Tax Energy, Fuel the Future

A Quantitative Modelling Approach to Assess Policy Strategies for Sustainable Transformation of the Dutch Non-Residential Building Stock

MSc. Thesis Engineering & Policy Analysis

Stijn Blaas

Delft University of Technology

Tax Energy, Fuel the Future

A Quantitative Modelling Approach to Assess Policy Strategies for Sustainable Transformation of the Dutch Non-Residential Building Stock

by

Stijn Blaas

S.G. Blaas
4666771

First Supervisor:	L. de Vries
Second Supervisor:	A. Correljé
Supervisors CE Delft:	K. Kruit & F. Hesselink
Project Duration:	October, 2024 - June, 2025
Faculty:	Faculty of Technology, Policy and Management, Delft

Cover: Helicopter view of the 'Zuidas' in Amsterdam (Dutchphoto, 2020)

Acknowledgement

Writing this thesis has marked the final and most intense stage of my student life—a phase I now look back on with both gratitude and perspective. Although the last few months have at times felt like the thesis had completely taken over my life, I feel grateful for the experience and the support I received along the way.

First and foremost, I would like to thank my supervisors and committee members: Laurens de Vries, Aad Correljé, Katja Kruit, and Florian Hesselink.

Laurens and Aad, thank you for your academic guidance and for pushing me to be more structured and realistic throughout the process. Your feedback helped me set the bar higher and improve both my planning and research direction. It was a valuable lesson in professionalism and preparation.

Katja, your sharp and timely insights helped me sharpen my focus. Despite your packed schedule, you always made time for critical feedback that challenged my thinking—and I truly appreciated that.

Florian, thank you for your incredible patience and support during our many weekly check-ins. Whether the questions were conceptual or practical, you always helped me move forward with clarity. Your involvement truly made this process more manageable—and even enjoyable.

I also would like to thank everyone at CE Delft with whom I had insightful conversations, shared some laughs, and found support when I needed a second opinion. The little things—like coffee breaks, after-work drinks, or shared lunches—made the graduation process more enjoyable.

I want to thank my housemates, Gijs, Emiel, Tim, Thomas and Thomas, for their ongoing support, timely distractions, and quiet understanding when deadlines loomed. Living with you made these intense months not only bearable but also filled with laughter and perspective.

Last but not least, I want to thank my parents, Ingrid and Jos, and my sister, Marit, for their continuous support throughout my entire time as a student. I've always known I could count on you, and I'm really grateful for that.

This thesis brought many challenges, and most of the time felt like a roller coaster, but it also brought growth. I learned how to navigate complex research, how to plan more effectively, and—most of all—how to just begin, even when things feel unclear.

To everyone who contributed to this experience, directly or indirectly: thank you. I finish this journey with a sense of fulfilment, ready to take a deep breath and look forward to what's next.

Stijn Blaas
Delft, June 2025

Executive Summary

Introduction

The decarbonisation of buildings is crucial for achieving global and national climate targets. In the Netherlands, non-residential service buildings—such as offices, schools, hospitals, and retail facilities—account for approximately 30% of emissions from the built environment. Despite this substantial share, the transition of existing non-residential buildings has lagged behind, due to financial, organisational, and policy-related barriers. Current policies focus mainly on new constructions, while most existing buildings risk remaining gas-dependent without stronger intervention.

Sustainable investments typically occur during natural replacement cycles, which only happen once or twice before 2050. Missing these moments could lock in high-carbon technologies for decades. Although various heating alternatives exist, the business case for sustainable solutions remains weak compared to natural gas, even after subsidies. As a result, additional policy measures are needed to steer building owners toward low-carbon technologies during investment moments.

Knowledge Gap

Existing computational models are not well equipped to simulate policy effects in the non-residential sector. They often fail to capture the sector's diversity in building functions, sizes, and cost structures. Consequently, there is limited insight into how different policy instruments can influence CO_2 reductions, end-user costs, and the distribution of impacts across building types and sizes.

Objective and Research Question

This study addresses the knowledge gap by analysing how selected policy interventions affect CO_2 emission reductions, end-user costs, and distributional effects across the Dutch non-residential service building stock.

The main research question is:

> *How do policy interventions improve CO_2 emission reductions in the Dutch non-residential service building stock, in terms of their effectiveness, cost-effectiveness, and distributional effects?*

To answer this question, the CEKER model was adapted to capture the functional and economic diversity of the non-residential sector. Policy interventions evaluated include gas price increases, mandatory energy label standards, and a gas connection ban, individually and in combination. Each policy scenario was modelled under different electricity price futures to ensure robustness against energy market uncertainties.

Methodology

The CEKER model, originally developed for the residential sector, was adapted to capture the diversity of the Dutch non-residential service building stock. Key adaptations included building categorisation by function and size, recalibration of CAPEX and OPEX parameters for non-residential heating technologies, updated energy demand profiles based on energy labels, and integration of sector-specific energy tariffs.

Twelve policy scenarios were developed, varying gas taxation, mandatory energy label standards, and gas heating availability (gas bans). Each scenario was simulated under three electricity price conditions (base, +50%, −50%) to test robustness against energy market uncertainties.

Model outputs—CO_2 emissions and annualised end-user costs—were evaluated along three main criteria:

- **Effectiveness:** Total CO_2 emission reduction relative to the base case.
- **Cost-effectiveness:** Additional annualised costs per tonne of CO_2 reduced.
- **Distributional effects:** Differences in costs and emission reductions across building types and size categories.

Building owners were assumed to act rationally, selecting the cost-optimal heating solution at the natural replacement moment of their heating systems. This approach reflects a techno-economic upper bound: it estimates the maximum emission reduction achievable if investment decisions are made purely on economic grounds, without behavioural or organisational barriers.

Key Findings

Effectiveness

- Combined policy packages—such as a 100–200% gas tax increase combined with a minimum Energy Label A requirement—achieve the largest emission reductions.
- Economic interventions alone (e.g., gas tax increases) shift investment behaviour but achieve lower total reductions than mixed policy packages.
- Regulatory standards alone (e.g., mandatory energy labels) create investment trigger points but require additional financial incentives to be cost-effective.

Cost-Effectiveness

- A moderate gas price increase (+100%) is the most cost-effective stand-alone intervention when measured in cost per tonne CO_2 reduced.
- Mixed policy packages achieve deeper reductions at only moderately higher costs per tonne, making them more attractive from a long-term policy perspective.

Distributional Effects

- Small buildings (0–500 m^2) achieve high CO_2 reductions but face higher retrofit costs relative to larger buildings.

- Assembly buildings show high abatement potential but also experience high absolute retrofit costs.
- These segments are less likely to transition without targeted financial support.

Robustness to Electricity Price Uncertainty

- Policy combinations maintain effectiveness even when electricity prices vary by ±50%.
- A mixed approach combining economic incentives and regulatory obligations proves more stable than single-instrument strategies.

Policy Recommendations

Based on the findings, the following recommendations are made:

- Gradually increase the energy tax on natural gas to strengthen the business case for sustainable heating solutions.
- Introduce a mandatory minimum Energy Label D requirement by 2030–2035 to trigger envelope upgrades at natural investment moments.
- Provide targeted financial support (e.g., subsidies, low-interest loans) for small buildings and assembly buildings to mitigate high retrofit costs.
- Avoid immediate full gas bans; instead, use a phased approach combining price signals and regulatory standards to allow flexibility for technically challenging cases.

This strategy stretches the emission reduction potential close to 0.5 Mt CO_2 at low or moderate future electricity prices, and to approximately 1.2 Mt CO_2 under high electricity prices, without imposing disproportionate costs on vulnerable building owners.

Limitations and Suggestions for Further Research

The model results should be interpreted with the following limitations in mind:

- Energy prices, technology costs, and emission factors were assumed to be static for 2030, without reflecting dynamic developments such as changes in district heating supply.
- Investment behaviour was modelled as fully rational and cost-optimising, omitting real-world barriers like short payback thresholds and capital constraints.
- The model assumed universal technical feasibility and did not account for spatial variation (e.g., urban density, infrastructure), which affects the applicability of certain technologies.
- Tenant-landlord dynamics were not included, overlooking split incentives and rent-related investment barriers in leased buildings.

Future research could enhance realism by modelling dynamic adoption rates, regional infrastructure differences, ownership segmentation (commercial versus public real estate), and landlord-tenant dynamics in retrofit decisions.

Abstract

The decarbonisation of Dutch non-residential service buildings is vital for achieving national climate goals. Yet current policies have primarily focused on new constructions, leaving the existing building stock—responsible for a significant share of emissions—underregulated. Financial, organisational, and behavioural barriers delay or prevent timely investments in sustainable heating. Since major heating system replacements typically occur only once or twice before 2050, failure to act during these moments risks locking in carbon-intensive technologies for decades. Targeted policy measures are therefore needed to steer building owners toward low-carbon alternatives at these critical decision points.

This study investigates how selected policy interventions can accelerate CO_2 emission reductions in the Dutch non-residential service sector, assessed through their effectiveness, cost-effectiveness, and distributional impacts. The CEKER techno-economic model, developed by CE Delft and originally tailored to the residential sector, was adapted to reflect the heterogeneity of the non-residential building stock in terms of function, size, and energy demand. The model simulates rational, cost-minimising investment decisions made at natural heating system replacement moments. Twelve policy scenarios were analysed, including increases in the energy tax on natural gas, mandatory energy label standards, and a ban on gas-based heating systems, both as stand-alone measures and in combined scenarios. All scenarios were tested across three electricity price futures to assess policy robustness.

Results show that combined interventions—particularly higher gas taxes paired with mandatory insulation standards—achieve the highest CO_2 reductions (up to 1.2 Mt). Economic measures alone are more cost-effective per tonne of CO_2, but less effective overall. Smaller buildings ($\leq 500\,m^2$) and assembly buildings exhibit high abatement potential but face relatively high retrofit costs.

Policy recommendations include gradually increasing the energy tax on natural gas, mandating a minimum energy label (e.g., Label D by 2030–2035), and offering targeted financial support for small buildings ($\leq 500\,m^2$) and assembly buildings. These results represent a techno-economic upper bound, assuming fully rational investment behaviour without non-financial barriers. As such, they provide a benchmark for evaluating the environmental impact, economic efficiency, and fairness of alternative policy strategies.

Nomenclature

Abbreviations

Abbreviation	Definition
CAPEX	Capital Expenditure
CEKER	‘CE Kosten voor Eindgebruikers Rekenmodel’
EE	Energy Efficiency
EEM	Energy Efficiency Measures
ETS	European Trading System
EPBD	Energy Performance of Buildings Directive
LCET	Low-Carbon Energy Technology
MEPS	Minimum Energy Performance Standard
NPV	Net Present Value
OPEX	Operational Expenditure
RCT	Rational Choice Theory
SME	Small to Medium-sized Enterprises

Symbols

Symbol	Definition	Unit
A	Building surface area	[m^2]
c	System-specific connection value	[kW/m^2]
C_{capex}	Total capital expenditure	[€]
$C_{\text{capex, annual}}$	Annualised capital expenditure	[€/year]
C_{opex}	Annual operational expenditures	[€/year]
C_{variable}	Variable cost per unit of energy used	[€/unit]
f	Maintenance rate	[-]
n	Economic lifetime of the system	[year]
P	Required system capacity	[kW]
r	Discount rate	[-]
L_{current}	Current energy label of the building	[-]
L_{required}	Minimum required energy label	[-]
$\tau_{\text{effective}}$	Effective weighted tariff	[€/m^3]
τ_{grey}	Grey gas delivery tariff	[€/m^3]
τ_{green}	Green gas delivery tariff	[€/m^3]
γ	Share of grey gas in gas mixture	[-]

Symbol	Definition	Unit
γ_{green}	Fraction of green gas used	[-]
S	Subsidy amount	[€]
p_{subsidy}	Subsidy percentage	[-]
Q_{current}	Current space heating demand	[GJ/year]
Q_{new}	Space heating demand after insulation upgrade	[GJ/year]
η	Energy saving percentage	[-]
E_{carrier}	Annual CO_2 emissions for an energy carrier	[kg CO_2/year]
Q_{carrier}	Annual energy use per energy carrier	[GJ/year]
e_{carrier}	Emission factor for energy carrier	[kg CO_2/GJ]
$D_{\text{end-use}}$	Final energy demand for a specific end-use	[GJ/year]
$\eta_{\text{end-use}}$	System efficiency for a specific end-use	[-]
U_{carrier}	Total annual energy use per energy carrier	[GJ/year]
C_{total}	Total energy cost	[€]
C_{variable}	Variable energy cost	[€]
C_{fixed}	Fixed energy cost	[€]
U_z	Energy consumption in tax zone z	[unit]
p_{delivery}	Delivery rate tariff	[€/unit]
$p_{\text{tax,z}}$	Energy tax in tax zone z	[€/unit]
p_{supplier}	Supplier fee	[€/unit]
p_{ETS2}	ETS2 surcharge	[€/unit]
p_{fixed}	Fixed fee for energy carrier	[€/year]
$p_{\text{natural gas}}$	Delivery tariff for natural gas	[€/m^3]
$p_{\text{green gas}}$	Delivery tariff for green gas	[€/m^3]
VAT	Value-added tax rate	[-]

Contents

List of Figures

List of Tables

1 Introduction

This Master's thesis, carried out at CE Delft, investigates how selected policy instruments can reduce CO_2 emissions in the Dutch non residential service building stock. To that end, the CEKER model—originally developed for residential applications—has been adapted to reflect the unique characteristics of the non-residential built environment, drawing on CE Delft's internal data and expert knowledge. In this chapter, we first demonstrate the urgency of decarbonising non residential buildings, then identify the knowledge gap that is addressed, and finally articulate the study's objective. A brief reading guide concludes the chapter, outlining how each subsequent section builds toward policy relevant conclusions.

1.1. Problem Definition

The Paris Agreement (2015) underlines that decarbonising buildings is essential for meeting global climate goals. In the EU, buildings still account for roughly 36% of energy-related emissions and 40% of final energy use, while the weighted renovation rate hovers around 1% per year (Directorate-General for Energy, 2024; Maduta et al., 2022).

The Netherlands has embedded the same 2050 net zero ambition in its Climate Act (Klimaatwet, 2023; Tweede Kamer der Staten-Generaal, 2019). In 2022 the built environment emitted 19.6 Mt CO_2 eq, of which 5.4 Mt ($\approx$ 30%) came from non-residential service buildings such as offices, schools, and hospitals (CBS, 2022). Policy targets call for a reduction to 3.3 Mt by 2030 and zero by 2050 (PBL, 2024a).

While new constructions have been efficiently managed over the past 25 years through EPC and BENG standards (European Commission, 2024; RVO, 2017b), retrofitting existing buildings remains a challenge (van den Bergh et al., 2021). Investment decisions by building owners are slowed by financial, policy-related, and organisational barriers (Jonker et al., 2024), while the payback period, financial resources, and access to information are decisive in choosing to transition away from natural gas (Tollenaar et al., 2024).

Sustainability improvements are planned during natural replacement cycles of building components or installations—a process that may occur only once or twice per building until 2050 (Jonker et al., 2024). This means that any improvements made during these moments must be robust enough to make sure that the building meets sustainability standards by 2050. In many cases, climate-neutral heating remains more expensive than using natural gas, even with subsidies (Hoogervorst, 2024). As a result, natural gas heating remains the norm, and despite current policies, sustainable heat is not sufficiently appealing for many to adopt on a wide scale (Tollenaar et al., 2024; van den Bergh et al., 2021).

1.2. Knowledge Gap

To analyse the effects of potential new (or existing) policy interventions, computational models are used within this research field. However, current computational models fall short in integrating the unique characteristics of the non-residential service sector, resulting in a lack of insight into how various policy instruments actually influence CO_2 emission reductions and end-user costs within the non-residential service building stock. Consequently, they struggle to accurately analyse the effectiveness, cost-effectiveness, and distributional effects of potential new policy interventions that aim to reduce CO2 emissions by stimulating sustainable investments.

1.3. Research Objective and Question

In this study, the CEKER model ('CE Kosten voor Eindgebruikers Rekenmodel') is employed to investigate the impact of policy interventions that stimulate sustainable investments by building owners in the non-residential service sector (Kruit, 2021). CE Delft developed the CEKER model to provide policymakers, planners, and administrators with a tool for assessing an affordable heat transition. The model calculates end-user costs associated with sustainable heating solutions by accounting for both investment expenditures (CAPEX) and operational expenses (OPEX). It evaluates a range of heating technologies (e.g., heat pumps and district heating) and allows for the simulation of policy options through adjustable parameters.

However, while the CEKER model provides valuable insights for the residential sector, its application to non-residential buildings has certain limitations. Non-residential buildings exhibit greater heterogeneity in user function, building size, and energy demand profiles compared to residential buildings. As a result, specific cost components and energy demand profiles in the non-residential sector are not accurately represented by a model originally designed for residential applications.

To fill the knowledge gap, the CEKER model is adapted to better capture the diverse characteristics of the non-residential service sector, while answering the main research question of this research:

> *"How do policy interventions improve CO_2 emission reductions in the Dutch non-residential service building stock, in terms of their effectiveness, cost-effectiveness, and distributional effects?"*

The primary objective of this study is to assess how specific policy instruments can effectively reduce CO_2 emissions in the Dutch non-residential service building stock. To this end, the research will quantify each intervention's emission reduction potential, assess its cost effectiveness from the end user perspective, and analyse the distribution of costs and emission reductions across building types and sizes. The resulting insights will inform the design of new policy strategies for decarbonising the Dutch non-residential service sector.

1.4. Reading Guide

This report is structured as follows.

Chapter 1 introduces the problem, identifies the knowledge gap, and outlines how it is addressed.

Chapter 2 provides the reader with a theoretical background needed for understanding concepts and theories used in this research.

Chapter 3 describes the research methodology, including the research questions, overall approach, scope, modelling framework, and research strategy.

Chapter 4 outlines the characteristics of the Dutch non-residential built environment, including the system components, current policies, model scope and the conceptual model.

Chapter 5 discusses the original CEKER model, its structure and functionalities, identifies its limitations for application to the non-residential built environment, and describes the adaptations made to address these limitations, including the model validation, verification, and sensitivity analysis.

Chapter 6 presents the experiment design, selected policy interventions and their rationale. It also describes the reference case and the development of different policy scenarios.

Chapter 7 presents the results of the model simulations across the scenarios, covering impacts on heating solutions, energy use, emissions, costs, and sector-specific differences.

Chapter 8 provides a discussion of the key findings, compares results with existing literature, reflects on the model and approach, and formulates policy implications and recommendations.

Finally, Chapter 9 concludes the study and Chapter 10 provides a personal reflection on the academic journey and the experience of conducting the master's thesis research.

2

Theoretical Background

2.1. Introduction

This chapter establishes the theoretical foundations for analysing sustainability investments in non residential buildings and for evaluating the policy interventions that shape them. We begin by reviewing the decision-making process itself—when and why building owners choose to undertake energy upgrades, the barriers and drivers that influence those choices, and how these decisions are represented in techno-economic models based on Rational Choice Theory. We then develop a unified typology of policy instruments—drawing on Vedung, Hood and Howlett—and introduce the "Three E's" of ex-ante evaluation (effectiveness, efficiency, equity) as the framework for assessing modelled outcomes and policy impacts.

