking to increase value by controlling the cost base
2000	Kooymans	"Corporate Real Estate" is a term that is generally used in a broad sense to

		refer to real estate owned by a corporation, whether it is for investment or for use
2001	Brueggeman & Fisher	The use of real estate as part of business operations and their activities are commonly referred as CRE
2002	Wills	Real property assets that is essential for its production or continuance in business. It does not include those real property assets that are held for investment purposes.
2003	Krumm & De Vries	Corporate Real Estate is a substantial asset base and an important cost factor
2010	Hartmann, Linneman, Pfnur, Moy, & Siperstain	Owing to its enormous asset value and associated costs, real estate is increasingly recognized as an important competitive factor among non-real estate related firms.
2013	Khanna, Van Der Voordt, & Kopples	CRE can be seen as a secondary channel of corporate communication.
2014	Abdul Jalil & Heywood	CRE contribution move beyond physical contribution into intangible roles, including human resources and financial contributions.
2016	Zhao & Sing	CRE is the single largest fixed capital investment of many public listed firms which not substitutable by other capital goods, such as equipment and plants.

Table 2, Definitions of CRE throughout time (Source: Fadzil, 2019)

APPENDIX B VABI REPORT 100M2 SCENARIO 3(+)

Vabi Elements

Building Simulation

Project 100m2 Vabi (MT) 4.0.vp

Project number: 1

Variant: Scenario 3

Calculated on: 03/05/2025

Produced with:

Vabi Elements 3.12.1.19
Vabi calculation engine Building Simulation version 3.6.12

Project data

General

Name project	
Project number	1
Description	100m2 building
Variant name	Scenario 3(+)
Variant description	Adding Floor heating, a Heatpump and Solar panels. Everything is operating on electricity

Address

Principal
Consultant

Climate file

Climate file	NEN5060 ref TO1 zeer streng
Start date	1-1-1906
End date	31-12-1906
Number of calculated days [-]	365
National days and holidays	National days and holidays not taken into account

Starting conditions

Solar radiation ground reflection (from climate file) [-]	0,2
Calculated with shading from own building	Yes
Calculated with shading from building parts	No
Calculated with shading from recessed windows	No
Calculated with shading from surrounding buildings	No
Calculated with shading from canopies	No
Openable windows	Present
Windows open when indoor temperature is (during operation time) [°C]	26.0
Windows open when indoor temperature is (outside operation time) [°C]	Window parts remain closed

System information

Heat and cold generation

Generation configuration Heatpump

Heat generator	Present
Cold generator	Present

Central air handling

Air handling Simple Balance Ventilation with WTW

Central air handling	Present
Flow control variable volume system	Present
Mechanical ventilation	Balanced

Local installation

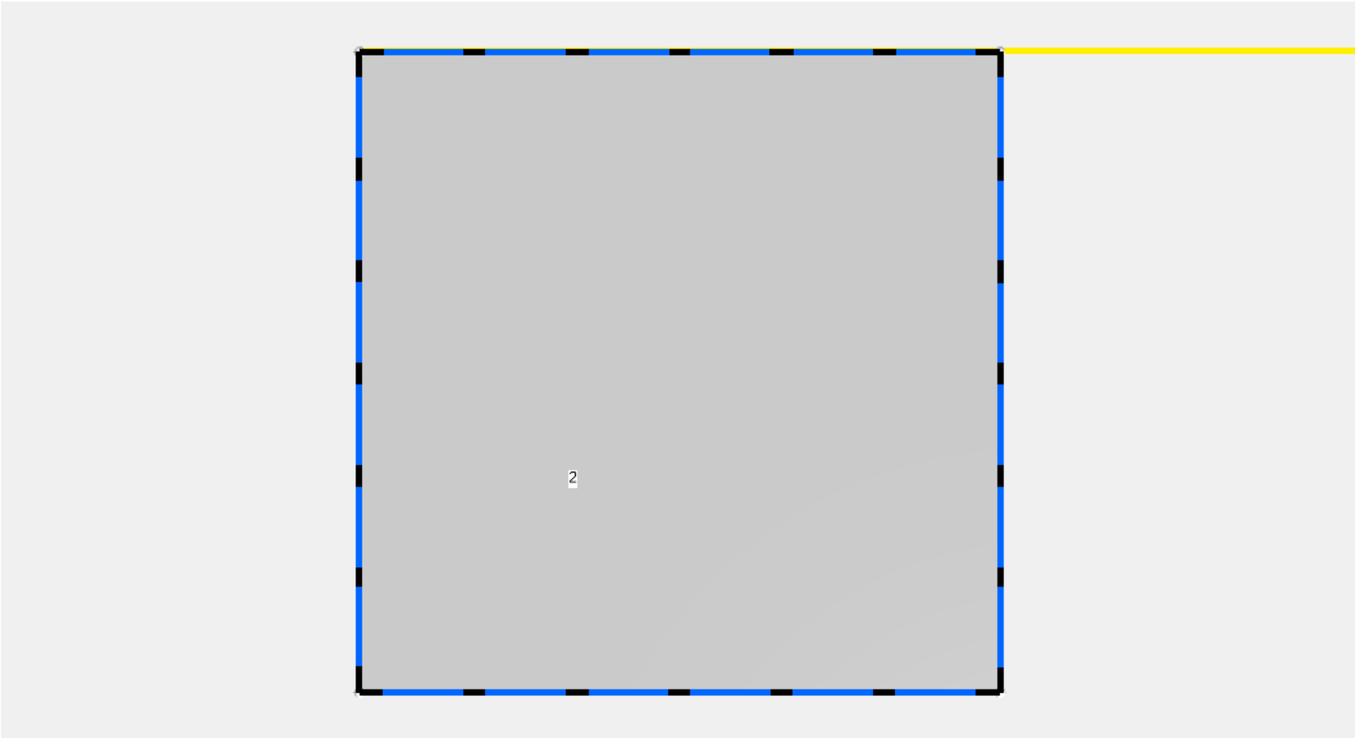
Local system	Absent

Pictures and drawings

No pictures or drawings present.

Floor plans

Floor plan height 28 mm

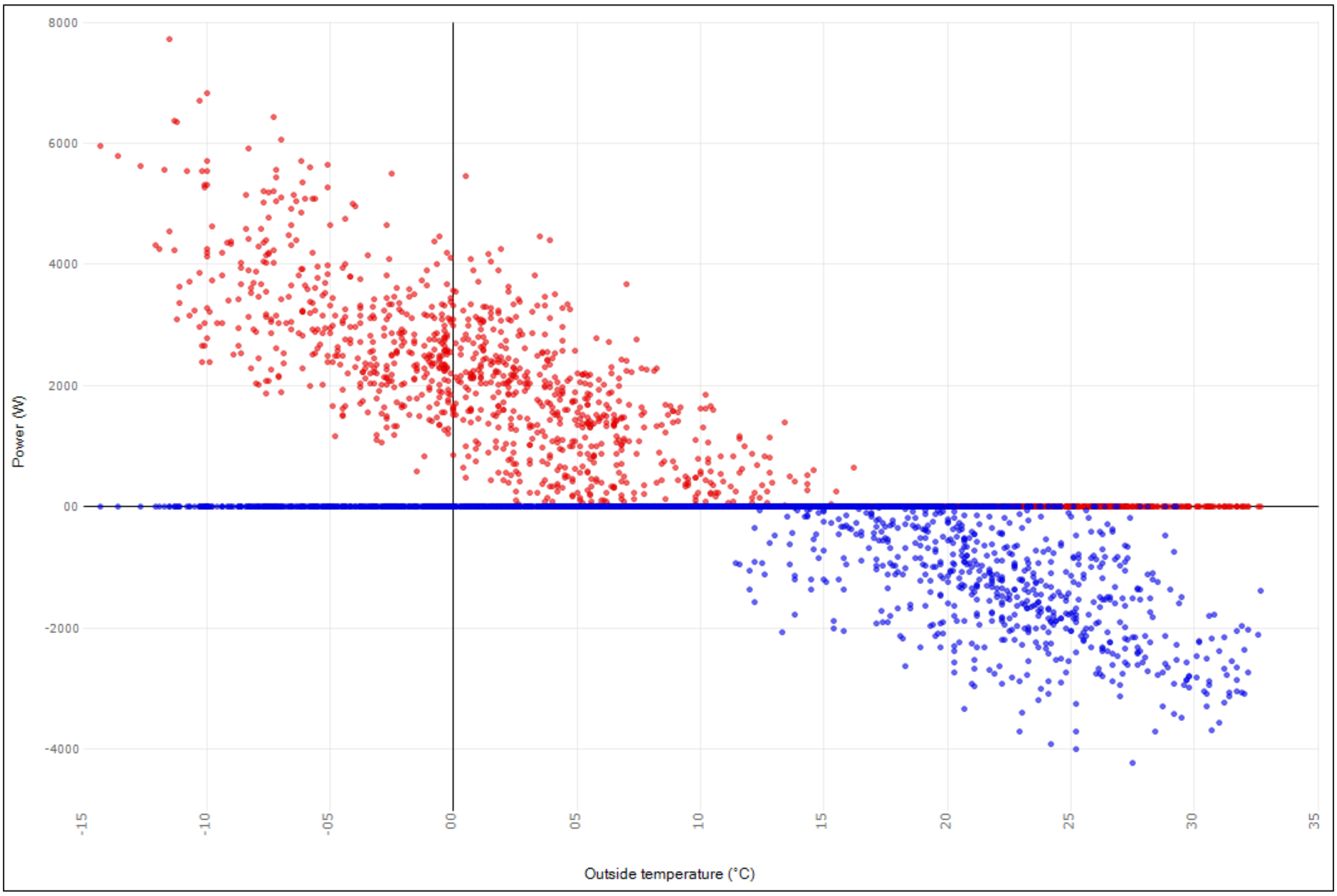


Totals

Temperature statistics

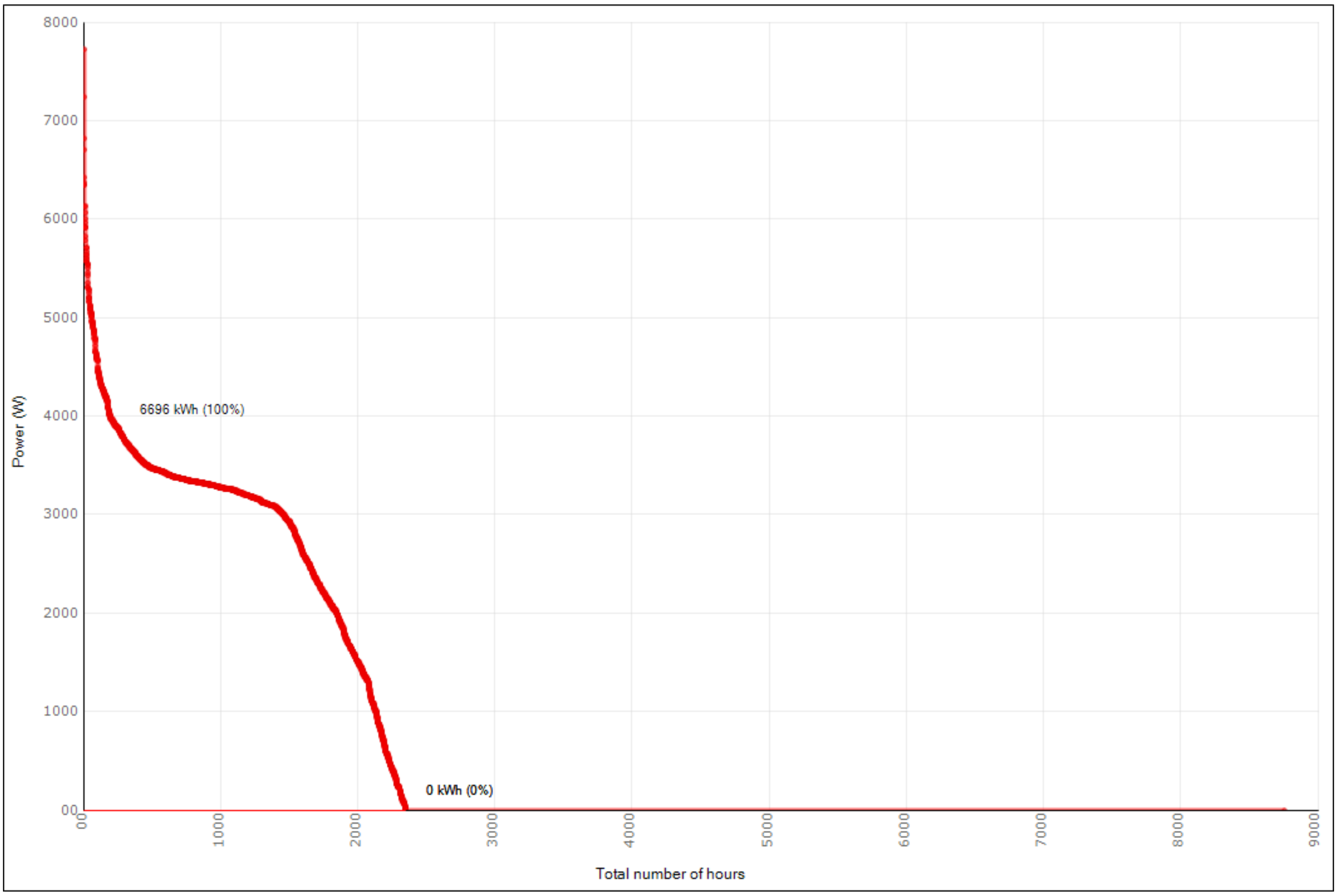
Energy statistics

Energy need profile



Period	During use

Load duration curve

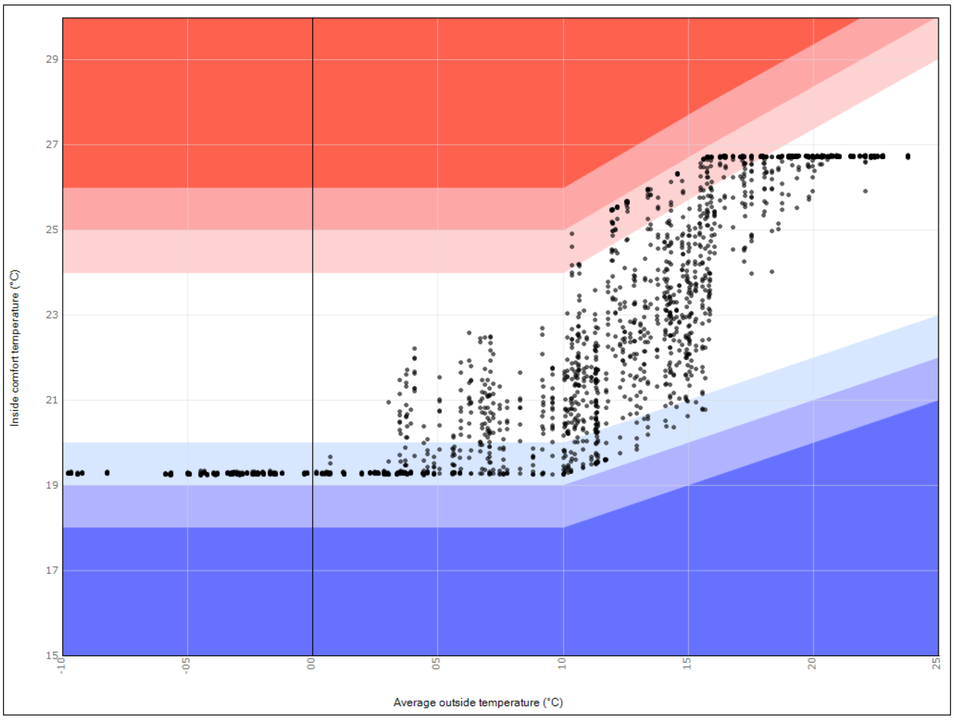


Overview of all rooms

Results for room 1 – Building 100m2

Usage function	Office function
Room type	Habitable space