Specifically:

- Section 2.2.1 examines the lifecycle "trigger points" that prompt retrofit decisions and the implications for policy design.
- Section 2.2.2 surveys the economic and non-economic factors—upfront costs, split incentives, market signals, occupant needs—that enable or impede investment.
- Section 2.2.3 describes how Rational Choice Theory and techno-economic upper bound scenarios benchmark the maximum cost-effective uptake of energy measures.
- Section 2.3.1 defines and categorises policy tools into regulatory, economic, informational and organisational classes.
- Section 2.3.2 outlines the ex-ante evaluation criteria—effectiveness, cost-effectiveness and equity—that will guide our appraisal of model outputs and policy packages.
- Section 2.3.3 links specific instruments to the barriers they address and illustrates how mixed policy packages can optimise timing, depth and fairness of sustainability upgrades.

Together, these theoretical elements provide a coherent, theory-driven basis for the model and analysis presented in subsequent chapters.

2.2. Investment Decision-Making for Sustainability Upgrades in Non-Residential Buildings

This literature review synthesises current knowledge on when owners tend to make these upgrade decisions, what factors influence them, the role of policy interventions (e.g. subsidies or mandates) in shaping the timing and uptake of upgrades, and how researchers model these decisions – with a focus on frameworks grounded in *Rational Choice Theory* and *"techno-economic upper bound"* scenarios. The goal is to understand not only the economic rationale behind retrofits, but also behavioural, institutional, and policy dynamics that drive or hinder sustainability investments in the service-sector building stock.

2.2.1. Timing of Sustainability Investment Decisions

Investment in energy retrofits or upgrades usually coincides with key *"trigger points"* in a building's lifecycle. Rather than occurring randomly, decisions often cluster around moments when an upgrade is most practical or necessary:

- **Major Renovations or Remodelling:** When a building undergoes a, owners often consider energy efficiency measures as part of the project. Building codes may require bringing the energy performance up to a certain standard whenever a *"major renovation"* is undertaken (RICS, 2024).
- **Equipment End-of-Life Replacement:** The natural replacement cycle of building systems is a trigger as well (Nägeli et al., 2020). Owners typically upgrade heating, cooling, or lighting systems when existing equipment has aged or failed, reaching its end-of-life.
- **Change of Ownership or Tenancy:** Transactions like the sale of a property or turnover of a major tenant often prompt sustainability upgrades (Sebi et al., 2019). For instance, building performance disclosure is mandated at sale, motivating building owners to invest in efficiency to improve the energy label and asset value, or to avoid penalties (Government of the Netherlands, 2009).
- **Regulatory Deadlines:** In some cases, government regulations themselves create trigger points by stipulating that by a certain date, buildings must meet new efficiency criteria (Eichholtz et al., 2024). In the Netherlands, an example is the label C obligation for office buildings, which states that as of January 1, 2023 all office buildings larger than 100 m^2 must have at least the energy label C, or else they may no longer be used as offices (Arnoldussen et al., 2016).

The demand for energy retrofits is generally not purely energy driven; instead, it is often an addition to other motives. Studies show that building owners rarely perform deep energy renovations in isolation, rather they *"take advantage of these moments"* (renovations, repairs, transactions) to include energy improvements *"with reduced additional cost and disruptions"* (BPIE, 2017) . This has two implications: first, efficiency upgrades might occur less frequently than their theoretical optimum (since owners wait for trigger events), and second, aligning or creating policies or programs with these natural trigger points can greatly improve uptake of sustainable investments.

2.2.2. Factors Influencing Investment Decisions

Even when a trigger presents the opportunity to upgrade, the decision to invest in sustainability measures is influenced by multiple factors. The literature identifies a range of economic and non-economic drivers and barriers that influence these decisions:

- **Upfront Costs and Economic Payback:** The economic rationale is usually paramount. Building owners weigh the capital cost of an upgrade against the expected savings (lower energy bills, maintenance savings, increased property value) over time. In theory, a rational investor would undertake all upgrades that are cost-effective (positive net present value). In practice, however, owners often require very short payback periods before they green-light an energy retrofit. Surveys in the commercial real estate sector indicate that decision-makers commonly expect energy projects to pay for themselves in 3–5 years or less (Benson et al., 2011). Indeed, many corporate real-estate managers impose hard hurdles – one report notes that companies frequently "require energy efficiency projects to have payback periods of less than three years" (Kapur et al., 2011). High upfront cost is consistently cited as a top barrier to energy-efficiency investments in buildings (Olsthoorn et al., 2017). Even if technically economical over the lifespan, such projects compete with other uses of capital and may be rejected if the opportunity cost of money is too high or the returns are seen as too slow.
- **Split Incentives (Principal–Agent Problems):** The split incentive issue – where the investor in efficiency is not the one reaping the benefits – is a well-known barrier in the building sector. Empirical studies confirm that landlord–tenant arrangements have a negative effect on the likelihood of the adoption of EEM. For example, a large survey of organisations in Germany found that being in a rented space was the number one barrier cited against implementing measures like heating system replacement or insulation (Olsthoorn et al., 2017). Another survey conducted by Jonker et al. (2024) in the non-residential built environment of the Netherlands confirms the presence of the split-incentive dilemma. This principal–agent problem leads to under-investment in sustainability measures *even if* the upgrades are financially sound overall.
- **Financial Constraints and Competing Priorities:** Even when an upgrade makes economic sense, an owner must have access to capital and the willingness to allocate budget to the project. Many organisations face *capital constraints* or simply prioritise other investments over energy. A common refrain is that energy efficiency is *"not part of the core mission"* of the business (Kapur et al., 2011, p. 5). Whereas in drafting annual budgets, efficiency projects can be pushed aside in favour of investments deemed more essential to core operations (Kapur et al., 2011). Limited internal *staff capacity or expertise* can also play a role – if an organization does not have the internal expertise through their staff energy projects may never get seriously evaluated. Conversely, having staff capacity or expertise, strongly increases uptake of efficiency measures (Olsthoorn et al., 2017).
- **Regulatory and Market Signals:** Building owners do respond to *external signals*, such as current and anticipated regulations, energy pricing, and market trends. If energy prices are high or volatile, the value of savings increases, improving the business case. Strong *government commitment* to efficiency and climate goals creates a positive backdrop for investment (Kim & Medal, 2024). Conversely, policy uncertainty or stop-and-go incentives can hinder investor

confidence. Buildings with green certifications or high energy performance can enjoy higher rents and occupancy, creating a market-driven incentive for owners to invest in upgrades that improve their energy labels (Benson et al., 2011). Thus, *market pressure and normative factors* can influence the decision, beyond pure cost calculus.

- **Occupant Impact and Other Factors:** The *occupants' needs and comfort* requirements influence the owner's choices: measures that improve thermal comfort, indoor air quality, or lighting can be appealing in schools, offices, or hotels due to the productivity and well-being benefits. In fact, *occupant satisfaction and well-being* has been identified as one of the key factors influencing retrofit decisions, alongside the purely economic and technical factors (Kim & Medal, 2024). It was also found that *"internal value"* (the organisation's own commitment or culture) and *coordination* among decision-makers were prominent factors, as was *system compatibility* (the chosen solution fits the existing building systems) (Kim & Medal, 2024).

In summary, building owners make retrofit decisions based on a mix of economic calculations and contextual factors. On the economic side, *upfront cost and return on investment* dominate, which explains phenomena like demands for short paybacks and the persistent "energy efficiency gap" (many cost-effective measures remain unrealized)(Bremer et al., 2024). On the contextual side, issues of ownership structure (split incentives), organizational priorities, access to capital and expertise, regulatory environment, and building-specific needs can either enable or impede action. The most cited barriers in surveys tend to be cost and split incentives while commonly noted drivers include cost savings, regulatory compliance, enhanced comfort, asset value, and corporate responsibility (Kim & Medal, 2024; Olsthoorn et al., 2017). Successful investment decisions require aligning the efficiency project with the owner's financial criteria *and* fitting it into the organizational and functional context of the building.

2.2.3. Modelling Investment Decisions: Rational Choice Theory

Rational choice theory (RCT) provides a framework for much of modern economic modelling, including analyses of energy efficiency investments. It assumes that individuals and organisations act as rational agents: they make decisions by systematically evaluating the costs and benefits of each option, selecting the alternative that maximises their utility or profit (Becker, 1976). In this framework, preferences are stable and transitive, decisions are internally consistent, and actors respond predictably to incentives and constraints.

In the context of energy and climate policy, RCT underpins *techno-economic modelling* approaches that aim to identify the most cost-effective technological pathways to reduce emissions. These models assume that actors (e.g. building owners) will adopt any Energy Efficiency Measure (EEM) that meets a given economic criterion — for example, a positive net present value (NPV), or a payback period below a specified threshold. In this setup, all economically rational options are assumed to be implemented, generating an estimate of the *maximum* technically and economically feasible CO_2 emission reduction potential (Gillingham & Palmer, 2014; Mundaca et al., 2010). This is often referred to as **techno-economic upper bound**.

This upper bound serves a benchmarking function: it provides a reference against which actual observed adoption rates, and associated emission reductions, can be compared. It highlights the *gap be-*

tween what could be done economically and what is actually done, commonly referred to as the *energy efficiency gap* (Bremer et al., 2024; Jaffe & Stavins, 1994). This gap arises from a variety of real-world factors that influence rational decision-making, as discussed in Subsection 2.2.2. These market imperfections are not explicitly incorporated in techno-economic models based on RCT, and as such, the modelled results represent *idealised decision outcomes* under perfect rationality and complete information.

In this study, rational choice theory is used as a *modelling assumption* within a techno-economic framework to simulate investment decisions by non-residential building owners in the Netherlands. The model identifies cost-effective EEMs (e.g. heating system replacements, insulation improvements) that would be rationally adopted given their economic characteristics. The resulting estimates of EEM uptake and emission reductions are not predictions of real-world behaviour, but instead represent a *normative benchmark*: what could be achieved if all decision-makers acted in economically optimal ways.

While behavioural realism is important for empirical policy analysis, incorporating such complexity would detract from the clarity and purpose of this model. As such, this study does *not* model behavioural heterogeneity or adoption constraints, but acknowledges them as reasons why real-world adoption will likely fall short of the upper bound identified. The techno-economic scenario thus serves as an informative reference point for assessing the need and potential role of supporting policy interventions.

2.3. Typology of Policy Instruments and Policy Evaluation in Sustainability Context

2.3.1. Policy Instrument Definitions and Classifications

Building on the definition of policy instruments as the tools through which governments steer socio-economic behaviour (Acciai & Capano, 2018; Salamon, 2002), Vedung's tripartite schema distinguishes by coerciveness three broad types—regulatory "sticks", economic "carrots" and informational "sermons" (Vedung, 1998). Hood's NATO framework then maps instruments to resource capacities—nodality (information), authority (legal power), treasure (fiscal means) and organization (administrative delivery) (Hood, 1983; Trein, 2024). Howlett (2000) further shows that each NATO type can be deployed substantively (direct delivery) or procedurally (process shaping). From the combined analysis of three seminal frameworks—Vedung's coercion-based typology (Vedung, 1998), Hood's resource-based NATO scheme (Hood, 1983), and Howlett's substantive versus procedural distinction (Howlett, 2000)—four fundamental policy instrument classes emerge:

- **Regulatory** (sticks / Authority): legally binding rules and sanctions.
- **Economic** (carrots / Treasure): fiscal incentives and disincentives.
- **Informational** (sermons / Nodality): communication, transparency and outreach.
- **Organizational** (Organization): direct deployment of government capacity and resources.

Deployable both *substantively* (direct provision) and *procedurally* (shaping decision processes), these four categories constitute a toolkit for designing and evaluating sustainability policies (Trein, 2024).

2.3.2. Ex Ante Evaluation Criteria for Policy Interventions

Ex-ante evaluation refers to the systematic assessment of a policy or intervention *before* it is implemented, using forecasts and models to predict its impacts and trade-offs (Munda et al., 2020). In environmental policy research, traditional *effectiveness*, *efficiency* and *equity* criteria dominate numerous studies, while other factors such as feasibility and acceptability are considered less consistently (Goulder & Parry, 2008; Gysen et al., 2006; Mavrot et al., 2025).

In this study, we adopt the “Three E’s” of policy analysis as our core evaluative framework (Hartnett, 2023; Kraft & Scott, 2020):

- **Effectiveness:** the extent to which the intervention achieves its objective (e.g. CO_2 reduction).
- **Efficiency (Cost-Effectiveness):** assesses the costs of the policy relative to its effectiveness. The ratio of outcomes to resource inputs, evaluated through cost-effectiveness metrics.
- **Equity:** the fairness of costs and benefits distribution across stakeholder groups

These three criteria capture the principal trade-offs in environmental policy design (Goulder & Parry, 2008). While additional dimensions (political acceptability, legal constraints, risk) may inform a more detailed assessment, anchoring our evaluation in effectiveness, efficiency and equity ensures comparability with the broader literature. We return to how these criteria are operationalised in our model, linking simulated outcomes to policy interventions, in Section 3.5.

2.3.3. Policy Interventions Affecting the Decision to Invest

A broad range of policy instruments is needed in order to reach the full emission reduction potential in the building sector. These policy instruments, when well designed, will strengthen each other over time (Kruit et al., 2020). Building on our four instrument classes and the investment drivers/barriers (Section 2.2.2), policy measures in the built environment are designed to target specific obstacles, while being appraised via our “Three E’s” (effectiveness, efficiency, equity):

- **Economic (Financial Incentives):** *Barrier addressed:* high upfront costs, short payback expectations. Grants, rebates, tax credits or low-interest loans reduce capital hurdles and bring forward end-of-life or investment trigger points (Akhatova & Kranzl, 2024; Sebi et al., 2019).
- **Regulatory (Performance Mandates & Standards):** *Barrier addressed:* split incentives and inertia among the worst-performers. Minimum Energy Performance Standards (MEPS) and retrofit deadlines set clear compliance dates and create ’trigger moments’ for investment decisions (Section 2.2)(European Commission, 2024; Kruit, 2023; RICS, 2024).
- **Organizational (Codes & Replacement Rules):** *Barrier addressed:* Financial Constraints and Competing Priorities. Equipment and building codes that mandate high-efficiency replacements or insulation upgrades on re-roofing tap into routine maintenance cycles, delivering consistent long-term gains with minimal extra disruption (Sebi et al., 2019).
- **Informational (Outreach & Technical Assistance):** *Barrier addressed:* limited expertise Mandatory audits, Energy Performance Certificates, training and public campaigns raise awareness of opportunities (Government of the Netherlands, 2009; Olsthoorn et al., 2017).

Linking to Evaluation Criteria The design characteristics of each instrument, along with the segment of the building stock it targets, determine how we assess its performance against the Three E's:

- *Effectiveness:* e.g. modelling CO_2 reductions under each intervention.
- *Efficiency:* e.g. calculating cost per tonne abated and compare interventions.
- *Equity:* e.g. analysis of differences between building sizes and user types.

By matching instruments to the specific drivers and barriers identified earlier, and embedding these links in our ex-ante evaluation, our model not only forecasts outcomes as a techno-economic upper bound (benchmark) but also tries to partially address the real-world conditions that determine uptake.

3 Methodology

3.1. Introduction

This chapter outlines the methodological approach taken to answer the central research question. It describes how the study was structured, how policy interventions were selected and evaluated, and how the CEKER model was adapted for use in the non-residential service building sector. By detailing the research design, modelling approach, and evaluation framework, this chapter provides the basis for understanding how the subsequent results were generated and interpreted.

3.2. Research Questions and Objectives

This section formulates the central inquiry of this thesis and the subordinate questions and objectives that guide this research. The aim is to clarify not only *what* policy instruments will be assessed, but also *how* and *why* their performance will be evaluated.

3.2.1. Central Research Question

The main research question that guides this study is:

> *How do policy interventions improve CO_2 emission reductions in the Dutch non-residential service building stock, in terms of their effectiveness, cost-effectiveness and distributional effects?*

The formulation of the question using *how* rather than *what* reflects the study's objective to go beyond a purely quantitative comparison of policy outcomes. It seeks to understand not only the differences in effectiveness, cost-effectiveness, and distributional effects across interventions, but also the mechanisms through which these interventions enhance CO_2 emission reductions. Specifically, the study explores how policy instruments address key barriers in the investment decision-making process, how they influence the distribution of heating technology choices among building owners, and how these shifts in technology adoption patterns contribute to sector-wide emission reductions. In doing so, the research aims to provide a more comprehensive understanding of the underlying dynamics through which policy interventions shape decarbonisation outcomes in the non-residential building stock.

3.2.2. Sub Questions

To break down this investigation into manageable parts, four sub-questions are posed:

1. What are the key components in the non-residential service building system, and how do they interact?
2. Which policy interventions show promise for reducing CO_2 emissions in the non-residential service sector, and will therefore be selected for analysis in this study?
3. Through which modifications can the CEKER model be adapted to capture the heterogeneity of non-residential service buildings?
4. How do the policy interventions affect CO_2 emission reduction and end-user costs, and how do those impacts vary by building type and size?

3.2.3. Research Objective

The primary objective of this study is to assess how specific policy instruments can effectively reduce CO_2 emissions in the Dutch non-residential service building stock. To this end, the research will quantify each intervention's emission reduction potential, assess its cost-effectiveness from the end-user perspective, and analyse the distribution of costs and emission reductions across different building types and sizes. The resulting insights aim to inform the design of new policy strategies for decarbonising the Dutch non-residential service sector.

This main research objective can be broken down into the following sub-objectives:

1. **Identify key components and interactions within the non-residential service building system**, to develop a system understanding necessary for accurately modelling policy effects.
2. **Select promising policy interventions**, to define realistic and policy-relevant scenarios for simulation.
3. **Adapt the CEKER model**, so that it adequately reflects the characteristics and heterogeneity of the non-residential service sector.
4. **Simulate and analyse policy scenarios**, focusing on impacts on CO_2 emissions, end-user costs, and distributional effects across building types and size classes.
5. **Interpret and contextualise findings**, by comparing results with existing literature and policy studies to place them within a broader academic and policy framework.
6. **Develop model-based policy recommendations**, aimed at supporting data-driven decision-making for accelerating CO_2 reductions in the non-residential sector.

By pursuing these objectives, the thesis provides not only a comparison of instruments but also model-based guidance for policymakers who aim to design future decarbonisation strategies for the non-residential service sector.

3.3. Quantitative Modelling Approach

This study adopts a quantitative modelling approach to systematically analyse the effects of different policy interventions on the non-residential building sector. Key economic variables, such as investment expenditures (CAPEX), operational costs (OPEX), and potential emission reductions associated with alternative heating solutions, are incorporated into the model to evaluate the effectiveness, cost-effectiveness, and distributional impacts of each intervention.

A key advantage of the quantitative modelling approach lies in its internal consistency and transparency: each model output is traceable to a defined set of input assumptions and calculation rules. This ensures that results are reproducible and that the effects of specific policy instruments, such as energy taxation or normative regulation, can be isolated and systematically compared across scenarios. These features facilitate model-based policymaking by comparing alternative policy pathways under controlled conditions.

As noted by Munda et al. (2020), quantitative policy modelling does not provide definitive answers but offers policymakers and other stakeholders a scientifically sound framework for conducting a coherent, systematic, and transparent analysis. Similarly, Smith-Spangler (2012) emphasises the importance of transparency and model validation, urging model developers to clearly communicate the model's structure, data sources, equations, assumptions, and validation methods to ensure the reliability of the results in a quantitative modelling approach.

3.4. The CEKER Model

The CEKER model is a techno-economic simulation tool used for policy evaluation in the built environment, focusing on the annualised end-user costs of heating solutions (Dehens et al., 2021; Kruit, 2021). It accounts for technology characteristics, investment costs (CAPEX), operational expenditures (OPEX), and building-specific parameters, making it suitable for assessing the financial implications of transitioning to sustainable heating solutions from an end-user perspective.

The model enables scenario-based policy analysis, simulating the impact of interventions such as pricing, subsidies, and regulations on both end-user costs and CO_2 emissions. It incorporates various heating technologies, including gas boilers, heat pumps, and district heating, and allows for detailed cost comparisons across building types.

Working with the CEKER model and adapting it to the non-residential built environment was a requirement from CE Delft for this specific thesis research. Besides being a formal requirement, CEKER is a relevant choice for our study because it enables the calculation of end-user costs per building, unlike national models (e.g., CEGOIA, a national cost model at CE Delft; Schepers, 2020). CEKER's unique structure allows for detailed financial analysis, directly linking policy scenarios (e.g., gas tax increase, energy labels) to the financial outcomes for building owners.

In this study, the CEKER model is adapted to the Dutch non-residential service sector, accounting for the heterogeneity of building types and sizes. This adaptation allows for a more accurate assessment of the economic feasibility and distributional impacts of policy interventions at the individual building level, supporting the study's objectives of evaluating CO_2 reductions and the cost implications of various policy options. A more detailed analysis on the workings of CEKER and how it is adapted in this study can be found in Chapter 5.

The following section discusses how the outputs from the CEKER model are interpreted to inform policy recommendations aimed at reducing CO_2 emissions in the non-residential service sector.

3.5. Interpretation of Model Outcomes

Building on the ex-ante assessment criteria discussed in Section 2.3.2, this section explains how the model outcomes are interpreted in this study. The aim is to systematically evaluate the effectiveness, cost-effectiveness, and equity of different policy interventions based on quantitative outputs generated by the CEKER model. This approach ensures that the assessment remains aligned with established policy analysis frameworks while maintaining relevance for the study's objectives.

Investment behaviour is modelled around natural replacement moments, occurring when the economic lifespan of a heating system ends. At these decision points, the CEKER model identifies the cost-optimal heating solution available to the building owner, based on prices projected for 2030. Across all scenarios, building owners are assumed to act rationally, selecting the economically most attractive technology option available.

As a result, the model outcomes represent *techno-economic upper bounds* of achievable emission reductions: they reflect the maximum decarbonisation potential attainable if building owners respond purely to cost signals. The base case illustrates this potential under the current policy environment, while the policy scenarios illustrate how different interventions could extend or shift this potential. A more detailed discussion of these modelling assumptions and their theoretical basis can be found in Section 2.2.3.

The CEKER model produces two primary outputs:

- **CO_2 Emissions:** Total and relative emissions under each policy scenario.
- **End-User Costs:** Annualised costs (CAPEX + OPEX) borne by building owners.

These outputs are used to evaluate policy scenarios along three complementary criteria:

1. **Effectiveness** Measures the total and relative CO_2 reduction achieved by each scenario. This includes both absolute emission reductions (in megatonnes) and relative performance compared to the base case.
2. **Cost-Effectiveness** In this research, cost-effectiveness is evaluated by comparing the costs associated with reducing CO_2 emissions across different policy scenarios. The goal is to assess the economic viability of policies by calculating the additional costs (CAPEX and OPEX) incurred for each ton of CO_2 emissions avoided. The formula for cost-effectiveness is as follows:

$$\text{Cost-effectiveness} = \frac{\Delta\text{CAPEX} + \Delta\text{OPEX}}{\Delta\text{CO}_2\ \text{Reduction}} \tag{3.1}$$

   Where:

   - ΔCAPEX is the change in capital expenditures (CAPEX) relative to the base case, measured in euros per year (€/year).
   - ΔOPEX is the change in operational expenditures (OPEX), which includes maintenance and energy costs, also measured in euros per year (€/year).

- ΔCO_2 Reduction is the annual reduction in CO_2 emissions relative to the base case, measured in tons of CO_2 (CO_2/year).

This formula calculates the cost-effectiveness in euros per ton of CO_2 reduced (€ / ton CO_2). This standardised indicator helps assess the financial efficiency of policy interventions by comparing the additional costs incurred against the emissions avoided.

Note that energy costs are included under OPEX, as they represent recurring costs related to the operation of the heating systems, and are not treated separately.

3. **Distributional Effects** Examines how impacts differ across building types and size classes. It analyses whether certain groups (e.g., small vs. large buildings, offices vs. schools) experience disproportionate cost burdens from a policy in transitioning to more sustainable heating solutions. While equity, as discussed in Section 2.3.2, includes broader concerns such as the distribution of benefits and societal costs, these aspects cannot be captured directly in the CEKER model. Therefore, distributional effects are used as a proxy to assess fairness in terms of cost distribution. This allows us to address equity considerations within the scope of the available model outputs.

These three criteria collectively form a framework for interpreting model results and evaluating trade-offs among environmental impact, economic feasibility, and equity.

In Figure 3.1 the flow of the research method (CEKER) to the model output, how we will evaluate the model output, and how the findings will ultimately feed into the formulation of policy recommendations is illustrated.

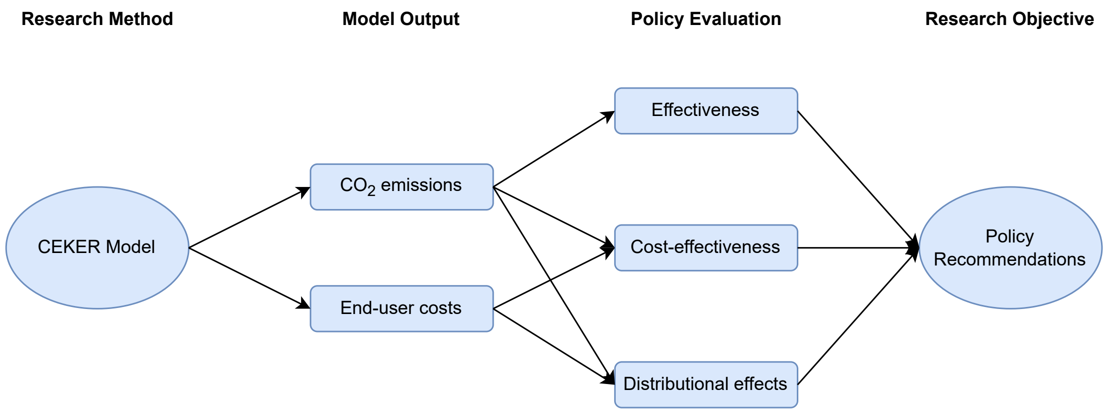

Figure 3.1: Relationship between model outputs and the three evaluation metrics

3.6. Research Scope

This study focuses on the non-residential service sector in the Netherlands, particularly existing buildings, which pose the greatest challenge for sustainability improvements (van den Bergh et al., 2021). The primary goal is to explore how these buildings can transition from gas-based heating systems to sustainable alternatives to meet climate targets. Newly constructed buildings are excluded, as they are already subject to stringent regulations like the BENG norm, which ensures compliance with higher sustainability standards (RVO, 2017b). Similarly, buildings with existing sustainable heating systems are excluded, as the focus is on those still relying on gas.

The research concentrates on building owners, who typically make investment decisions for the entire building (Jonker et al., 2024). Tenant-related issues, such as the split incentive dilemma (Garcia-Teruel, 2024), are not addressed to simplify the analysis and keep the focus on the techno-economic potential of policy impacts under idealised assumptions of economic rationality (see Section 2.2.3).

The study is limited to the service sector, excluding agricultural and industrial buildings, as their energy consumption is primarily driven by production needs rather than space heating. This focus ensures that the analysis remains relevant to policy interventions aimed at improving energy efficiency in the service sector, including offices, education, healthcare, assembly, sports, accommodation, and retail.

3.7. Research Strategy

In this section, we present a detailed plan to answer the research questions. This plan outlines the specific methods, tools, procedures, and steps that will be followed throughout the study. The research is divided into four distinct phases, each building upon the previous one.

Below is an overview of the research strategy, aligned with the four phases illustrated in Figure 3.2. Each phase addresses specific sub-questions, methods, and tools, culminating in a final policy recommendation.

3.7.1. System and Policy Analysis

In the first phase of this research, Sub-Question 1 (SQ.1) and Sub-Question 2 (SQ.2) are addressed:

SQ.1*: What are the key components in the non-residential service building system, and how do they interact?*

SQ.2*: Which policy interventions show promise for reducing CO_2 emissions in the non-residential service sector, and will therefore be selected for analysis in this study?*

In this exploratory phase, the focus is on gaining a deeper understanding of the non-residential service sector of the built environment. A literature review (Chapter 2) and conceptual modelling form the foundation of this phase, drawing on both academic and grey literature, with sources retrieved from databases such as Scopus and Elsevier. Tools like Google and Mendeley assist in the collection and organisation of the literature.

The outcome of this phase is an understanding of the non-residential system and the conceptual model that not only establishes the system boundaries but also informs the adaptation of the CEKER model in Phase 2. This theoretical framework is described in Chapter 4, which includes the system structure, policy landscape, and modelling scope.

Additionally, an overview of active policy instruments is compiled through a review of literature, policy reports, and various analyses. Based on the active policies in the system and policies that could address potential barriers in the investment decision, a set of policy interventions (or combinations thereof) is chosen for analysis. These interventions vary based on categories or parameter settings

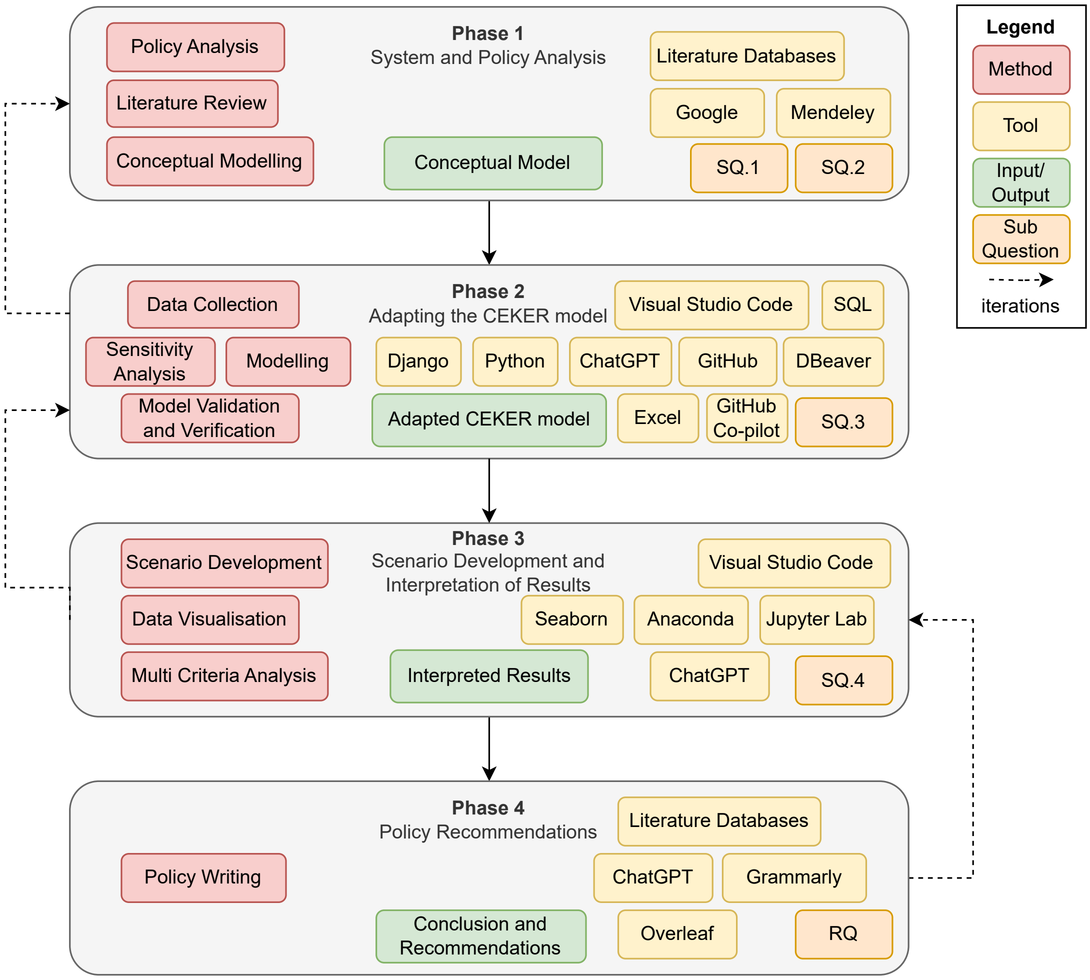

Figure 3.2: Research Flow Diagram

(e.g., establishing energy performance standards or adjusting taxes on specific energy sources). The selected policy mix is used in the scenario development described in Chapter 6.

3.7.2. Adapting the CEKER Model

Here, Sub-Question 3 is addressed:

***SQ.3**: Through which modifications can the CEKER model be adapted to capture the heterogeneity of non-residential service buildings?*

A quantitative techno-economic modelling approach is used to expand and adapt the CEKER model to the non-residential building stock. This adapted CEKER model is maintained in a GitHub repository under a separate branch to prevent conflicts with the original residential model. The adaptation process occurs in a CodeSpace environment using Visual Studio Code (Python) and integrates with Django for database communication and user management. DBeaver (SQL) provides quick data insights from the CEKER database, and Excel handles parameter adjustments via CSV files.

Tools like ChatGPT, GitHub Pro, and GitHub Copilot assist in code generation and optimisation. The model undergoes continuous validation and verification, extreme-value tests check logical responses in the behaviour of the model, and a validation of the model makes the outcomes of the model more reliable. The final deliverable is an adapted, validated, and verified CEKER model. This model development process, along with its structure, assumptions, and limitations, is documented in Chapter 5.

3.7.3. Interpretation and Comparison of Results

In this phase, Sub-Question 4 is addressed:

SQ.4*: How do the policy interventions affect CO_2 emission reduction and end-user costs, and how do those impacts vary by building type and size?*

The effects of the policy interventions on the model outputs (emissions and end-user costs) are visualised and interpreted. Using the adapted CEKER model from Phase 2, a *base case* dataset is generated in Visual Studio Code. Scenario parameters identified in Phase 3 (e.g., energy prices, constraints) are adjusted in JupyterLab (run via Anaconda, in Python) to create new output results for each scenario, which are added to a dataset with all the resulting outputs per scenario. Data visualisation tools, including the Seaborn Python library, produce clear graphs to compare the model outcomes of CO_2 emissions and end-user costs for each intervention.

The outcomes of this analysis, including detailed figures and scenario comparisons, are presented and discussed in Chapter 7.

3.7.4. Policy Recommendations

Finally, the study answers the main research question:

RQ*: How do different policy interventions or combinations of interventions affect CO_2 emission reductions and end-user costs, taking into account the effectiveness, cost-effectiveness, and distributional effects?*

The interpreted results from Phase 3 are compared with existing literature to discuss limitations, differences from other studies, and the broader relevance for policymakers. This reflection and evaluation, which includes methodological and policy implications, is provided in Chapter 8.

LaTeX (via Overleaf) is used to compile the thesis, providing a clean, structured format. ChatGPT and Grammarly support language checks and clarity. The final deliverable—a model-informed policy recommendation—is based on both simulated outcomes and theoretical insights, aiming to inform cost-effective and fair climate policies for the Dutch non-residential built environment. The main conclusions and corresponding answers to the research questions are presented in Chapter 9.

4
The Dutch Non-Residential Built Environment

4.1. Introduction

In this chapter, the focus is placed on the non-residential built environment in the Netherlands. The purpose of this section is to define and explore the various components of the system that must be understood in order to properly model and analyse the impacts of policy interventions. By addressing the system components, we establish a foundation for adapting the CEKER model to the unique characteristics of the non-residential service sector. The chapter starts with an analysis of the relevant components involved in the transition to a climate-neutral built environment. It begins by identifying key actors, building types, heating solutions and cost structures within the non-residential sector.

Following the system analysis, current policy interventions relevant to the non-residential sector that are in place are introduced. Hereafter the scope of our model is discussed and the reasoning behind our assumptions that make up the model scope. Finally, the chapter concludes with the output of this chapter, a conceptual model that visualises the system's components, their interrelations and policies that we, setting the stage for the subsequent adaptation of the CEKER model in Chapter 5.

This chapter provides the necessary context for the modelling work to follow and supports the identification of relevant parameters and relationships, ensuring the model accurately reflects the real-world dynamics of the non-residential built environment.

4.2. System Components

This section elaborates on the key components that shape the non-residential built environment, including actors, building types, heating solutions, and investment costs. The system consists of different actors that play a role in policy making or the investment decision, different types of buildings with each a different kind of heat and energy demand, heating solutions consisting of heating technologies and insulation levels and costs that come with the investments into these heating solutions.

4.2.1. Actors

This study focuses on the key actors in the non-residential built environment system, primarily building owners and policymakers. Understanding their roles and influence is necessary for analysing the effects of policy interventions and understanding how they impact investment decisions regarding sustainable heating solutions.

- **Building Owners**: As the primary decision-makers, building owners (both owner-users and owner-lessors) are responsible for investments in energy-efficient technologies and the operational costs of their buildings. They are directly impacted by policy interventions, which influence their decision to invest in EEM (as discussed in Section 2.2.2).
  - **Owner-users** are those who both own and occupy the building, meaning they are directly involved in the operational decisions of the property and the investments made in its energy systems.
  - **Owner-lessors** are property owners who lease their buildings to tenants. They are responsible for making investment decisions but do not directly occupy the building, which means that any energy savings or improvements made do not necessarily benefit them directly. However, they still have an interest in ensuring that their buildings comply with regulations and attract long-term tenants.
- **Policymakers**: Policymakers shape the regulatory environment through laws, regulations, and financial incentives. They establish policies that drive the transition to more sustainable heating solutions, such as MEPS and fiscal incentives. In this context, policymakers refer to governmental bodies at various levels, including national governments, regional or provincial authorities, and municipal governments, who create and enforce regulations and financial incentives that influence the built environment. They are responsible for setting Energy Efficiency (EE) standards, determining fiscal incentives, and creating the broader policy landscape in which building owners must operate.