Floor area [m²]	100,00
Volume [m³]	259,89
Counting hours	Office Working Hours
Summer clothing [CLO]	0,70
Winter clothing [CLO]	1,00
Metabolism [MET]	1,52

Temperature statistics

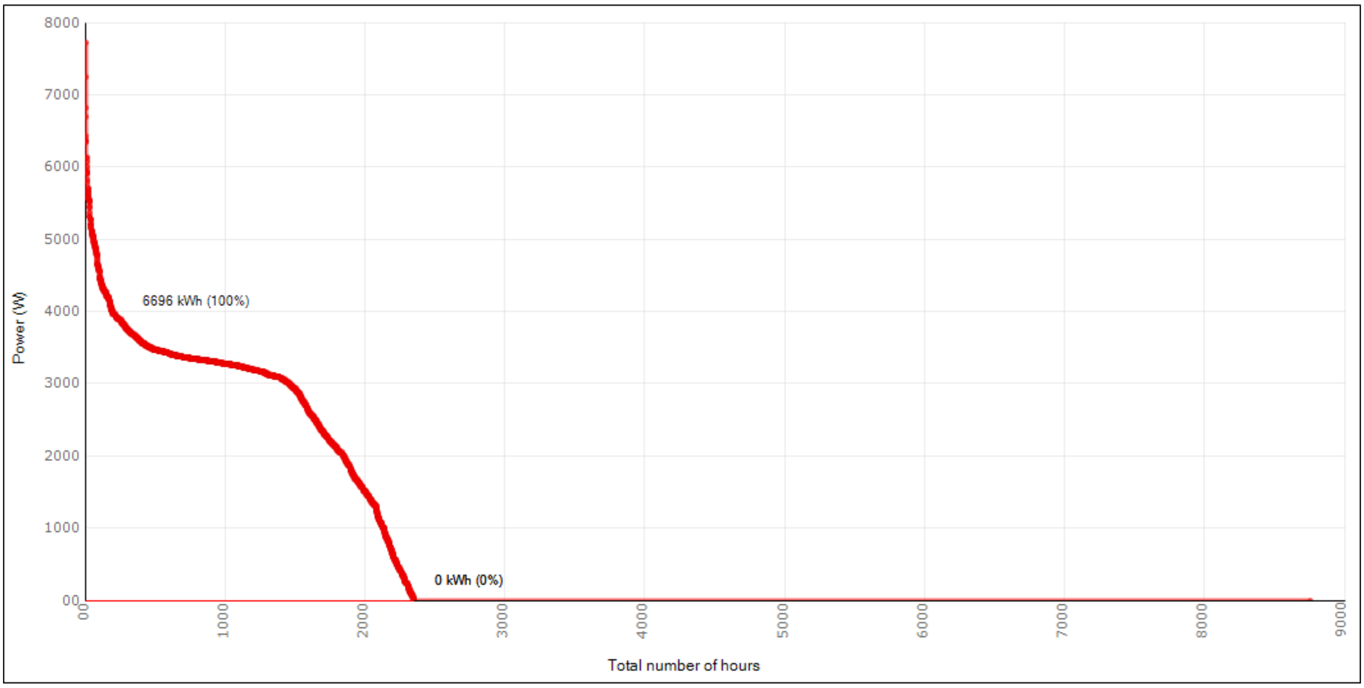


Description	Underheating hours	Overheating hours	Total	% of hours	Satisfy to RGD
Class A	837	203	1040	45.14	No
Class B	837	203	1040	45.14	No
Class C	0	0	0	0.00	Yes
Class D	0	0	0	0.00	Yes

Energy statistics

Emission	Energy heating [kWh]	Power heating [W]	Date power heating	Energy cooling [kWh]	Power cooling [W]	Date power cooling
Central	23	250	6/20/1906 6:00 PM	979	928	2/21/1906 8:00 AM
Local 1	4045	3599	11/5/1906 1:00 AM	0	---	---
Local 2	2651	7730	1/15/1906 8:00 AM	867	4212	8/10/1906 1:00 PM
Total	6719	7730	1/15/1906 8:00 AM	1846	4212	8/10/1906 1:00 PM

Load duration curve

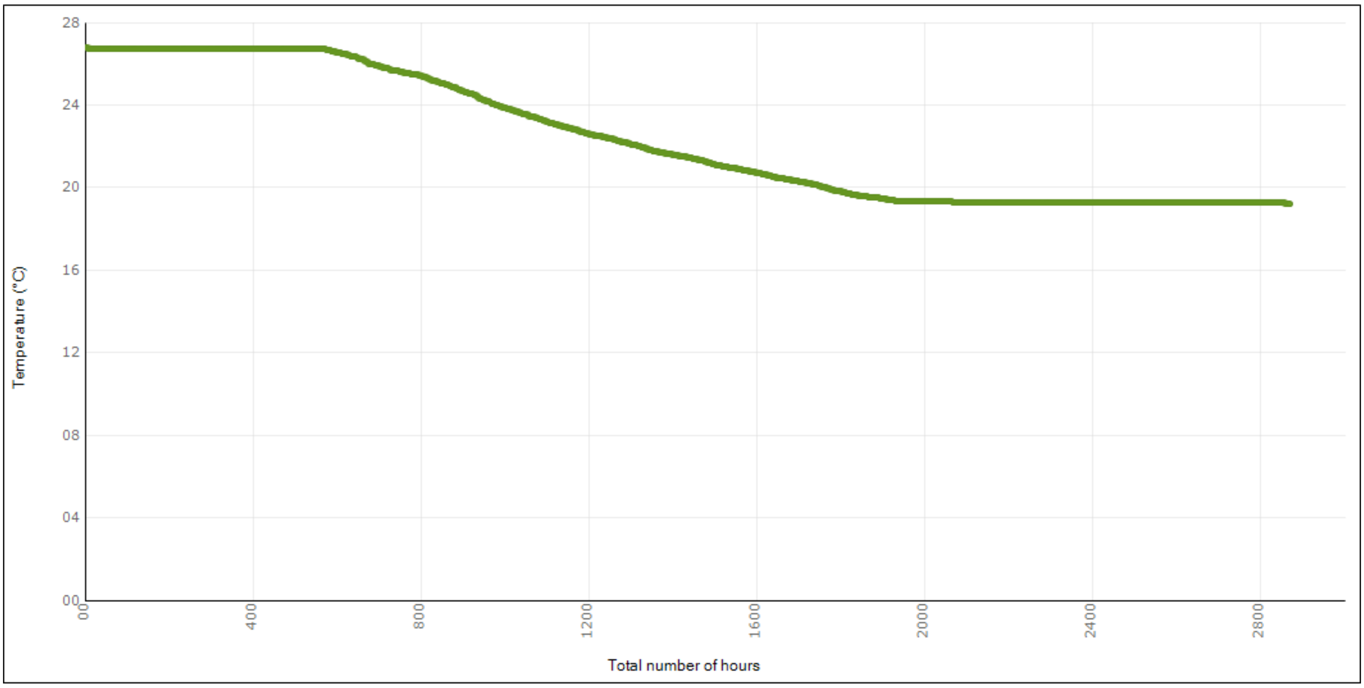


Comfort data

The comfort data are according the specified summer comfort at the room requirements.

ATG calculation method	No summer comfort defined according to ATG

Temperature frequency



Building parts

Description	Type	Adj. to	Adj. temp. [°C]	Orien [°]	Slope [°]	Area [m²]	Frame area [m²]
Wall (MT1) (improved)	Wall	Outside air	---	0	90	20,13	---
Wall (MT1) (improved)	Wall	Outside air	---	90	90	18,63	---
Wall (MT1) (improved)	Wall	Outside air	---	180	90	17,13	---
Wall (MT1) (improved)	Wall	Outside air	---	270	90	18,63	---
Floor (MT1) (Improved)	Floor	Outside air	---	---	180	100,00	---
Roof (MT1) (improved)	Roof	Outside air	---	---	0	100,00	---
Window - Wooden frame, HR++ Glass	Window	Outside air	---	0	90	2,06	0,21
Window - Wooden frame, HR++ Glass	Window	Outside air	---	0	90	2,06	0,21
Window - Wooden frame, HR++ Glass	Window	Outside air	---	0	90	2,06	0,21
Window - Wooden frame, HR++ Glass	Window	Outside air	---	0	90	2,06	0,21
Window - Wooden frame, HR++ Glass	Window	Outside air	---	0	90	2,06	0,21
Window - Wooden frame, HR++ Glass	Window	Outside air	---	0	90	2,06	0,21
Window - Wooden frame, HR++ Glass	Window	Outside air	---	90	90	2,31	0,23
Window - Wooden frame, HR++ Glass	Window	Outside air	---	90	90	2,31	0,23
Window - Wooden frame, HR++ Glass	Window	Outside air	---	90	90	2,31	0,23
Window - Wooden frame, HR++ Glass	Window	Outside air	---	90	90	2,31	0,23
Window - Wooden frame, HR++ Glass	Window	Outside air	---	90	90	2,31	0,23