While **tenants (users)** can influence the overall energy demand in buildings and are affected by energy-related decisions or interventions, they are not the primary actors in this study, as their role is more indirect. Their impact is noted primarily through the split incentive dilemma , where owners bear the upfront investment costs, but tenants benefit from the reduced energy costs. However, this study focuses on the building owners and their decision-making process, as they control the investment in EEMs.

This study limits its focus to actors with the highest power and interest, namely building owners and policymakers, as they are the central figures in the decision-making and implementation of policies. A more detailed actor analysis, including a power-interest grid, can be found in Appendix A.2. This grid visualises the influence and interest of the various actors in the system, helping to contextualise their roles in policy formulation and decision-making.

4.2.2. Buildings

User Types

The Standard Industrial Classification (SBI), broken down by main categories and its relation to the energy sectors, is detailed in Appendix A.3 (KVK, 2022). The term *non-residential building stock* refers to all buildings that are not residential. Within this category, the *service sector* is defined as a subset, corresponding to SBI main classes G through U. In addition, there are non-residential buildings classified under the industrial, agricultural, or energy production sectors. These specific classifications are excluded from this analysis, as discussed in Section 3.6.

The CEKER model uses the BAG dataset (in Dutch 'Basisregistratie Adressen en Gebouwen') as the foundation for all building-level calculations. In this study, we rely on the enriched BAG dataset which distinguishes between the following user functions (Sipma, 2023):

- Assembly
- Detention
- Healthcare
- Industry
- Office
- Accommodation
- Education
- Sports
- Retail
- Other functions

This study includes only the assembly, healthcare, office, accommodation, education, sports, and retail functions. These categories fall directly under the non-residential service sector. Other functions, such as industrial or "other" use, are considered outside the scope of this analysis due to their limited relevance or overly broad definitions.

Building Sizes

The non-residential building stock generally consists of larger buildings and shows a greater variation in building sizes. These proportions have been identified in the enriched BAG dataset used in this study (Sipma, 2023).

Table 4.1: Building Stock by Size Class

Size Class	Share of Buildings	Share of Floor Area (m^2)	Average Size (m^2)
0–500 m^2	76%	13%	121
500–1000 m^2	11%	10%	705
1000–5000 m^2	11%	31%	2 014
>5000 m^2	2.3%	46%	14 351
Total	1 027 998	743 687 029	723

This provides insight into the distribution and number of non-residential buildings, as well as their associated floor areas. As shown in Table 4.1, the vast majority of buildings (76%) are relatively small (under 500 m^2), yet these account for only 13% of the total floor area. In contrast, buildings larger than 5000 m^2 represent a small fraction of the stock (2.3%) but make up nearly half (46%) of the total floor area. This indicates a highly skewed distribution where a small number of very large buildings dominate in terms of spatial footprint.

Heat Demand

Heat demand is primarily determined by the building's characteristics, including insulation level, type, and construction year. A larger building inherently has a lower heat demand per square metre of usable floor area under identical conditions, due to the more favourable ratio of heat loss surface to heated volume. This demand is considered constant for a given building based on its specific characteristics, but the energy demand to meet it varies depending on the efficiency of the heating system (see next Section 7.2). More efficient systems require less input energy to satisfy the same heat demand.

Another factor influencing energy consumption is the level of insulation or the building's energy label. Buildings with a higher energy label typically consume less energy. Older buildings often have poorer insulation, which results in a higher heat demand. In the enriched BAG dataset, this has been accounted for by linking the indicative energy label to the year of construction. Chapter 5 provides more detail on how heat demand and energy demand are incorporated into the model.

In addition to space heating, other types of energy demand must also be considered when assessing buildings and the adoption of potential heating solutions. Buildings require energy for hot tap water, space cooling, ventilation, and appliances.

Most of these energy demands are estimated based on the building's floor area and user function, ensuring that differences in size and usage type are adequately reflected in the model outcomes.

4.2.3. Heating Solutions

In this study, we use the term *heating solutions* to refer to alternatives to gas-based heating systems, such as the conventional central heating boiler. A heating solution in our analysis consists of a primary system, a secondary system, and an insulation level.

There is a wide range of options when it comes to selecting a primary heating system, also referred to as "measures" in the built environment. This study focuses on the most common primary heating systems used when switching to alternative heat sources. Various other system variants exist, but these are not included in this analysis. An extensive list of heating systems that are seen as viable by the Dutch government (viable according to the government is having a payback period of 5 years or less), is called in Dutch the 'Erkende Maatregelenlijst (EML)' (RVO, 2022a).

Below is a brief overview of the selected primary heating systems, each accompanied by a short description:

- **Condensation boiler**: A high-efficiency gas boiler that recovers latent heat from exhaust gases through condensation, achieving thermal efficiencies above 90%. It is a common replacement for older conventional boilers and serves as a stand-alone system for space heating and hot water.

- **Hybrid air heat pump**: A combination system that includes both an air-to-water heat pump and a gas-fired boiler. The heat pump operates under moderate temperature conditions, while the boiler supports peak demand or very low outdoor temperatures. This setup offers improved efficiency with flexibility in colder climates.
- **All-electric air-to-water heat pump**: A fully electric system that extracts heat from outside air and transfers it to water for space heating and hot water. It requires no gas connection and is most efficient in well-insulated buildings with low-temperature heat distribution systems, such as underfloor heating or low-temperature radiators.
- **All-electric water-to-water heat pump**: A fully electric system that uses heat from groundwater or soil via a ground loop (often called geothermal or brine systems). It typically has higher efficiency (COP) than air-based systems but requires more extensive installation. This system also requires no gas connection and is most efficient in well-insulated buildings with low-temperature heat distribution systems, such as underfloor heating or low-temperature radiators.
- **Heat Exchanger Middle Temperature (MT)**: A heating system connected to a medium-temperature district heating network. It transfers heat via a heat exchanger from the central network to the building's internal system. Suitable for buildings with moderate insulation and radiators, and requires no on-site fuel combustion.

As mentioned in the description of the all-electric heat pump, underfloor heating and low-temperature radiators are necessary for the all-electric heat pump to function properly. Only for these heating systems, the secondary heating system Low Temperature Radiators are combined.

For insulation level, the energy label serves as an indicator of the building's thermal performance. Throughout this study, the terms *insulation level* and *energy label* will be used interchangeably, as both refer to the energy efficiency of the building envelope, excluding the heating system.

This study uses the energy labels as defined in the NTA 8800:2024 standard (NEN, 2024), ranging from label G (very poorly insulated) to A+++++ (highest achievable energy performance). Chapter 4 provides a more detailed explanation of how energy labels are applied within the model.

As noted earlier, certain heating systems require a higher level of building insulation to function effectively. In consultation with experts from CE Delft, it was agreed to define label D as the minimum insulation level and label A as the maximum insulation level for the purpose of this study. This simplification enables a more manageable and consistent analysis. More on this rationale is discussed in Chapter 6.

If a building already meets the required insulation level (i.e., label D for minimal insulation or label A for maximum insulation), no additional insulation investment is applied in the model.

Based on these definitions, the following combinations of heating system and insulation level are used to construct the set of heating solutions implemented in this study, as shown in Figure 4.1.

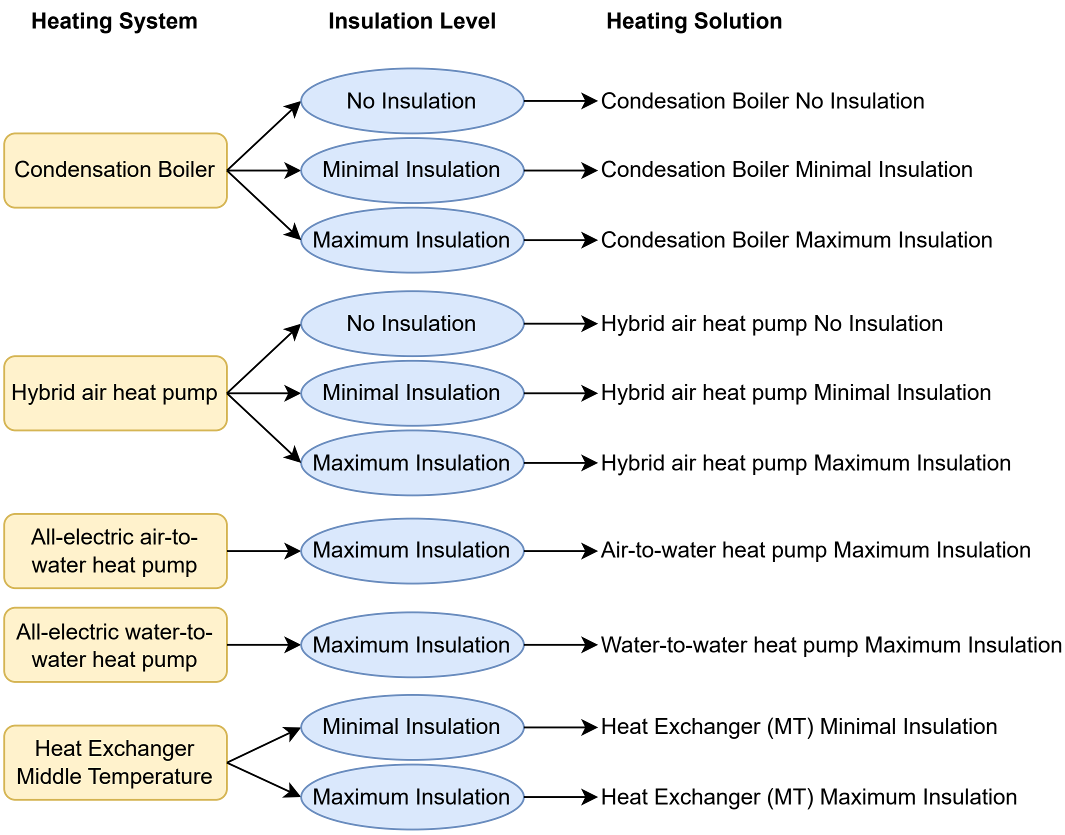

Figure 4.1: Combinations of primary heating systems and insulation levels used in this study

Depending on system efficiency, each heating solution leads to a different energy consumption outcome. While the heat demand of a building is considered fixed—based on characteristics such as insulation level and floor area—the input energy required to meet this demand varies by system: more efficient systems require less input energy to deliver the same thermal output.

The model calculates energy consumption per solution by allocating the total demand across space heating, hot tap water, cooling, ventilation and appliances. For each primary heating system, energy is drawn from different carriers (electricity, gas or district heat). For instance, all-electric systems rely entirely on electricity, whereas hybrid systems operate on a mix of sources. This study assumes fixed usage shares for the hybrid air heat pump (75% electricity, 25% gas). Energy demand per function is derived from floor area and building use; further details on these assumptions and parameters are provided in Chapter 4.

Based on total energy use, the model estimates CO_2 emissions per heating solution by applying carrier-specific emission factors projected for 2030. The emission calculation methodology and factor values are also detailed in Chapter 5.

4.2.4. Costs

Costs are divided into two main categories: investment costs (Capital Expenditure, CAPEX) and operational costs (Operational Expenditure, OPEX). CAPEX is calculated per heating solution and is based on the required heating capacity, which is estimated using the building's floor area. A distinction is made between small-scale (<100 kW) and large-scale (>100 kW) systems, as unit costs per kW differ. Separate investment values are defined for both primary systems (e.g. heat pumps, boilers) and secondary systems (e.g. low-temperature radiators), where applicable. Insulation levels are also part of a heating solution and therefore included in the CAPEX of a heating solution. Insulation costs, also referred to as envelope upgrade costs, are calculated as lump-sum investments associated with improving a building's energy label (e.g. from label G to A). These costs vary by current label, target label, building size and user function.

OPEX includes system-specific maintenance and energy costs. Maintenance costs are estimated as a fixed percentage of the initial investment of the heating system. Energy costs vary per energy carrier and usage profile. The energy tax is also part of the energy costs and is calculated based on Dutch tax brackets for energy use. Supplier costs, also called delivery rate, are also included in the total energy price. Also an estimation of the ETS2 price (European Trading System-2) for the built environment is made by PBL (2024b) in the 'Klimaat en Energieverkenning 2024' report.

Besides energy prices and investment costs, we also include the available subsidies, such as grants for insulation measures or specific heating technologies. These are applied as a reduction on the relevant investment costs. A more detailed overview of cost assumptions is discussed in Chapter 5

4.3. Active Policy Interventions in the Non-Residential Built Environment

The Dutch government employs various policy interventions to drive the sustainability of the non-residential building sector (service-oriented buildings such as assembly halls, healthcare facilities, offices, educational institutions, accommodations, sports venues, and retail). Below, the key national measures are discussed by intervention type. All measures are supported by official sources from the Ministry of the Interior and Kingdom Relations, RVO, or relevant legislation.

4.3.1. Taxes as an Incentive for Energy Savings

- *Energy Tax on Natural Gas and Electricity:* Reformed under the 2019 Climate Agreement, the tax structure now makes natural gas more expensive and electricity relatively cheaper, thereby providing a strong incentive to pursue sustainable alternatives (Rijksoverheid, 2019).
- *Renewable Energy Surcharge (ODE):* Until 2023, the Renewable Energy Surcharge (ODE) was a separate levy on energy consumption to fund renewable energy projects. In 2023, the surcharge was reduced to zero and has been fully integrated into the energy tax as of 2024. Due to the degressive structure of the energy tax and the fixed tax reduction per electricity connection, non-residential buildings with high energy consumption benefit relatively less from tax relief compared to small-scale users (Milieu Centraal, 2025).

4.3.2. Subsidies for Sustainable Investments

- *DUMAVA:* Supports social real estate (e.g., schools, government buildings) for sustainability measures like insulation, solar panels, and heat pumps (RVO, 2023b).
- *ISDE – Business:* Subsidy for sustainable heat and small-scale renewable systems like heat pumps and solar water heaters (RVO, 2017b).
- *SDE++:* Supports large-scale renewable energy or CO_2 reduction projects, e.g., PV installations or climate technologies (RVO, 2023a).

4.3.3. Fiscal Arrangements and Green Financing

- *Energy Investment Allowance (EIA):* Allows businesses to deduct 40% of investment cost for energy-efficient technologies from taxable profit (RVO, 2025b).
- *MIA and Vamil:* Provide additional tax deductions (up to 45%) and flexible depreciation for green investments (RVO, 2025a).
- *BMKB-Groen:* Provides government guarantees for SME loans focused on green building upgrades (RVO, 2025c).

4.3.4. Regulations and Obligations

- *Mandatory Energy Savings:* Companies with high energy use must implement all energy-saving measures with a payback of 5 years or less (RVO, 2022a).
- *Energy Label C Requirement for Offices:* As of January 1, 2023, offices larger than 100 m^2 must have at least energy label C, or cannot be used as offices (Rijksoverheid, 2024; RVO, 2018).
- *Mandatory Energy Label for Sale or Rent:* Buildings must have a valid energy label when sold, rented, or delivered (European Commission, 2024; RVO, 2017c).
- *Natural Gas Ban in New Construction:* Since July 2018, new buildings may not connect to the gas grid, encouraging electric or sustainable alternatives (RVO, 2022b).
- *Nearly Zero-Energy Building (BENG) Requirements:* Since 2021, all new buildings must meet BENG criteria, with limits on energy demand, fossil energy use, and minimum renewable share (RVO, 2017a).
- *Minimum Renewable Requirements for Major Renovations:* Since 2022, major renovations must integrate a minimum level of renewable energy based on building characteristics (RVO, 2021).

4.3.5. Need for Targeted and Combined Policy Interventions

Transitioning the built environment towards sustainability requires coordinated investments across three key domains: upgrading the building envelope, replacing heating systems and associated infrastructure, and decarbonising the energy carriers (Kruit, 2023). To fully realise the Dutch heat transition, the maximum feasible potential (techno-economic upper bound) in all three areas must be exploited.

While existing subsidies, current energy prices, and prevailing tax incentives make single or moderate insulation improvements financially attractive, deep renovation projects remain economically challenging under present market conditions (Kruit, 2023). Regulatory instruments, by contrast, offer the possibility to drive more ambitious changes. At present, minimum energy performance requirements apply primarily to new construction and office buildings; extending such standards to other categories within the non-residential sector could accelerate the phase-out of low-performing buildings.

There is a clear economic rationale for prioritising highly cost-effective energy efficiency measures—so-called 'low-hanging fruits'—which tend to have relatively low costs and technological simplicity. However, the magnitude of the transition required means that focusing exclusively on such shallow interventions is insufficient. Deep renovation and structural system changes are necessary components for achieving the full decarbonisation of the non-residential sector (Rosenow et al., 2017).

Historically, decarbonisation efforts in the Dutch building sector have relied heavily on 'soft' policy measures such as subsidies and energy taxation. Given the current technological maturity and financial viability of many sustainable solutions, there is an urgent need to transition towards a more comprehensive and binding policy framework that secures long-term emission reductions (Kruit, 2023).

4.4. Justification for the Selected Policy Interventions

This study investigates three primary types of policy interventions to promote sustainable heating in the non-residential building sector: (1) an increase in energy taxation on natural gas, (2) a mandatory minimum energy label requirement, and (3) a prohibition on the use of gas-based heating technologies (gas ban). The selection of these interventions is grounded in both empirical evidence and theoretical considerations on investment barriers, policy effectiveness, and recent developments in the Dutch and broader European context.

4.4.1. Addressing Barriers in Investment Decision-Making

Theoretical and empirical studies show that high upfront costs and the lack of strong financial incentives are key barriers to the adoption of energy efficiency measures in non-residential buildings (Olsthoorn et al., 2017; Sebi et al., 2019; Tollenaar et al., 2024). Increasing the cost of fossil fuel use through energy taxation addresses the upfront economic barrier by improving the business case for sustainable alternatives such as heat pumps and district heating.

The gas price spikes during the European energy crisis of 2021–2022 provide a real-world demonstration of this mechanism. Koster et al. (2022) observed that the sharp increase in natural gas prices improved the economic attractiveness of alternative, non-gas-based heating systems. Similarly, a European study on heat pump adoption found that energy prices are the most visible driver of uptake (Anczewska et al., 2025). This suggests that energy taxation can create strong, broad-based market incentives for sustainability investments, aligning with rational economic behaviour (Becker, 1976; Gillingham & Palmer, 2014).

However, rather than relying solely on continued price increases, a complementary or alternative strategy is to introduce a regulatory ban on gas-based heating technologies. A gas ban directly removes gas options from the market, forcing a shift towards sustainable technologies regardless of relative energy prices. This stricter intervention targets situations where financial incentives alone may be insufficient to drive rapid change. Although a gas ban represents a more extreme and likely less feasible real-world policy measure, it is of particular interest in this study to explore its impacts on emission reductions and end-user costs. Conceptually, a continued increase in gas prices would ultimately converge towards the same effect as a complete gas phase-out, making it relevant to examine the cost and performance implications of such a scenario.