Description	Type	Adj. to	Adj. temp. [°C]	Orien [°]	Slope [°]	Area [m²]	Frame area [m²]
Window - Wooden frame, HR++ Glass	Window	Outside air	---	90	90	2,31	0,23
Window - Wooden frame, HR++ Glass	Window	Outside air	---	180	90	2,56	0,26
Window - Wooden frame, HR++ Glass	Window	Outside air	---	180	90	2,56	0,26
Window - Wooden frame, HR++ Glass	Window	Outside air	---	180	90	2,56	0,26
Window - Wooden frame, HR++ Glass	Window	Outside air	---	180	90	2,56	0,26
Window - Wooden frame, HR++ Glass	Window	Outside air	---	180	90	2,56	0,26
Window - Wooden frame, HR++ Glass	Window	Outside air	---	180	90	2,56	0,26
Window - Wooden frame, HR++ Glass	Window	Outside air	---	270	90	2,31	0,23
Window - Wooden frame, HR++ Glass	Window	Outside air	---	270	90	2,31	0,23
Window - Wooden frame, HR++ Glass	Window	Outside air	---	270	90	2,31	0,23
Window - Wooden frame, HR++ Glass	Window	Outside air	---	270	90	2,31	0,23
Window - Wooden frame, HR++ Glass	Window	Outside air	---	270	90	2,31	0,23
Window - Wooden frame, HR++ Glass	Window	Outside air	---	270	90	2,31	0,23

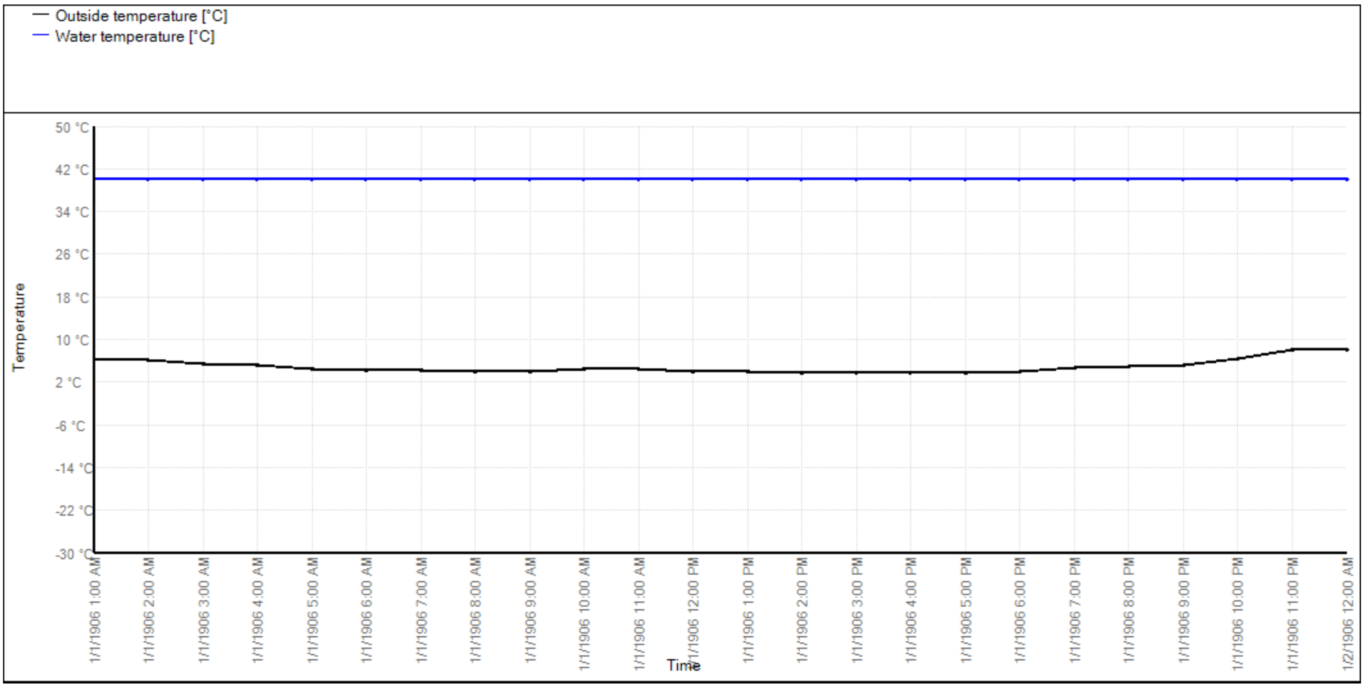
Blinds

Description	Blinds type	Control type	Switching level day [W/m²]	Switching level night [W/m²]
Window - Wooden frame, HR++ Glass	External blinds	Automatic control	250	300
Window - Wooden frame, HR++ Glass	External blinds	Automatic control	250	300
Window - Wooden frame, HR++ Glass	External blinds	Automatic control	250	300
Window - Wooden frame, HR++ Glass	External blinds	Automatic control	250	300
Window - Wooden frame, HR++ Glass	External blinds	Automatic control	250	300
Window - Wooden frame, HR++ Glass	External blinds	Automatic control	250	300
Window - Wooden frame, HR++ Glass	External blinds	Automatic control	250	300
Window - Wooden frame, HR++ Glass	External blinds	Automatic control	250	300
Window - Wooden frame, HR++ Glass	External blinds	Automatic control	250	300
Window - Wooden frame, HR++ Glass	External blinds	Automatic control	250	300
Window - Wooden frame, HR++ Glass	External blinds	Automatic control	250	300
Window - Wooden frame, HR++ Glass	External blinds	Automatic control	250	300
Window - Wooden frame, HR++ Glass	External blinds	Automatic control	250	300
Window - Wooden frame, HR++ Glass	External blinds	Automatic control	250	300
Window - Wooden frame, HR++ Glass	External blinds	Automatic control	250	300
Window - Wooden frame, HR++ Glass	External blinds	Automatic control	250	300
Window - Wooden frame, HR++ Glass	External blinds	Automatic control	250	300
Window - Wooden frame, HR++ Glass	External blinds	Automatic control	250	300
Window - Wooden frame, HR++ Glass	External blinds	Automatic control	250	300
Window - Wooden frame, HR++ Glass	External blinds	Automatic control	250	300
Window - Wooden frame, HR++ Glass	External blinds	Automatic control	250	300
Window - Wooden frame, HR++ Glass	External blinds	Automatic control	250	300
Window - Wooden frame, HR++ Glass	External blinds	Automatic control	250	300
Window - Wooden frame, HR++ Glass	External blinds	Automatic control	250	300