At the same time, regulatory interventions such as mandatory energy performance standards address non-economic barriers, including split incentives and organisational inertia, that inhibit investment even when cost-attractive opportunities exist (Olsthoorn et al., 2017; Rosenow et al., 2017). A mandatory energy label requirement forces building owners to act, creating new "trigger points" for investment decisions (Jonker et al., 2024; RICS, 2024; Sebi et al., 2019). Without such measures, purely price-based incentives may fail to reach buildings owned by actors who are insensitive to energy cost changes or who face internal decision-making barriers (Kapur et al., 2011).

4.4.2. Evidence of Effectiveness from Recent Policy Developments

The effectiveness of energy taxation and mandatory standards is also supported by empirical evaluations. Besides the improved economic attractiveness of alternative, non-gas-based heating systems and a decrease of CO2 emissions, during the European energy crisis of 2021–2022 (Burgering, 2025), a review of Dutch building sector policies by Vringer et al. (2016) concluded that the existing energy tax is a key pillar for achieving cost-effective energy savings. By making fossil fuel consumption more expensive, it encourages building owners to select the most economical abatement options first.

In the case of regulatory interventions, the mandatory energy label C requirement for office buildings in the Netherlands provides an illustrative success. Enforcement of this requirement as of 2023 has been observed to drive substantial upgrades in building stock performance, with early evidence suggesting that it is achieving its intended effect (Arnoldussen et al., 2016; Eichholtz et al., 2024). As noted by Vringer et al. (2016), further extending such mandatory standards to a broader range of non-residential buildings could significantly accelerate the sector's decarbonisation.

4.4.3. Rationale for Investigating a Policy Mix

While each intervention has merits individually, extensive literature stresses that no single policy instrument is sufficient to overcome the range of barriers present in the building sector (Rosenow et al., 2017). Economic instruments effectively motivate cost-sensitive actors, while regulatory instruments ensure minimum standards across all ownership structures, including those facing split incentives or low responsiveness to price signals.

Studies confirm that policy packages combining financial and regulatory measures perform better than single-instrument approaches, especially under conditions of market uncertainty or behavioural inertia (Goulder & Parry, 2008; Özer et al., 2024).

Therefore, this study not only investigates the effectiveness of the energy tax and energy label requirement as standalone interventions but also analyses their combined impact as a policy mix. By doing so, it reflects best practices in contemporary climate policy design and provides a more robust assessment of viable strategies for decarbonising the Dutch non-residential service sector.

This approach reflects the conceptual understanding that economic, regulatory, and prohibitive measures each target different types of barriers, as outlined in Vedung's and Hood's typologies in Section 2.3.1 (Hood, 1983; Vedung, 1998).

4.5. Model Scope

To maintain analytical clarity and policy relevance, the scope of the techno-economic model is delineated across several dimensions. Each dimension reflects deliberate choices based on the research question, data availability, and modelling constraints.

Geographical Scope

The analysis is limited to the Netherlands, in order to reflect the country's specific building stock, institutional context, and applicable policy instruments. This national focus aligns directly with the central research question of this study, which is explicitly framed around the Dutch policy context.

Physical Scope

The model focuses on individual buildings as defined in the Dutch *Basisregistratie Adressen en Gebouwen* (BAG) dataset, rather than on occupiable units. This enables a building-level analysis of the energy performance and retrofit potential of the national service sector stock. This approach is consistent with the methodological choice to focus on building owners, not tenants, as discussed in the methodology section.

Sectoral Scope

The study is restricted to existing, non-residential buildings in the service sector, defined using SBI codes G through S and U. This includes offices, retail, healthcare, education, hospitality, and cultural facilities. Buildings in the industrial and agricultural sectors, as well as new constructions, are excluded. This selection reflects the scope of the research, which specifically targets the decarbonisation potential of the service sector (see Section 3).

Heating Technologies and Envelope Performance

The model considers primary and secondary heating systems listed in the Recognised Energy Efficiency Measures List (EML). Evaluated technologies include hybrid heat pumps, all-electric heat pumps, and medium-temperature heat exchangers. Building envelope quality is represented through energy label categories, used as a proxy for insulation level. These technologies were retained from the original model framework, and in consultation with CE Delft experts, were judged to adequately reflect the relevant technological landscape for the non-residential sector without requiring structural changes to the model.

Policy Representation

While the Dutch policy landscape includes a wide array of financial, fiscal, and regulatory instruments, only a simplified representation of two mechanisms is included: (1) an illustrative investment subsidy and (2) a generic green loan mechanism. This simplification was chosen to maintain the model's tractability and transparency, given time constraints and the goal of isolating techno-economic effects.

Regulatory and Fiscal Instruments

The model incorporates the effects of energy pricing (via the energy tax on gas and electricity), as well as regulatory constraints, such as the prohibition of gas connections in existing buildings and mandatory energy label requirements.

Energy Carriers and Emissions Accounting

The energy carriers considered are natural gas, electricity, and district heat. The emissions analysis is limited to CO_2 (Scope 1 and Scope 2), based on the assumption that the operational energy demand from buildings directly translates into emissions through these carriers. Scope 3 emissions and other greenhouse gases are excluded. This focus is consistent with existing literature and common practice in emission modelling, and positions the study in relation to broader international climate policy efforts.

4.6. Conceptual Model

In Figure 4.2, the mechanism of policy interventions within the system is illustrated. When a policymaker raises the energy tax on gas, the OPEX of the current gas-based heating system increases, which in turn raises total lifecycle costs and improves the financial attractiveness of more sustainable heating solutions. In our model, the building owner then selects the lowest-cost heating solution (a fully rational decision); the difference in CO_2 emissions between the reference and the newly chosen system represents the emission reduction achieved by the tax intervention.

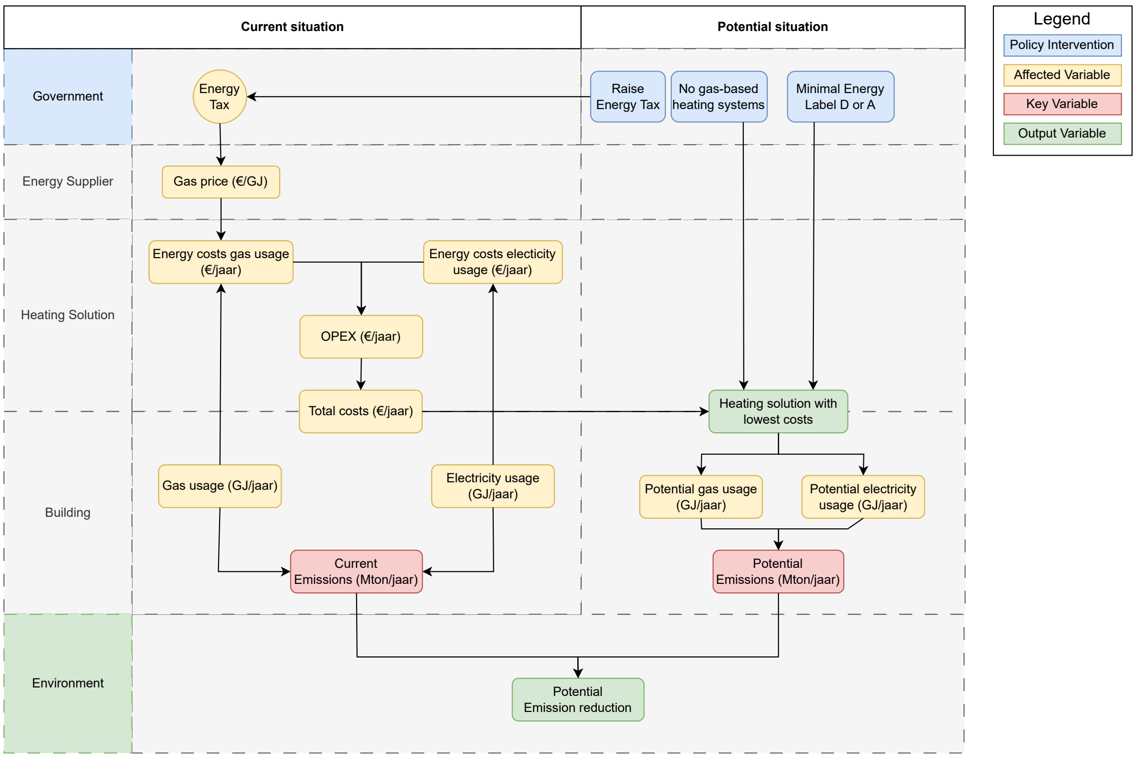

Figure 4.2: Causal relationships between policy interventions and model variables

Alternatively, if regulations restrict gas-based heating systems or mandate a minimal energy label of D or A, the owner's choice is constrained to compliant options. The emission reduction is then calculated as the difference between the emissions of the most cost-attractive sustainable solution under the regulation and those of the baseline system. This framework directly links policy interventions to owner decision-making and quantifies their impact on emissions.

5
The CEKER Model

5.1. Introduction

This chapter introduces the CEKER model (*CE Kosten voor Eindgebruikers Rekenmodel*), a techno-economic simulation tool used to evaluate policy interventions in the built environment. It describes the model's original structure and purpose, identifies its limitations for application to non-residential service buildings, and outlines the adaptations made for this research. The chapter concludes with a model validation and verification, followed by a sensivity analysis that serves as input for the experiment design in the subsequent Chapter 6.

5.2. Original Structure and Functionality of the CEKER Model

The CEKER model was originally developed by CE Delft to support policymakers and planners in assessing the affordability of the heat transition for residential buildings (Dehens et al., 2021; Kruit, 2021). It estimates the annualised end-user costs of heating system transitions by combining capital expenditures (CAPEX), operational expenditures (OPEX), and building-specific parameters.

The model follows a cost-minimisation principle: at the moment of natural replacement (e.g., end of life of a heating system), it determines the most economically attractive technology option available to the building owner. It allows the simulation of various policy scenarios by adjusting parameters such as energy prices, taxes, subsidies, and regulatory constraints.

Key input categories include:

- Building characteristics (e.g., surface area, insulation level).
- Heating technology parameters (e.g., investment cost, efficiency, maintenance costs).
- Policy variables (e.g., gas tax, subsidies for heat pumps).

Key outputs are:

- Annualised end-user costs (CAPEX + OPEX).

- Technology adoption rates.
- Resulting CO_2 emissions.

The CEKER model operates at the building level, allowing detailed analysis of cost and emission impacts per building rather than aggregated at sectoral or national level.

5.2.1. Model Architecture

The CEKER model architecture, illustrated in Figure 5.1, follows a structured flow from static building characteristics and heating system parameters towards dynamic energy use, cost, and emission outcomes. It integrates multiple information streams — building surface area, energy label, heating system properties, fuel characteristics, and policy variables — to simulate investment decisions and operational performance at the building level.

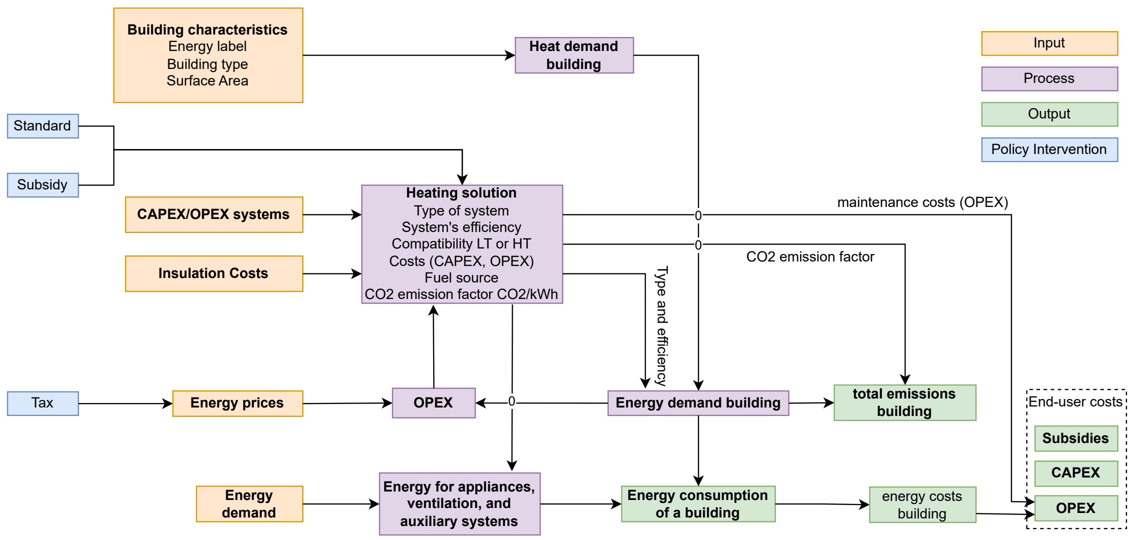

Figure 5.1: CEKER Architecture

5.2.2. Key Functionalities that Stayed the Same

While adapting CEKER to the non-residential service sector, several core functionalities of the original model were retained and needed no adaptation for the non-residential built environment. These include:

- **Annuity-based cost calculation:** Both capital expenditures (CAPEX) and operational expenditures (OPEX) are annualised using a standard annuity formula based on investment lifetime and discount rate (Equation 5.4).
- **CO_2 emission calculation:** Emissions are derived from the energy consumption per building and fuel-specific emission factors (Equation 5.18).
- **Incorporation of financial incentives:** Subsidy schemes (e.g., DUMAVA) are integrated into the investment cost calculations, following a structure similar to that used in the residential model (Equation 5.9).
- **Calculation of energy use:** Energy consumption per building remains determined by dividing

the relevant demand (e.g., space heating) by the system-specific efficiency, consistent with the original CEKER structure (Equation 5.12).

5.3. Limitations for Application to Non-Residential Buildings

While CEKER provides valuable insights for the residential sector, several limitations restrict its direct application to the non-residential service buildings. Each of these limitations has been addressed through specific model adaptations, as outlined in Section 5.4.

- **Functional heterogeneity**: Non-residential buildings serve diverse purposes (offices, schools, healthcare, retail) with highly variable energy demands. *Addressed by: building type categorisation and adjusted energy profiles (Section 5.4.5).*
- **Size variability**: Non-residential buildings vary more in size, surface area, and energy intensity than residential dwellings, affecting heating capacity needs and technology scaling (economies of scale).
Addressed by: capacity-based CAPEX calculation using building surface area (Section 5.4.1, Equation 5.2).
- **Cost structure differences**: Investment and operational cost profiles differ substantially, requiring separate CAPEX/OPEX parameterisation for non-residential heating technologies.
Addressed by: adapted CAPEX and OPEX parameters for non-residential systems (Section 5.4.1, 5.4.2, 5.4.3).
- **Energy demand profiles**: Heating loads and usage patterns differ from residential buildings, necessitating adjustments in baseline space heating demand and energy saving assumptions.
Addressed by: recalculation of space heating demand based on energy labels and building type (Section 5.4.5, Equation 5.11).
- **Insulation standards and impacts**: Energy label thresholds and their impact on heating demand reductions are different and less standardised across non-residential buildings, requiring custom modelling.
Addressed by: label-based insulation cost modelling and heating demand adjustments (Section 5.4.3).
- **Energy tariff structures**: Energy pricing (variable and fixed) for non-residential customers follows different structures (e.g., tiered taxes and fees) compared to residential, affecting operational cost estimation.
Addressed by: tiered energy cost estimation for gas and electricity (Section 5.4.7, Equation 5.15).

Without these adaptations, applying the original CEKER model to the non-residential service sector would misrepresent both investment costs, operational expenditures, and emissions impacts, leading to inaccurate policy evaluations and misguided recommendations.

5.4. Model Adaptations for Non-Residential Service Buildings

Detailed explanation of the adaptations made: categorisation of building types and sizes, adjusted CAPEX/OPEX parameters, changes in energy demand profiles, other model refinements.

5.4.1. Calculation of Primary System Costs

The model evaluates primary heating systems based on surface area, system-specific connection values, and heating capacity requirements.

1. Connection-Based Capacity Requirement Each heating system has an associated system-specific connection value c in kW/m^2. The required installed heating capacity P for a building is calculated as:

$$P = A \times c \tag{5.1}$$

where:

- P: required capacity [kW],
- A: building surface area [m^2],
- c: system-specific connection value [kW/m^2].

2. Large Consumer Classification Buildings are classified as "large consumers" based on the required heating capacity. A building is considered a large consumer if:

$$\text{large\_consumer} = \begin{cases} 1 & \text{if } P > 100 \text{ kW} \\ 0 & \text{otherwise} \end{cases} \tag{5.2}$$

This classification affects the CAPEX rates used for certain heating technologies (e.g., differentiating between small and large scale installations).

3. Capital Expenditure (CAPEX) The total system CAPEX per building is determined using a fixed installation cost plus a variable cost that depends on the installed capacity:

$$C_{\text{capex}} = C_{\text{fixed}} + P \times C_{\text{variable}} \tag{5.3}$$

where:

- C_{capex}: total capital expenditure [€],
- C_{fixed}: fixed installation cost [€],
- C_{variable}: variable cost per kW installed [€/kW],
- P: required system capacity [kW].

System-specific CAPEX parameters for different technologies are retrieved from a parameter table.

4. Annualised CAPEX Following the original CEKER model structure, CAPEX is annualised using the standard annuity formula:

$$C_{\text{capex, yearly}} = \frac{C_{\text{capex}} \times r}{1 - (1 + r)^{-n}} \tag{5.4}$$

where:

- $C_{\text{capex, yearly}}$: annualised CAPEX [€/year],
- r: discount rate [−],
- n: economic lifetime of the system [years].

The real-world estimation of the discount rate is 4,5% for non-residential buildings and was achieved through economic experts within CE Delft.

5. Operational Expenditure (OPEX) Operational expenditures are modelled as a fixed fraction f of the initial CAPEX:

$$C_{\text{opex}} = f \times C_{\text{capex}} \tag{5.5}$$

where:

- C_{opex}: annual operational expenditures [€/year],
- f: maintenance rate [−].

The maintenance rate f varies depending on the selected heating technology.

5.4.2. Calculation of Secondary System Costs

For certain heating solutions, low-temperature adaptation systems (LTAS) are required to enable effective heat delivery for all-electric heat pumps.

When applicable, the secondary system capital expenditure (CAPEX) per building is calculated as:

$$C_{\text{capex, secondary}} = A \times c_{\text{secondary}} \tag{5.6}$$

where:

- $C_{\text{capex, secondary}}$: total secondary system capital expenditure [€],
- A: building surface area [m^2],
- $c_{\text{secondary}}$: secondary system unit cost [€/m^2].

The annualised secondary system CAPEX is determined using the same annuity formula as presented in Equation 5.4.

Operational expenditures (OPEX) are modelled as a fixed fraction of the CAPEX.

LTAS is only applied to heating solutions that have an all-electric heat pumps as their primary heating system.

5.4.3. Label-Based Calculation of Insulation Costs

In the adapted model, insulation costs for non-residential buildings are determined based on the required energy label improvement needed to enable specific heating solutions. This reflects policy-driven technical standards, where certain low-carbon heating systems (e.g., heat pumps) require a minimum insulation level.

Upgrade Trigger Logic

An insulation upgrade is triggered if the building's current energy label L_{current} is worse than the required label L_{required}, and L_{current} is not already label A or better:

$$C_{\text{insulation}} = \begin{cases} 0 & \text{if } L_{\text{current}} \geq L_{\text{required}} \text{ or } L_{\text{current}} \geq A \\ \text{calculated} & \text{otherwise} \end{cases} \tag{5.7}$$

Cost Composition

If an upgrade is needed, the total insulation cost is calculated as:

$$C_{\text{insulation}} = C_{\text{fixed}} + C_{\text{variable}} \times A \tag{5.8}$$

where:

- $C_{\text{insulation}}$: total insulation cost [€],
- C_{fixed}: fixed base cost (e.g., logistics, design) [€],
- C_{variable}: variable cost per square metre [€/m^2],
- A: Building surface area [m^2].

Annualisation of Costs

The total insulation cost is annualised using the standard annuity formula presented in Equation 5.4.

5.4.4. Calculation of Subsidies for Systems and Insulation

To simplify the model, the DUMAVA subsidy scheme is uniformly applied to all buildings (RVO, 2023b). Under this scheme, a subsidy of 30% of total capital expenditure (CAPEX) is granted, provided that the insulation upgrade involves at least three energy label improvements. For example, an upgrade from label G to E does not qualify for the subsidy, whereas an upgrade from G to D does.

Subsidy amounts are calculated based on the total investment costs associated with each heating solution. The following logic is applied:

- If the heating solution involves a condensation boiler, no subsidy is granted.

- For minimal improvement scenarios, a subsidy is only granted if the current energy label is G.
- For maximum improvement scenarios, a subsidy is granted if the current energy label is G, F, E, or D.
- The subsidy amount is calculated as a fixed percentage of total CAPEX.

The resulting subsidy (S) per building is determined as:

$$S = -p_{\text{subsidy}} \times C_{\text{capex}} \tag{5.9}$$

where:

- S: subsidy amount [€],
- p_{subsidy}: subsidy percentage [-],
- C_{capex}: total capital expenditure [€].

Subsidy amounts are also annualised using the standard annuity formula (see Equation 5.4) to reflect their yearly financial impact.

5.4.5. Calculation of Space Heating Demand After Insulation

The adapted model adjusts the space heating demand of non-residential buildings based on the required insulation improvements associated with each heating solution. The adjustment is determined by comparing the building's current energy label L_{current} with the minimum required label L_{required} for the selected heating solution.

Label Order and Comparison

Energy labels are ordered from worst to best as follows:

$$\text{G} \prec \text{F} \prec \text{E} \prec \text{D} \prec \text{C} \prec \text{B} \prec \text{A} \prec \text{A+} \prec \text{A2+} \prec \text{A3+} \prec \text{A4+} \prec \text{A5+} \tag{5.10}$$

A building requires insulation improvement if L_{current} ranks lower (worse) than L_{required} according to this ordering.

Reduction in Space Heating Demand

If insulation is required, the model applies an energy saving percentage η based on the building's usage function and the label improvement required. The new annual space heating demand Q_{new} is calculated as:

$$Q_{\text{new}} = Q_{\text{current}} \times (1 - \eta) \tag{5.11}$$

where:

- Q_{new}: new space heating demand after insulation [GJ/year],

- Q_{current}: current space heating demand [GJ/year],
- η: energy saving percentage [-], dependent on building type and label improvement.

If no insulation upgrade is required (i.e., $L_{\text{current}} \geq L_{\text{required}}$), the heating demand remains unchanged (Formula 5.7).

The energy saving percentages are retrieved from system parameters based on building type and the required label jump.

The updated space heating demand Q_{new} is directly used as input for the calculation of energy use described in Section 5.4.6. For each building, the reduced heating demand lowers the projected energy consumption, which in turn reduces both the variable and total energy costs associated with heating.

By integrating the improved insulation performance into the energy cost calculation, the model consistently captures the financial benefits of lower energy use following building envelope improvements.

5.4.6. Calculation of Energy Use

The adapted model estimates the annual operational energy use of non-residential service buildings by calculating the energy demand for different end-uses, depending on the installed heating technology.

Only relevant energy carriers and systems for the studied heating solutions (e.g., electricity, natural gas, district heating) are considered. Heating options not included in this study, such as biomass boilers and split air conditioning systems, are excluded from the analysis.

Energy Use Categories

The model accounts for the following end-uses:

- **Space heating** — calculated based on the reduced heating demand and system efficiency.
- **Hot tap water** — based on building hot water needs and system efficiency.
- **Space cooling** — dependent on the cooling capacity of either the primary system or a secondary air conditioning system.
- **Ventilation** — reflecting the electricity demand for mechanical ventilation systems, which is especially relevant in well-insulated (high-label) buildings.
- **Appliances** — covering general electricity use from building equipment and devices, assumed independent of the heating solution.

Cooking energy use is not included, as cooking is not considered a significant end-use in the non-residential service sector for this study.

Calculation Method

For each end-use, the energy use per carrier is determined by adjusting the final demand by the efficiency of the associated technology.

The general formula for the energy use $U_{\text{carrier, end-use}}$ is:

$$U_{\text{carrier, end-use}} = \frac{D_{\text{end-use}}}{\eta_{\text{end-use}}} \tag{5.12}$$

where:

- $U_{\text{carrier, end-use}}$: annual energy use for a specific end-use and carrier [GJ/year],
- $D_{\text{end-use}}$: final energy demand for the end-use [GJ/year],
- $\eta_{\text{end-use}}$: system efficiency for the end-use [-].

The total annual energy use per building and energy carrier is then obtained by summing across all relevant end-uses:

$$U_{\text{carrier}} = \sum_{\text{end-uses}} U_{\text{carrier, end-use}} \tag{5.13}$$

Carrier-Specific Adjustments

For hybrid systems, space heating energy demand is split between electricity and gas according to predefined fractions. For district heating systems, hot tap water production may require auxiliary electricity use depending on the available temperature level of the heat network.

Integration with Cost and Emission Calculations

The calculated energy uses U_{carrier} per building and heating solution are subsequently used to estimate operational energy costs (Section 5.4.7) and CO_2 emissions (Section 5.4.8).

5.4.7. Estimation of Future Energy Costs

The adapted model estimates future operational energy costs for non-residential buildings by combining projected energy consumption (in GJ) with expected tariffs in the target year. For each energy carrier (electricity, gas, heat), both variable and fixed costs are considered.

Energy Cost Components

For each energy carrier, the model distinguishes:

- **Variable energy costs** — proportional to the amount of energy used, incorporating delivery rates, taxes, supplier fees, and ETS2 surcharges.
- **Fixed annual fees** — flat costs per building, covering grid connection and administrative fees.

The total cost per building is calculated as:

$$C_{\text{total}} = C_{\text{variable}} + C_{\text{fixed}} \tag{5.14}$$

where:

- C_{total}: total energy cost [€],
- C_{variable}: variable energy cost [€],

- C_{fixed}: fixed energy cost [€].

Variable Energy Costs — Tiered System

For electricity and gas, the model applies a tiered tax structure over five consumption zones:

$$C_{\text{variable}} = \sum_{z=1}^{5} U_z \cdot \left(p_{\text{delivery}} + p_{\text{tax,z}} + p_{\text{supplier}} + p_{\text{ETS2}}\right) \cdot (1 + \text{VAT}) \tag{5.15}$$

where:

- U_z: energy consumption within tax zone z [unit],
- p_{delivery}: delivery tariff [€/unit],
- $p_{\text{tax,z}}$: energy tax per consumption zone [€/unit],
- p_{supplier}: supplier fee [€/unit],
- p_{ETS2}: surcharge under the European Trading System [€/unit],
- VAT: value-added tax percentage.

For gas, a weighted delivery tariff is used depending on the share of green gas:

$$p_{\text{delivery, gas}} = \gamma \cdot p_{\text{natural gas}} + (1 - \gamma) \cdot p_{\text{green gas}} \tag{5.16}$$

where:

- γ: share of grey gas [-],
- $p_{\text{natural gas}}$: natural gas delivery rate [€/m^3],
- $p_{\text{green gas}}$: green gas delivery rate [€/m^3].

Fixed Energy Costs

Fixed energy costs per building are calculated as:

$$C_{\text{fixed}} = p_{\text{fixed}} \cdot (1 + \text{VAT}) \tag{5.17}$$

where p_{fixed} is the base annual fixed fee depending on the energy carrier.

5.4.8. Estimation of CO_2 Emissions

The adapted model estimates annual CO_2 emissions for each building and heating solution based on the operational energy use. Emissions are calculated separately for electricity, gas, and district heat, using energy carrier-specific emission factors.

Calculation Logic

For each building, the CO_2 emissions associated with a heating solution are calculated by:

- Estimating the annual energy use per energy carrier (electricity, gas, or heat).
- Multiplying the energy use by the carrier-specific emission factor for the target year.
- Adjusting gas emissions based on the projected green gas percentage.

The emission per energy carrier E_{carrier} is given by:

$$E_{\text{carrier}} = Q_{\text{carrier}} \times e_{\text{carrier}} \times (1 - \gamma_{\text{green}}) \tag{5.18}$$

where:

- E_{carrier}: annual CO_2 emissions for a specific carrier [kg CO_2/year],
- Q_{carrier}: annual energy use for the carrier [GJ/year],
- e_{carrier}: emission factor for the carrier [kg CO_2/GJ],
- γ_{green}: share of green gas [-] (only applicable to gas).

For gas consumption, the effective emission factor accounts for the share of green gas in the supply mix, reducing emissions proportionally.

Emission factors are obtained from system parameters and expressed in kg CO_2 per GJ of energy used. If necessary, emission factors are converted to consistent units before calculation.

Emission Carriers

Emissions are calculated separately for the following carriers:

- Electricity
- Natural gas (adjusted for green gas share)
- District heating

5.4.9. Overview of Model Outputs

Table 5.1 summarises the key outputs generated by the adapted CEKER model for non-residential service buildings. The outputs capture both investment- and operational-related metrics per building, including energy use, costs, subsidy impacts, and associated emissions.

Table 5.1: Summary of Model Outputs

Output	Description
Primary System Costs	Annualised CAPEX and OPEX for heating technologies per building
Secondary System Costs	Additional CAPEX and OPEX for Low-Temperature Adaptation Systems (LTAS)
Insulation Upgrade Costs	CAPEX and annualised costs for mandatory energy label improvements
Subsidy Amounts	Applied DUMAVA subsidies based on CAPEX and minimum label improvements
Heat Demand	Updated heating demand after insulation improvements
Energy Use	Annual energy use per carrier (electricity, gas, district heat) after applying system efficiencies
Operational Energy Costs	Annual variable and fixed energy costs per carrier (electricity, gas, heat)
CO_2 Emissions	Annual CO_2 emissions from operational energy use per energy carrier

5.5. Data Sources and Assumptions

This section outlines the primary datasets and assumptions used to adapt the CEKER model to the non-residential service building stock.

5.5.1. Enriched BAG as Building Stock Dataset

To support the adaptation of the CEKER model for the non-residential service sector, this study uses the *verrijkte BAG dataset* (Sipma, 2023). This enriched dataset was specifically developed to characterise the Dutch non-residential building stock for research purposes, providing detailed information at the individual building level.

A key advantage of the *verrijkte BAG dataset* is that it directly associates each building with indicative annual gas, electricity, and heat consumption values. These estimates are based on energy intensities (i.e., consumption per square metre) linked to building use functions, and further stratified by size class and energy label. The energy intensities originate from consolidated findings of previous studies on energy consumption in utility buildings (Sipma et al., 2024).

By multiplying these intensity figures with the corresponding gross floor area per building, an indicative annual consumption figure is obtained. This approach enables the model to derive building-specific energy demand profiles without needing additional assumptions or separate calculations for each building, as was necessary in the original CEKER model for residential buildings.

However, it is important to recognise the limitations of this method. The consumption figures are inherently indicative and involve considerable uncertainty at the individual building level, due to:

- Variations in operational patterns and occupancy within the same use category.
- Potential inaccuracies in recorded building characteristics (e.g., floor area, building use classifi-

cation).

- Aggregation effects: while individual building estimates are uncertain, aggregated results over larger samples are expected to approximate actual sector-level consumption more closely.

As a result, the adapted CEKER model inherits these underlying uncertainties. Model outputs should therefore be interpreted with caution, particularly when drawing conclusions about small subgroups or individual buildings. When results are aggregated across broader building categories, the reliability improves.

Besides using the enriched BAG dataset as primary input, limited preprocessing steps were performed to ensure the data was fit for use in the adapted CEKER model. Buildings were filtered based on dominant use functions, primary heating systems were inferred based on available data (construction year, energy label, and district heating connection), and outlier records were excluded. Key assumptions made during preprocessing are summarised in Appendix B.1.

5.5.2. Other Data Sources for Parameterisation

In addition to the enriched BAG dataset, several external data sources were used to adapt key parameters of the CEKER model to the non-residential service sector. These sources provided information on heating system characteristics, building insulation costs, energy tariffs, CO_2 emission factors, loan conditions, and heating demand improvements.

The following institutions and datasets were used:

- **Rijksdienst voor Ondernemend Nederland (RVO)**: technical and economic characteristics of heating technologies, insulation measures, and subsidies (e.g., DUMAVA).
- **Planbureau voor de Leefomgeving (PBL)**: energy tariff structures and tax rates for the non-residential sector, costs for upgrading envelope level.
- **Berenschot and TNO**: supplementary data on system costs, energy efficiencies, and building technologies.
- **Internal CE Delft Databases**: model-specific assumptions on financing conditions (e.g., discount rates), updated emission factors, heating system parameters, and projected energy prices.

5.6. Model Validation

In this validation, we examine the insulation costs, operational expenditures (OPEX), and investment costs of the heating system (CAPEX). An investment model tailored to specific cases of municipal utility buildings in Amsterdam was used for this comparison. These case studies originate from internal projects conducted by CE Delft, where detailed building-level analyses were performed. Thus, the underlying data stems from verified professional assessments and sector-specific experience.

Two building identifiers (`pandids`) were retrieved by matching addresses, allowing us to extract the corresponding entries from the enriched BAG dataset. These entries were then compared to the case-specific investment model outputs. The comparison results are shown in Figure 5.2.

As observed, the values align closely, indicating that, at least for these reference cases, the adapted

CEKER model provides reasonable and consistent cost estimations. This validation step supports the credibility of the CAPEX, OPEX, and insulation cost modelling approach used in the non-residential adaptation of the CEKER framework.

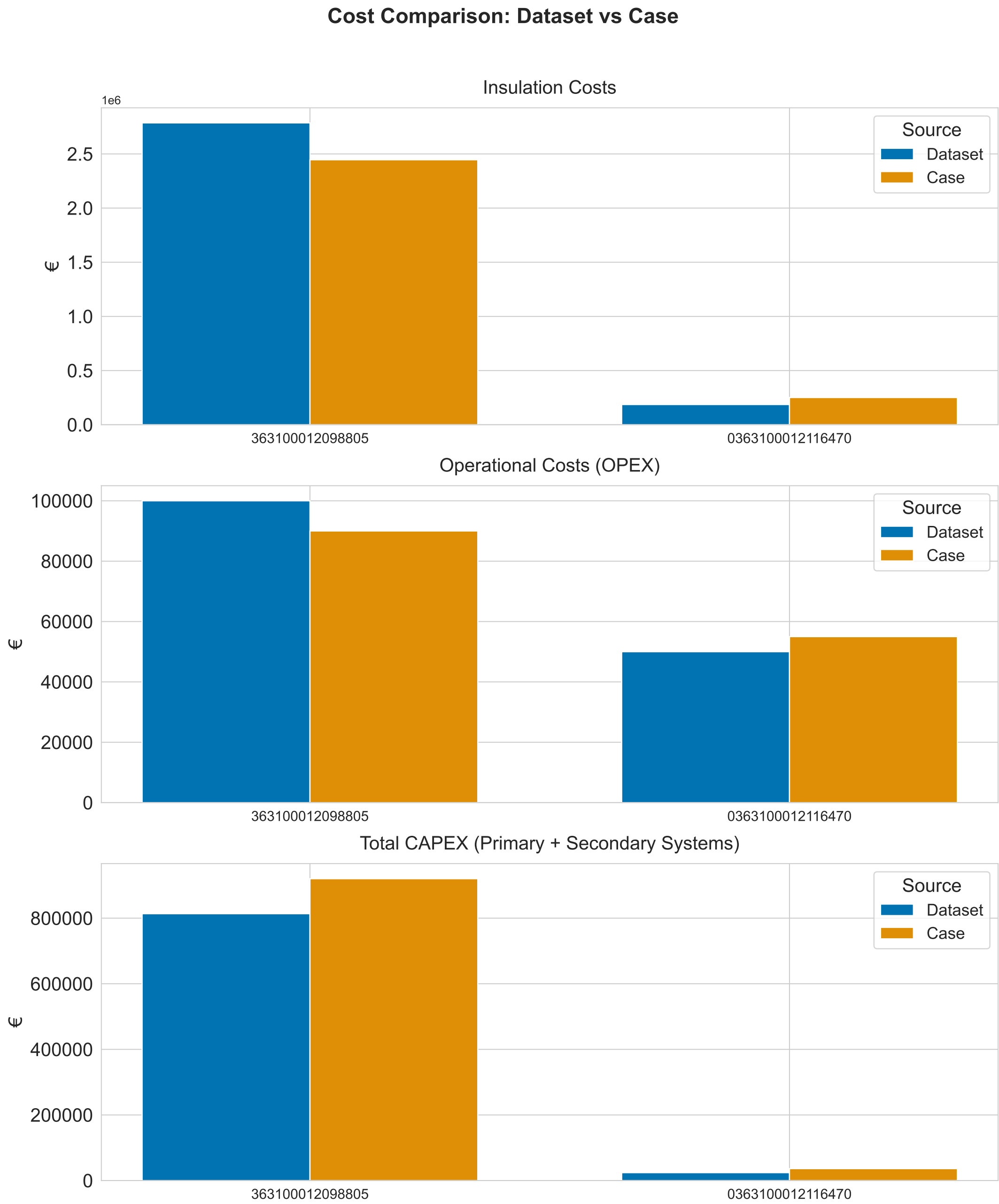

Figure 5.2: Verification of Distribution of Heating Solutions

5.7. Model Verification

To verify the internal consistency and logical functioning of the adapted CEKER model, an extreme-value test was conducted. In this test, energy carrier prices were artificially increased by a factor of 100 to observe whether the model's behaviour remains intuitive and plausible under extreme input conditions. Four verification scenarios were defined:

- **Base:** Reference scenario with standard 2030 energy prices.
- **GP-100X:** Gas price multiplied by 100.
- **EP-100X:** Electricity price multiplied by 100.
- **HP-100X:** District heat price multiplied by 100.

The verification results are shown in Figures 5.4 to 5.6.