Overview of all distribution nets

Distribution net Heating - Low temperature

Daily results



Date	1-1-1906
Period	Day

General input

Generation

Generation configuration Heatpump (Gebruikt)

Generators

Generator Heat generator - Heat pump ground water (40 degrees)

Heat or cold generator	Heat generator
Type	Heat pump
Heat-pump type	Compression
Source heat pump	Outside air
Energy carrier	Electricity
Preferent generator	Yes
Input conversion efficiency	Part-load efficiency
Conversion efficiency [-]	4,000
Thermal power [W]	4000
Source temperature for determining thermal power [°C]	0,0
Supply temperature for determining thermal power [°C]	40,0
Modulating power control	Yes
Lower limit of power-control modulation [-]	0,40
Calculated average efficiency [-]	3,600

Distribution nets

Name distribution net	**Distribution type**
Heating - Low temperature	Hot-water net

Distribution

Distribution net Heating - Low temperature

Temperature curve

Name temperature-curve point	To day [°C]	Ti dag [°C]	To night [°C]	Ti night [°C]
1	10,0	40,0	10,0	40,0
2	10,0	40,0	10,0	40,0
3	10,0	40,0	10,0	40,0
4	10,0	40,0	10,0	40,0
5	10,0	40,0	10,0	40,0
6	10,0	40,0	10,0	40,0

Air handling

Air handling Simple BalanceVentilation with WTW

Central air handling	Present
Atmospheric pressure at sea level for determination of specifications [Pa]	101300
Mechanical air supply	Present
Temperature rise by supply fan [K]	0,5
Supply air flow rate [m³/h]	300,0
Air flow control	VAV (variable volume system)
Type of VAV	Fan speed control (VAV)
Reduction control per room down to [%]	80
Mechanical air exhaust	Present
Temperature rise by exhaust fan [K]	0,5
Exhaust air flow rate [m³/h]	300,0
Heating coil	Absent
Cooling coil	Absent
Heat recovery	Present
Heat recovery type	Twin-coil heat exchanger
Heat recovery efficiency [-]	0,600
Heat recovery exchange power [W/K]	152
Heat recovery bypass control	Outdoor temperature controlled bypass
Minimum outside temperature for bypass heat recovery [°C]	16,0
Maximum outside temperature for bypass heat recovery [°C]	24,0
Humidity recovery	No
Mixing box	Absent
Humidifier	Absent
Dehumidifier	Absent
Conditional night ventilation	Absent
Conditional night cooling	Absent
Conditional night heating	Absent
Air distribution	Curve on outside air

Temperature curve air distribution

Name temperature-curve point	To or Tr day [°C]	Ti dag [°C]	To or Tr night [°C]	Ti night [°C]
1	8,0	20,0	12,0	16,0
2	16,0	16,0	28,0	30,0
3	24,0	18,0		

Ventilation/infiltration

Infiltration and natural ventilation

#	Name room	Infiltration at wind speed 0 m/s [1/h]	Infiltration at wind speed 3 m/s [1/h]	Infiltration at wind speed 6 m/s [1/h]
2	Gebouw 2	0,10	0,20	0,30

Ventilation through openable windows

Daytime

#	Name room	Ventilation at wind speed 0 m/s [1/h]	Ventilation at wind speed 3 m/s [1/h]	Ventilation at wind speed 6 m/s [1/h]
2	Gebouw 2	0,00	0,00	0,00

Nighttime

The windows cannot be opened.

Mechanical ventilation

#	Name room	Supply daytime (on) [m³/h]	Exhaust daytime (on) [m³/h]	Supply nighttime (stand-by) [m³/h]	Exhaust nighttime (stand-by) [m³/h]	Supply cond. night vent. (night cool. and heat.) [m³/h]	Exhaust cond. night vent. (night cool. and heat.) [m³/h]
2	Gebouw 2	300	300	0	0	100	100

In any listing with (off) there is no ventilation.

Internal heat gain

Room 2 - Gebouw 2

Persons

Internal heat gain persons [W/m²]	6,7
Summer clothing [CLO]	0,7
Winter clothing [CLO]	1,0
Metabolism [MET]	1,52
Internal heat gain latent part persons [-]	0,40
Internal heat gain sensible part persons [-]	0,60

Hour [2]	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Mon	0	0	0	0	0	0	0	0	643	643	643	643	643	643	643	643	0	0	0	0	0	0	0	0
Tue	0	0	0	0	0	0	0	0	643	643	643	643	643	643	643	643	0	0	0	0	0	0	0	0
Wed	0	0	0	0	0	0	0	0	643	643	643	643	643	643	643	643	0	0	0	0	0	0	0	0
Thu	0	0	0	0	0	0	0	0	643	643	643	643	643	643	643	643	0	0	0	0	0	0	0	0
Fri	0	0	0	0	0	0	0	0	643	643	643	643	643	643	643	643	0	0	0	0	0	0	0	0
Sat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sun	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nat.Hol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Equipment

No internal heat gain equipment declared.

Lighting

Internal heat gain lighting [W/m²]	4,0
Lighting control	Sweep pulse
Internal heat gain latent part lighting [-]	0,00
Internal heat gain sensible part lighting [-]	1,00
Internal heat gain convective part of sensible part lighting [-]	0,72

Hour [2]	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Mon	0	0	0	0	0	0	0	0	384	384	384	384	384	384	384	384	0	0	0	0	0	0	0	0
Tue	0	0	0	0	0	0	0	0	384	384	384	384	384	384	384	384	0	0	0	0	0	0	0	0
Wed	0	0	0	0	0	0	0	0	384	384	384	384	384	384	384	384	0	0	0	0	0	0	0	0
Thu	0	0	0	0	0	0	0	0	384	384	384	384	384	384	384	384	0	0	0	0	0	0	0	0
Fri	0	0	0	0	0	0	0	0	384	384	384	384	384	384	384	384	0	0	0	0	0	0	0	0
Sat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sun	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nat.Hol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Time schedules

Operation mode per room

Room 2 - Gebouw 2

Hour [2]	**01**	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Mon	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2
Tue	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2
Wed	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2
Thu	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2
Fri	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2
Sat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sun	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nat.Hol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

0 = Off (out of service), 1 = On (daytime), 2 = Standby (night / weekend operation).

Operation mode per system

Air handling Simple BalanceVentilation with WTW

Hour [2]	**01**	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Mon	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2
Tue	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2
Wed	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2
Thu	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2
Fri	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2
Sat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sun	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nat.Hol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

0 = Off (out of service), 1 = On (daytime), 2 = Standby (night / weekend operation).