First, when the gas price is multiplied by 100 (GP-100X), all gas-based heating solutions disappear from the building stock. This leads to a complete shift towards electric and district heating systems. Consequently, the model predicts the highest CO_2 emission reduction under this scenario, which is consistent with expectations.

Figure 5.3: Legend for Different Heating Solutions

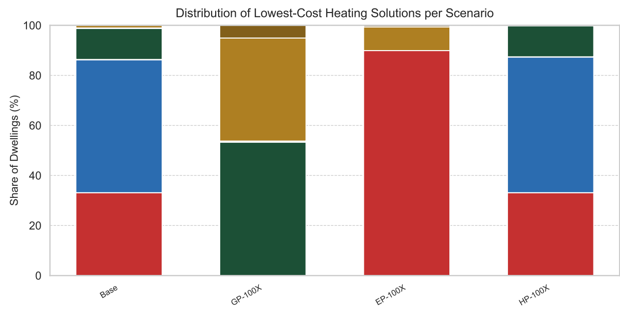

Figure 5.4: Verification of Distribution of Heating Solutions

Second, when the electricity price is multiplied by 100 (EP-100X), all electric heating technologies, including air-to-water and water-to-water heat pumps, disappear. The condensation boiler becomes the dominant heating technology. This technology shift results in substantially higher emissions compared to the base case. Moreover, the total yearly costs for buildings rise sharply. This is explained by the fact that, even though electricity is no longer used for space heating, it is still required for other purposes (e.g., appliances and ventilation), and the extreme electricity price inflates these operational costs.

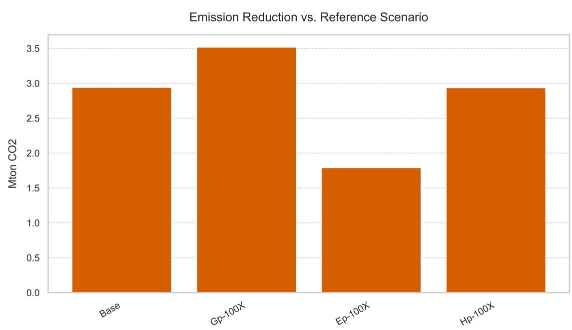

Figure 5.5: Verification of Emission Reductions

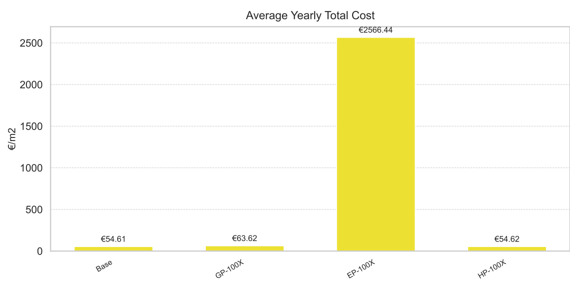

Figure 5.6: Verification of Average Yearly Costs

Third, when the district heat price is multiplied by 100 (HP-100X), all district heating-based solutions (heat exchangers) are eliminated. This shift away from district heating is also consistent with the model's cost-optimisation logic.

These verification results demonstrate that the model reacts logically and consistently to extreme changes in input parameters. The expected disappearance of specific heating technologies under prohibitively high price conditions, and the corresponding impacts on emissions and costs, provide strong evidence that the adapted CEKER model behaves correctly under stress conditions.

5.8. Sensitivity Analysis

5.8.1. Background on Sensitivity of Model Outcomes to Price Assumptions

Given that investment decisions in the CEKER model are based on rational cost optimisation at the building level, model outcomes are inherently sensitive to input price assumptions. In the current analysis, the base case gas, heat, and electricity prices reflect expected market conditions in 2030. However, the future evolution of energy prices is highly uncertain, and even modest deviations could shift the annual costs of different heating solutions, thereby influencing technology adoption and, consequently, emission outcomes.

For instance, a decline in electricity prices, possibly due to overcapacity in renewable production, might make fully electric systems such as air-to-water and water-to-water heat pumps more attractive relative to gas-based alternatives (Szekeres & Jeswiet, 2018). Conversely, unexpected gas price shocks, as seen during geopolitical tensions in 2022, may accelerate the transition regardless of policy interventions. Heat prices are largely tied to gas costs (Komorowska & Surma, 2024), meaning changes in gas pricing would also impact the attractiveness of district heating options.

Given this uncertainty, a sensitivity analysis is performed to test the robustness of model outcomes to variations in electricity and heat price trajectories. If significant sensitivities are identified, these will be incorporated into the main scenario design.

5.8.2. Results of the Sensitivity Analysis

To evaluate the model's robustness against energy price uncertainties, a sensitivity analysis was conducted on two key input variables: electricity price and heat (district heating) price. Five scenarios were modelled:

- **Base:** Reference scenario with 2030 energy price assumptions.
- **HP-50-U:** Heat price increased by 50%.
- **HP-50-D:** Heat price decreased by 50%.
- **EP-50-U:** Electricity price increased by 50%.
- **EP-50-D:** Electricity price decreased by 50%.

Impact on Heating Solution Selection

Figure 5.8 shows the distribution of lowest-cost heating solutions under each price scenario.

The results indicate that electricity prices have a significant influence on heating system selection:

- In EP-50-U (electricity price up), gas-based systems (e.g., condensation boilers and heat exchangers) become more attractive.

Figure 5.7: Legend for Different Heating Solutions

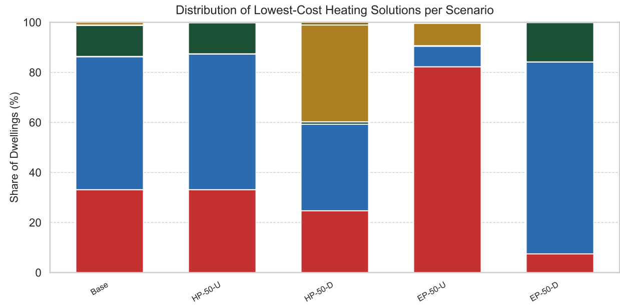

Figure 5.8: Distribution of Heating Solutions in the Sensitivity Analysis

- In EP-50-D (electricity price down), fully electric systems, particularly air-to-water and water-to-water heat pumps, dominate.

When heat prices are varied:

- A 50% increase in heat price (HP-50-U) makes heat exchangers less attractive, but otherwise has limited impact.
- A 50% decrease in heat price (HP-50-D) significantly increases the adoption of heat exchangers across the non-residential building stock.

Impact on CO_2 Emissions

These trends are further reflected in the CO_2 emission outcomes shown in Figure 5.9. A 50% increase in electricity prices (Scenario 3) results in a 28.1% rise in total emissions compared to the base case, driven by a shift back to more emission-intensive gas systems. Other price changes, particularly variations in heat prices, have only marginal impacts on overall emissions.

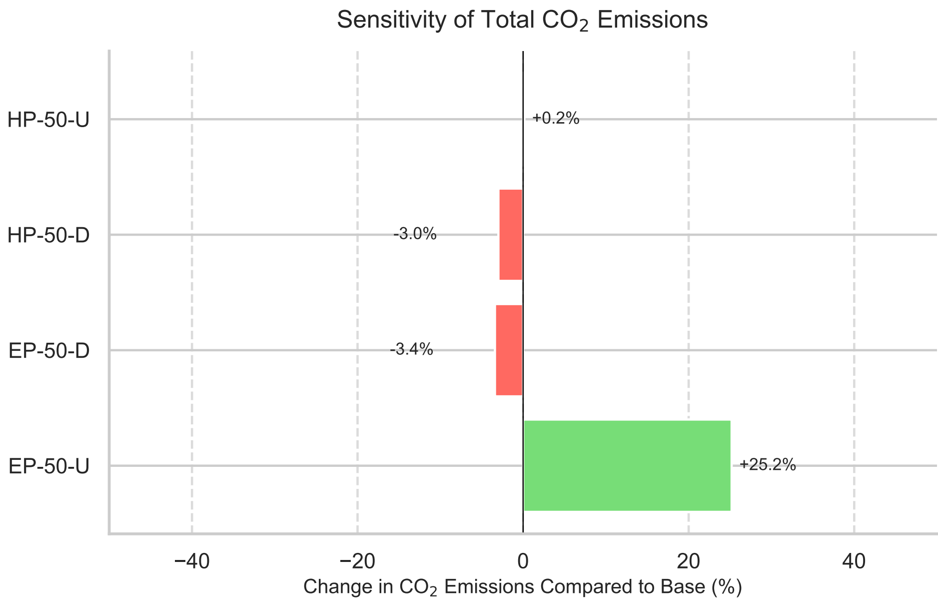

Figure 5.9: Emission Reduction in the Sensitivity Analysis

Impact on Total Costs

The cost analysis in Figure 5.10 confirms these observations:

- EP-50-U leads to a 26.9% increase in average total yearly costs per square metre.
- EP-50-D results in a 31.6% reduction in costs.
- Costs stay insensitive to Heat Price increase and decrease.

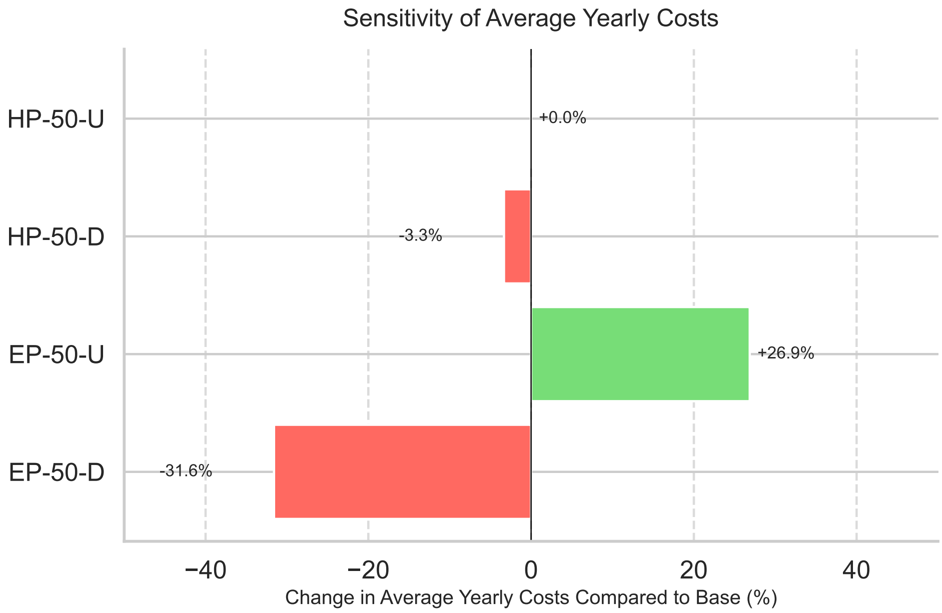

Figure 5.10: Change in Average Yearly Costs per Scenario (Sensitivity Analysis)

Sensitivity to electricity prices is significantly higher than to heat prices, which remain relatively stable across all scenarios. As seen in the Figure, in the Heat Price Scenario of 50%, the costs change by 0.02%.

This can be explained by the fact that in the base case, the adoption of heat exchangers is already limited. Consequently, even a significant increase or decrease in heat prices has only a marginal effect on the overall distribution of heating solutions. Since few buildings use district heating in the base case, the impact on both total costs and emissions remains small when heat prices are varied.

Implications for Scenario Development

Based on these findings, both a high and low electricity price variant are included in the main scenario analysis. This ensures that policy recommendations remain robust under different plausible energy market conditions and enhances the credibility of the final outcomes.

5.9. Limitations and Assumptions of the Adapted CEKER Model

While the adapted CEKER model enables detailed cost and emission estimations for non-residential service buildings, several methodological limitations and assumptions must be recognised:

5.9.1. Modelling Limitations

- **Static technology costs and performance:** Investment costs, operational expenditures, and system efficiencies are assumed static for the 2030 horizon. Future technological improvements or cost reductions are not dynamically modelled.
- **No technology adoption barriers:** It is assumed that all technically feasible heating solutions can be installed in any building. Practical barriers such as space constraints, permit issues, or network capacity are not included.
- **No dynamic energy supply modelling:** Electricity and heat emission factors are assumed fixed for 2030.
- **No phasing or gradual ramp-up:** Policy interventions (e.g., mandatory insulation upgrades) are assumed to be fully effective by 2030, without accounting for transition periods or policy ramp-up effects.

5.9.2. Key Assumptions

- **Rational decision-making:** Building owners are assumed to make cost-optimal investment decisions based on full lifecycle cost minimisation, without behavioural barriers.
- **Uniform financial conditions:** A fixed discount rate of 4.5% is applied to all buildings, based on expert consultations at CE Delft. No differentiation is made based on ownership type or financial health.
- **Subsidy application:** It is assumed that all eligible buildings correctly apply and receive subsidies (e.g., DUMAVA) without administrative delays or budget limitations.
- **Energy tariffs and taxes:** Future energy prices are modelled deterministically based on central 2030 estimates, with tiered tax structures implemented for gas and electricity.

These limitations and assumptions are important to consider when interpreting the model outcomes. They reflect a deliberate trade-off between model detail, data availability, and analytical tractability within the scope of this thesis.

A more detailed discussion of how these limitations affect the interpretation of model outcomes is provided in Section 8.4.

6
Experiment Design

6.1. Introduction

This chapter outlines the design of the policy intervention scenarios modelled in this study. The experiments aim to explore how different economic and regulatory instruments influence the adoption of sustainable heating technologies, CO_2 emission reductions, and end-user costs within the Dutch non-residential service building sector.

The selection of interventions—namely, increases in energy taxation, mandatory energy performance standards, and a gas connection ban—is grounded in theoretical and empirical considerations discussed in Section 4.4. These interventions target key investment barriers identified in the literature and reflect a combination of market-based incentives and regulatory measures.

Each scenario operationalises specific adjustments to gas prices, building energy performance requirements, or available heating technologies, as detailed below. The results of these experiments are presented and analysed in Chapter 7.

6.2. Policy Scenarios

To assess the impact of different policy interventions on the decarbonisation of the non-residential building sector, a set of policy scenarios has been developed. These scenarios vary along two primary dimensions: economic interventions (gas price increases) and regulatory interventions (mandatory energy label requirements or a gas ban). Table 6.1 provides an overview of the scenarios modelled. Each scenario is compared to a base case without additional policy interventions.

Table 6.1: Overview of Policy Scenarios Modelled

Scenario	Gas Price Adjustment	Energy Label Requirement	Gas Ban
Base	No Adjustment	None	No
G100	+100%	None	No
G200	+200%	None	No
BAN	No Adjustment	None	Yes
LD	No Adjustment	Label D	No
LA	No Adjustment	Label A	No
G100+LD	+100%	Label D	No
G100+LA	+100%	Label A	No
G200+LD	+200%	Label D	No
G200+LA	+200%	Label A	No
BAN+LD	No Adjustment	Label D	Yes
BAN+LA	No Adjustment	Label A	Yes

6.2.1. Gas Price Increase Scenarios

In the pricing-based scenarios, we simulate policy interventions that discourage the use of natural gas by raising its cost through increased energy taxes. Specifically, we model gas price increases of +100% and +200% relative to the baseline 2030 tariffs, applied uniformly across all five consumption zones of the Dutch energy taxation system (Vattenfall, 2025). These two levels were selected to represent moderate and high gas price futures, respectively, allowing us to assess the (rational) behavioural sensitivity of building owners to varying price signals.

Historical developments during the European energy crisis of 2021–2022, when natural gas prices surged to multiple times their previous levels, underscore the plausibility of such price trajectories (IEA, 2022; Trading Economics, 2022). By covering this range, the study captures both realistic medium-term adjustments and more extreme high-price scenarios. It should be noted, however, that applying uniform multipliers across all tax brackets simplifies the complex structure of real-world energy taxation and may affect the interpretation of distributional impacts (see Section 8.4).

6.2.2. Gas Ban Scenarios

In the gas ban scenarios, a regulatory intervention prohibits any new investments in gas-based heating technologies. Under these conditions, building owners are constrained to select alternative heating solutions, such as electric heat pumps or heat exchangers. The gas ban represents a stricter policy approach compared to pricing instruments: rather than altering relative cost incentives, it removes gas heating as an option entirely. Although a full gas ban may be less feasible politically in the short term, it is analytically valuable to assess its effects on system costs, technology choice, and emission reductions, especially given that extreme gas price increases would ultimately converge toward similar outcomes in technology selection.

6.2.3. Mandatory Energy Label Scenarios

The mandatory energy label scenarios introduce minimum energy performance requirements for buildings, set at either Label D or Label A. These thresholds were selected in consultation with CE Delft experts based on their relevance to the technical feasibility of sustainable heating systems.

Specifically, Energy Label D corresponds to the minimum insulation level required for the cost-effective deployment of medium-temperature heat exchangers, while Energy Label A reflects the insulation quality necessary for the efficient application of all-electric heat pump systems. These thresholds also align with the definitions of 'minimal insulation' (Label D) and 'maximum insulation' (Label A) as used in the construction of heating solution packages in Section 7.2.

By mandating minimum energy performance levels, these scenarios seek to address structural barriers to deep decarbonisation, ensuring that building envelope quality does not become a bottleneck for the adoption of sustainable heating technologies.

6.3. Base Case

The *base case* serves as the comparative benchmark for evaluating the policy scenarios. In the base case, only existing policies are considered; no additional interventions, such as increased energy taxation, mandatory energy performance standards, or gas bans, are introduced to influence investment decisions in the non-residential service building stock.

Investment behaviour is modelled around natural replacement moments, occurring when the economic lifespan of a heating system ends. At these decision points, the CEKER model identifies the cost-optimal heating solution available to the building owner, based on prices projected for 2030. Building owners thus retain the freedom to reinvest in gas-based technologies—such as high-efficiency gas boilers—if these remain the economically most attractive options.

The base case therefore represents a *techno-economic upper bound* of achievable emission reductions under the current policy environment: it reflects the maximum decarbonisation potential that rational building owners could reach if acting solely on economic incentives and available technologies, without the influence of new policy interventions. More on the theoretical foundation of this techno-economic modelling approach and the upper bound concept can be found in Sections 2.2.3 and 3.5.

6.4. Electricity Price Sensitivity Variants

As established in the sensitivity analysis (Section 5.8), the CEKER model exhibits sensitivity to variations in electricity prices. Since most sustainable heating solutions, particularly all-electric heat pumps, depend heavily on electricity consumption, fluctuations in electricity prices have a substantial impact on costs and therefore also technology selection.

To ensure robustness of the policy evaluation across plausible future energy price conditions, all policy scenarios listed in Table 6.1 are modelled under three electricity price assumptions:

- **Base electricity price:** The expected 2030 electricity price level under central market projections.
- **High electricity price:** A +50% increase relative to the base case electricity price, reflecting tighter electricity markets or higher taxation.
- **Low electricity price:** A −50% decrease relative to the base case electricity price, reflecting overcapacity of renewables or lower market prices.