Occupation

This occupation schedule is applicable to switchable shading devices and to openable window parts.

Hour [2]	**01**	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Mon	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
Tue	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
Wed	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
Thu	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
Fri	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
Sat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sun	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nat.Hol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Counting hours per room

Room 2 - Gebouw 2

Hour [2]	**01**	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Mon	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
Tue	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
Wed	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
Thu	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
Fri	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
Sat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sun	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nat.Hol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

0 = Not counted, 1 = Counted. Counting hours are calculated based on the satrt and end period of the climate file.

Overview of all applied constructions

Transparent constructions

Construction Window - Wooden frame, HR++ Glass

Climate window	No
Blinds type	External blinds
Description blinds	Good
Control type	Automatic control
Switching level day [W/m²]	250
Switching level night [W/m²]	300
U value glass [W/(m².K)]	1,10
U value frame [W/(m².K)]	2,40
g fraction [-]	0,58

Input	**Glass system outside**	**Glass system inside**	**Blinds**
Type of glass	High efficiency plus plus glazing	---	
U value [W/(m²K)]	1.10	---	
G value [-]	0.58	---	
Energy transmission [-]	0.47	---	0.03
Energy absorption [-]	0.30	---	0.92
Energy reflection [-]	0.23	---	0.05
Light transmission (LTA) [-]	0.80	---	0.03
Light absorption [-]	0.08	---	0.92
Light reflection [-]	0.12	---	0.05
Calculated	**Blinds up**	**Blinds down**	
U value [W/(m²K)]	1.100	1.059	
G value [-]	0.580	0.030	
CF value [-]	0.071	0.198	
FC value [-]		0.052	

Opaque constructions

Name construction	Type	Layers?	Thick-ness [mm]	Rc [(m².K)/W]	U door/panel [W/(m².K)]	Mass [kg/m²]	Thermal active [3]
Floor (MT1) (Improved)	Face	Yes	495	3,82	---	899	Yes
Roof (MT1) (improved)	Face	Yes	400	7,03	---	465	No
Wall (MT1) (improved)	Face	Yes	450	5,62	---	417	No

Structure of constructions

Materials of construction Floor (MT1) (Improved)

Name construction layer	Type	Thickness [mm]	Resistance [(m².K)/W]	Lambda [W/(m.K)]	Specific mass [kg/m³]	Specific heat [J/(kg.K)]
Surface: internal R=0.13	Air gap	10	0,130	---	---	---
Floortiles (MT1)	Material	20	---	2,000	400	1500
Chape (MT1)	Material	70	---	2,350	2400	1000
Concrete Floor (MT1)	Material	300	---	2,350	2400	1000
Polyurethane (PUR) (MT1)	Material	95	---	0,027	30	1400

Finish

	Absorption [-]	Emission [-]	Convection [W/m²]
Top / outside	0.60	0.90	18.00
Bottom / inside	0.60	0.90	3.00

Materials of construction Roof (MT1) (improved)

Name construction layer	Type	Thickness [mm]	Resistance [(m².K)/W]	Lambda [W/(m.K)]	Specific mass [kg/m³]	Specific heat [J/(kg.K)]
Surface: external R=0.04	Air gap	10	0,040	---	---	---
EPDM Dakbedekking (MT1)	Material	20	---	0,170	1390	900
Polyurethane (PUR) (MT1)	Material	100	---	0,027	30	1400
Polyurethane (PUR) (MT1)	Material	80	---	0,027	30	1400
Concrete Floor (MT1)	Material	180	---	2,350	2400	1000
Surface: internal R=0.13	Air gap	10	0,130	---	---	---

Finish

	Absorption [-]	Emission [-]	Convection [W/m²]
Top / outside	0.60	0.90	18.00
Bottom / inside	0.60	0.90	3.00

Materials of construction Wall (MT1) (improved)

Name construction layer	Type	Thickness [mm]	Resistance [(m².K)/W]	Lambda [W/(m.K)]	Specific mass [kg/m³]	Specific heat [J/(kg.K)]
Surface: external R=0.04	Air gap	10	0,040	---	---	---
Masonry - Brick, outer leaf (MT1)	Material	90	---	1,050	1700	800
Insulation - Mineral wool, batt (MT1)	Material	80	---	0,036	25	1030
Masonry - Binnenspouwblad (MT1)	Material	140	---	0,300	1700	800
Insulation - Flexible woodfiber (MT1)	Material	100	---	0,038	55	2100
Plaster - Gypsum Plasterboard (MT1)	Material	20	---	0,500	900	1000
Surface: internal R=0.13	Air gap	10	0,130	---	---	---

Finish

	Absorption [-]	Emission [-]	Convection [W/m²]
Top / outside	0.60	0.90	18.00
Bottom / inside	0.60	0.90	3.00

Materials of construction Window - Wooden frame, HR++ Glass

Name construction layer	Type	Thickness [mm]	Resistance [(m².K)/W]	Lambda [W/(m.K)]	Specific mass [kg/m³]	Specific heat [J/(kg.K)]
Frame	Material	42	---	0.170	800	840
---	---	---	---	---	---	---
---	---	---	---	---	---	---

Finish

	Absorption [-]	Emission [-]	Convection [W/m²]
Top / outside	0.50	0.90	18.00
Bottom / inside	0.50	0.90	3.00

APPENDIX C WLC CALCULATIONS

Example of calculations made according to the WLCA method.

												Material/System Level			Building Level		
Scenario 2	Isolation Facade				Unit	Production A1-A3	Construction A4-A5	Transport C2	Waste processing C3	Disposal C4	Recycling potential D	Total (A1-A5)	Total (Without D)	Total	Total (A1-A5)	Total (Without D)	Total
		Woodviber insulation board		M3 per m2	m3	-173,7	3,696	7,117	255,8	0	-96,43	-170,004	92,913	-3,517	-1266,5298	692,2019	-26,20165
		Coniferous lumber (For timber frame construction)		0,03676	m3	-1534,671	2,831	0,6341	808	0	-299,54	-1531,84	-723,2059	-1022,746	-4195,17787	-1980,61	-2800,9459
		Veneer Plywood (Multiplex)			m3	-1835,32	5,421	1,045	1257	0	-162,54	-1829,899	-571,854	-734,394	-1704,09344	-532,539	-683,904413
		Gypsum Plasterboard perforated 12,5 mm			m2	1,572		0,03621		0,7302		1,572	2,33841	2,33841	117,114	174,2115	174,211545
		Gypsum lime plaster; 1400 kg/m3			m3	138,2		3,834		16,88		138,2	158,914	158,914	20,5918	23,67819	23,678186
	Isolation Floor																
		PUR 80mm Kooltherm® K10			m2	5,634	0,1837	0,0119	6,18		-2,66	5,8177	12,0096	9,3496	46,5416	96,0768	74,7968
	Glass																
		Buitenbeglazing, HR++ (dubbel) glas; coating / gasvulling (argon) , 4/16/4 mm			m2	38,28		0,09523	1,515	0,3624	-0,4744	38,28	40,25263	39,77823	2124,54	2234,021	2207,69177
	Isolation Roof																
		PUR 80mm Kooltherm® K10		x2	m2	5,634	0,1837	0,0119	6,18		-2,66	5,8177	12,0096	9,3496	1163,54	2401,92	1869,92
		Sikaplan® G polymeric waterproofing sheets; 1,5 mm			m2	4,62	0,6819		5,212		-4,93	5,3019	10,5139	5,5839	530,19	1051,39	558,39
	Sunshades																
		Raffstores (Automatic regulation), aluminium; Coilcoating			m2	49,9	2,79	0,11	7,9	0,026	-41,7	52,69	60,726	19,026	2924,295	3370,293	1055,943
	Heating			Power output in KW													
	100m2	Hybrid Heatpump, Addition of small air-water heatpump		3	Per KW	46,54		144,9	2,905	436,3	-19,12	46,54	630,645	611,525	139,62	1891,935	1834,575
	Ventilation			M3/h													
		Central balance ventilation with heath recovery		300	Piece	175,351768		0,517357463	0,1403166	0,1581362	-80,63805	175,35177	176,16758	95,52953	175,351768	176,1676	95,5295321
		Kanalen + Roosters:			M2	0,9522				0,001239	-0,6228	0,9522	0,953439	0,330639	95,22	95,3439	33,0639
	Lighting			Amount of panels													
		LED office luminaire	3900 Lux	6,25	Piece	31,81		0.001054	0.02764	5,455	-11,39	31,81	37,265	25,875	198,8125	232,9063	161,71875
		Needed:	500 Lux	per 8m2 1 paneel													
Scenario 3	Heating		Power output in KW														
m2 building	100m2	Air-water Heatpump	4		Per KW	46,54		144,9	2,905	436,3	-19,12	46,54	630,645	611,525	186,16	2522,58	2446,1
	Floorheating																
		Pex 200mm			m2	5,309		0,01124	4,917	0,002517	-1,682	5,309	10,239757	8,557757	530,9	1023,976	855,7757
		Ceramic tiles			m2	11,03	4,766	0.04641	0.07113	0.4107	-0,471	15,796	15,796	15,325	1579,6	1579,6	1532,5
Scenario 3 + PV																	
	PV panels	Photovoltaic system 1200 kWh/m²*a			m2	296,9				8,591	-1086	296,9	305,491	-780,509	29690	30549,1	-78050,9
	including:	PV module, cabling, fasteners and inverters															

See also the attached xls. file for the calculations of every scenario

Energy use and operational emissions:

	Amount	unit	Gas	Elec	unit
Energy use baseline (Scenario 1)	216,5	Kwh/m2	188,9	27,6	Kwh/m2
Energy use scenario 2	63,9	Kwh/m2	22,2	41,7	Kwh/m2
Energy use scenario 3	48,2	Kwh/m2	0,0	48,2	Kwh/m2
Energy use scenario 3+	0,0	Kwh/m2	0,0	-99,1	Kwh/m2

Emissie fact	Amount	Unit	unit	amount	unit	Unit	Energyfactor
Gas	2,134	Kg CO_2-eq	m3	0,218424	Kg CO_2-eq	kwh	9,77
Electricity	0,328	Kg CO_2-eq	kwh				

	Gas	Electric	
Total operational emissions scenario 1	4126,2	905,7	Kg CO_2-eq/Year
Total operational emissions scenario 2	485,8	1366,7	Kg CO_2-eq/Year
Total operational emissions scenario 3	0,0	1582,3	Kg CO_2-eq/Year
Total operational emissions scenario 3+	0,0	-3250,8	Kg CO_2-eq/Year

Embodied carbon emissions and payback times:

	Difference compared to scenario 1	
SC2	3179,4	Kg CO_2-eq
SC3	3449,6	Kg CO_2-eq
SC4	8282,7	Kg CO_2-eq

Scenario 2			**Scenario 3**			**Scenario 3+**		
	Embodied carbon			**Embodied carbon**			**Embodied carbon**	
	9,93E+03	kg CO_2 eq		1,51E+04	kg CO_2 eq		4,56E+04	kg CO_2 eq
	Payback time embodied carbon			**Payback time embodied carbon**			**Payback time embodied carbon**	
	3,12	Years		**4,36**	Years		**5,51**	Years

Material	Scenario 2	Scenario 3	Scenario 3+
Ren. Values	3,700155497	26,6667555	323,566755

APPENDIX D VABI DECLARATION

Datum: 08-05-2025

Bevestigingsdocument gebruik Vabi Elements Master thesis Laurens van der Laan

Ondergetekende verklaart hierbij dat Laurens van der Laan, student aan de Technische Universiteit te Delft (Faculteit Bouwkunde, mastertrack Management in the Built Environment), tijdens het uitvoeren van zijn masterthesis op verantwoorde wijze gebruik heeft gemaakt van het simulatieprogramma **Vabi Elements** voor het uitwerken van renovatiescenario's ten behoeve van energetische gebouwverbetering.

Tijdens dit proces heeft Laurens:

- Aangetoond de werking en logica van het Vabi-programma voldoende te begrijpen om zelfstandig simulaties op te zetten en te interpreteren;
- De relevante gebouw- en installatietechnische parameters ingevuld op basis van actuele normen en richtlijnen
- Afstemming gezocht met een deskundige vanuit Vabi waarbij zijn invoer, aannames en uitkomsten zijn besproken en gevalideerd op kantoor bij Vabi in Delft.

Op basis hiervan wordt bevestigd dat het gebruik van Vabi Elements in het kader van deze masterthesis op een correcte manier heeft plaatsgevonden.

Naam begeleider/expert

Esther Krombeen

Handtekening