These three price variants allow the analysis to capture the full range of potential vulnerabilities or shifts in the cost-effectiveness and adoption of different heating technologies if electricity becomes substantially cheaper or more expensive. By systematically applying all variants across all policy scenarios, the experiment design ensures that conclusions regarding the effectiveness, cost-effectiveness, and distributional impacts of interventions are robust across different plausible energy futures.

7
Results

7.1. Introduction

This chapter presents the outcomes of the scenario analysis based on the extended CEKER model. The aim is to systematically assess the effect of various policy interventions on CO_2 emissions in the non-residential service sector, while also evaluating their impact on end-user costs. In doing so, this chapter answers the second sub-question of this study:

"How do the policy interventions affect CO_2 emission reduction and end-user costs, and how do those impacts vary by building type and size?"

The analysis is based on the assumption that the year 2030 marks a natural investment moment for building owners whose heating systems have reached the end of their technical lifespan. In line with rational choice theory, the model simulates which heating solution would be selected as the lowest-cost option for each building, given the applicable policy conditions. This generates insights into cost-optimising behaviour under different interventions. Importantly, the model does not predict actual adoption patterns, but provides insights for evaluating scenario outcomes based on economic rationality.

As highlighted in Chapter 2 and 3, real-world investment decisions are influenced by a range of behavioural, organisational and institutional factors. Therefore, the results in this chapter should be interpreted as indicative rather than predictive, offering a structured basis for comparing the relative direction and magnitude of policy effects under idealised assumptions.

To analyse the policy interventions systematically, the results are structured along three analytical dimensions:

1. **Adoption potential and emissions:** identifying the distribution of lowest-cost heating solutions and their effect on CO_2 emissions;
2. **End-user costs:** assessing annualised financial impacts from the building owner's perspective;

3. **Sector-specific variation:** analysing outcome differences by building type and size.

The policy scenarios considered in this study are described in Chapter 6, and include both single-instrument and combined-instrument designs.

The **base case** assumes that all building owners make fully rational, cost-minimising investment decisions at the moment their current heating system reaches the end of its technical lifetime. This scenario incorporates currently active policies, as discussed in Chapter 5 and represents the techno-economic upper bound on CO_2 reductions under existing policy conditions (See Section 3.5 for a more detailed discussion).

All **subsequent scenarios** build upon this base case by introducing additional policy instruments, including higher energy taxes and regulatory mandates. The aim is to expand the techno-economic potential of the base case through more ambitious policy intervention. These scenarios therefore represent alternative futures that test the capacity of specific instruments to further reduce emissions and costs beyond what is achievable under current policies alone.

The chapter is organised as follows:

- **Section 7.2** presents the selected heating technologies under purely rational decision-making, providing insight into cost-optimal adoption patterns;
- **Section 7.3** quantifies CO_2 emission reduction compared to the base case;
- **Section 7.4** evaluates end-user costs, including cost-effectiveness in €/ton CO_2;
- **Section 7.5 and 7.6** explore sector-specific differences by building type and size, highlighting potential distributional and targeting implications.

7.2. Distribution of Heating Solutions

In Figure 7.2 on the left side, the distribution of heating solutions can be seen as a percentage of the total buildings, per scenario. On the right the distribution of heating solutions can be seen as a percentage of the total area. In Figure 7.1, a legend for Figure 7.2 is provided.

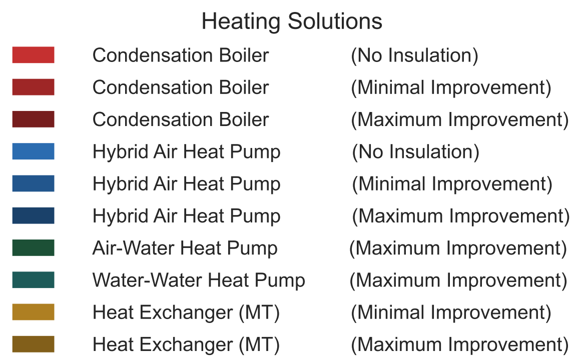

Figure 7.1: Legend for Different Heating Solutions

In the base case (Base), the market heavily favours gas-based solutions: condensation boilers dominate around 35% of buildings. Hybrid air heat pumps without insulation also cover a large portion,

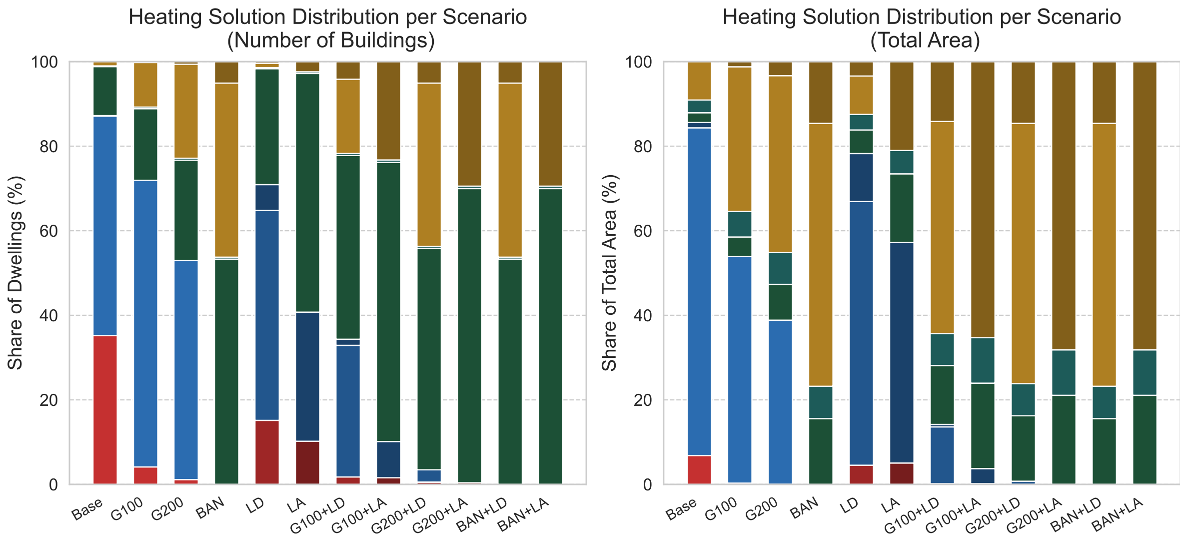

Figure 7.2: Distribution of Lowest-Cost Heating Solution per Scenario

especially in terms of area, suggesting larger buildings tend to favour this option.

As gas prices increase there's a clear transition away from condensation boilers. The Hybrid Air Heat Pump decreases a little but is still widely adopted under an increased energy tax price on gas. The Air-Water Heat Pump and the Heat Exchanger increase by a lot under a higher gas price, and make up for 50-60% when gas prices increase. The Water-Water Heat Pump also increases to 10% of the total area and is probably only adopted by buildings of the highest size, since the Water-Water Heat Pump is hardly to be seen in the first graph on the left (share of dwellings).

Under regulatory scenarios, banning gas investments (BAN) or mandating minimum energy labels (LD and LA), we see even sharper transitions. Banning new investments in gas-based heating technologies enforces a full shift to heat pumps and MT heat exchangers, where for half of the building owners, the air-water heat pump would be the most cost-attractive option, and for the other half, the heat exchanger (district heating connection) would be the most cost-attractive option.

If we combine these policy interventions, we can see a total shift towards sustainable heating solutions. Only in the G100+LD scenario, the gas-based heating solutions remain the most cost-attractive option for a small percentage of building owners.

High and Low electricity price Scenarios

Figure 7.3 shows the distribution of lowest-cost heating solutions across several policy scenarios under the assumption of high electricity prices. In the base case scenario, condensation boilers clearly dominate, with approximately 85% of building owners still opting for this technology. An additional 5% choose hybrid air heat pumps, meaning that around 90% of owners favour gas-based solutions when electricity is expensive. When looking at the distribution of heating solutions in terms of the share of total area, we can see that 10% of the building owners prefer a heat exchanger (district heating), while they make up 40% of the total area.

However, when the gas price is increased through energy taxation, there is a sharp decline in the

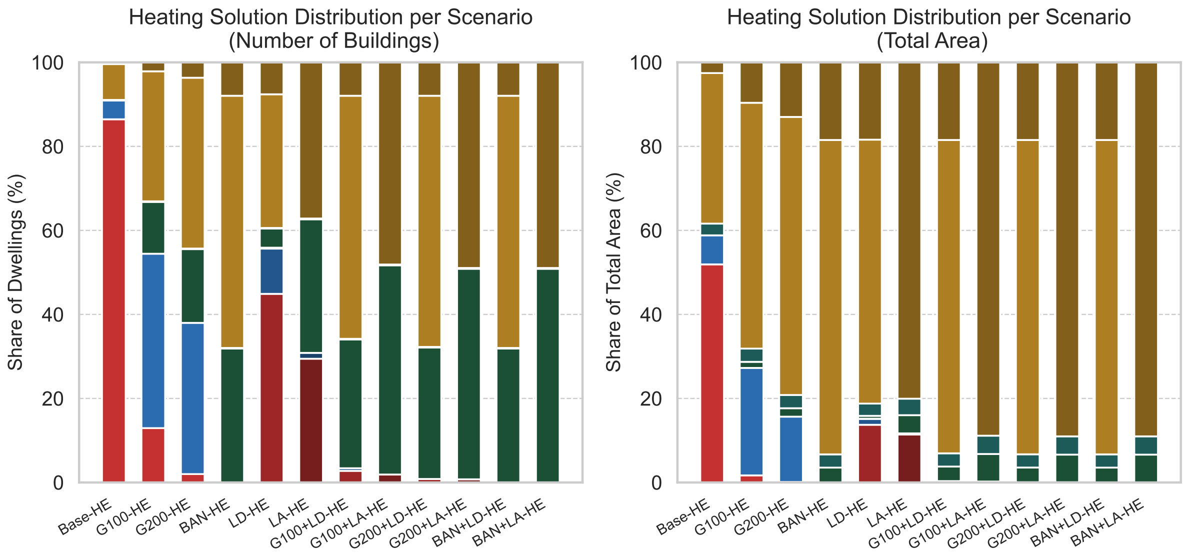

Figure 7.3: Distribution of Lowest-Cost Heating Solution per Scenario (High Electricity Price Scenario)

cost-effectiveness of gas-based solutions. As reflected in Figure 7.3, gas technologies become less attractive, with adoption rates falling to approximately 40–50%, indicating a shift toward more hybrid configurations.

Even under more stringent building requirements, such as mandatory minimum energy labels D or A, a significant portion—between 30% and 50%—of building owners still prefer gas-based heating systems. This suggests that gas technologies remain financially attractive despite regulatory efforts.

Interestingly, when examining the total heated area of the non-residential service building stock, district heating solutions (via heat exchangers) appear dominant across all policy configurations under high electricity price assumptions. This outcome, visible in Figure 7.3, is driven by a combination of high electricity and gas prices, which render heat supply from external networks more economically attractive. However, as discussed in Section 8.4, this assumption could be questioned in real-world settings, where heat prices are often indirectly linked to gas prices.

In contrast, the low electricity price scenario (illustrated in Figure 7.4) shows a different pattern. Gas-based technologies still feature prominently, but their composition changes. The hybrid air heat pump becomes substantially more attractive than the condensation boiler seen in the high-price scenario. In this case, even with increased gas taxation, the hybrid air heat pump maintains its position as the most cost-attractive option for 60–80% of building owners.

When minimum energy labels are mandated in the low electricity scenario, there is no significant shift in preferred heating technologies. Hybrid air heat pumps remain dominant, with regulatory interventions primarily leading to upgrades in building envelope performance rather than heating system changes.

Finally, when multiple policy instruments are combined, non-gas-based technologies begin to gain ground. As shown in Figure 7.4, district heating becomes the most attractive option for larger buildings, while air-water heat pumps emerge as the preferred choice for smaller ones.

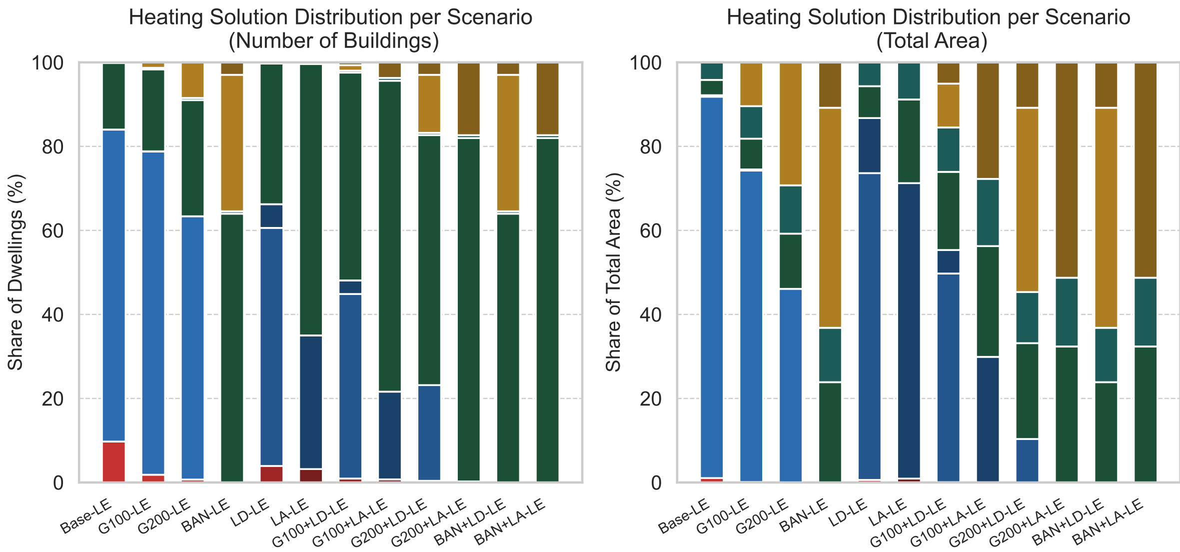

Figure 7.4: Distribution of Lowest-Cost Heating Solution per Scenario (Low Electricity Price Scenario)

Key Insights: Distribution of Heating Solutions

- **Gas-based heating dominates the base case:** In the standard scenario, gas-based solutions—condensation boilers and hybrid air heat pumps—remain the most cost-attractive for a large share of building owners, particularly in smaller buildings.
- **Raising gas prices shifts adoption patterns:** Introducing an energy tax on gas leads to a noticeable shift towards more sustainable heating technologies, including air-water heat pumps and district heating. This indicates that economic levers can effectively influence (rational) technology choice.
- **Combined policy interventions are most transformative:** When economic and regulatory measures are combined, a near-complete transition to sustainable heating technologies occurs. Only in marginal cases (e.g., G100+LD), gas solutions remain cost-attractive.
- **Electricity price strongly affects technology preferences:** In high electricity price scenarios, gas-based options are overwhelmingly favoured in the base case (~90%). Raising the gas price in such futures produces stronger behavioural shifts compared to low electricity price scenarios.
- **District heating becomes attractive in high-cost futures:** When both gas and electricity are expensive, district heating becomes the lowest-cost option for many building owners, especially for large buildings. However, this assumes a heat price decoupled from gas, which may not fully reflect real-world conditions.

7.3. Emission Reduction

In Figure 7.5, the emission reduction per scenario is compared to the emission reduction in the base case. As stated in the introduction of this Chapter, the base case is used as a starting point, where the effect of policy interventions is evaluated. This base case serves as the techno-economic upper bound under which active policy interventions would achieve a certain emission reduction. This techno-economic optimum is expanded by adding increasingly ambitious policy interventions, thus increasing the potential for CO_2 reduction.

Interestingly, even in the absence of additional policy interventions, the base case scenario already results in an emission reduction of 2.8 Mton CO_2 per year, as shown in Figure C.1 in Appendix C. This outcome reflects what is theoretically achievable under the assumption that all building owners make strictly cost-optimal investment decisions based on techno-economic parameters. In other words, it represents a level of emission reduction that could be achieved through purely market-driven behaviour, without the need for further regulatory incentives. However, as discussed in Section 8.4, this assumes a degree of rationality, perfect information, and zero behavioural or institutional barriers, conditions which are rarely met in real-world decision-making environments. As such, this base case serves more as a theoretical benchmark than a realistic policy-free pathway.

As we've seen in Section 7.2, more sustainable heating solutions are adopted when the gas price increases or regulatory measures are implemented. There is a direct cause-and-effect relationship here: when more sustainable heating solutions are adopted, the emission reduction in the building stock increases. The highest emission reductions achieved occur with a mandatory energy label A, combined with a gas price increase.

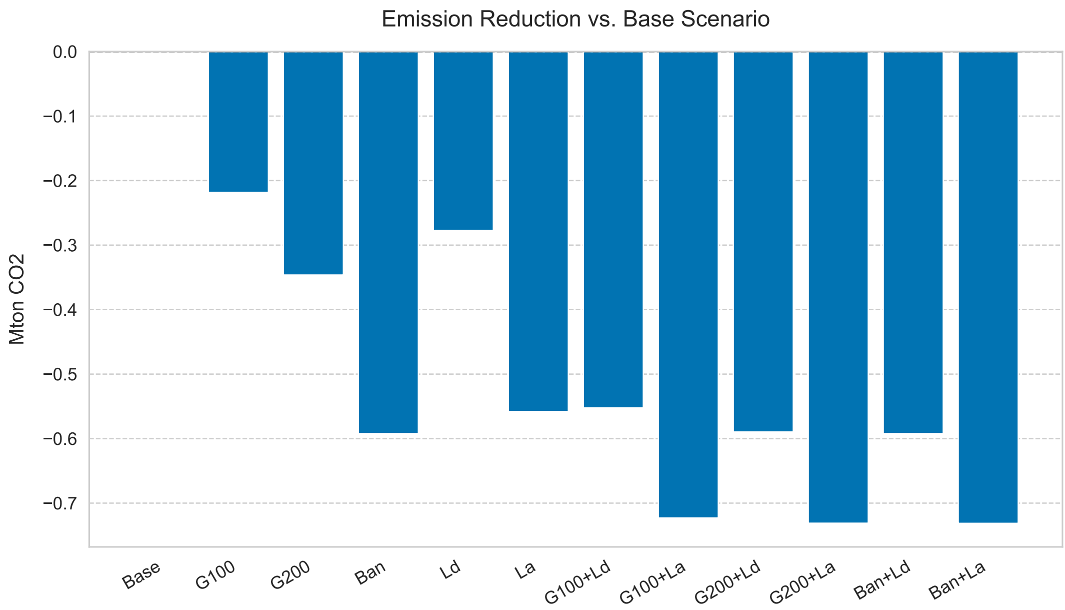

Figure 7.5: Total Annual Emission Reduction Compared to the Base Case

High and Low electricity price Scenarios

In Figure 7.6, the annual emission reduction per policy intervention scenario is compared against the base case, in the future scenario where the electricity price has increased by 50%. We can see that in a future where electricity prices are high, raising the gas price has an immediate and significant effect on emission reductions in the sector. This is due to the base case, where, in this future scenario, the condensation boiler is seen as the most cost-attractive heating technology by 85% of building owners (Section 7.2). Behaviour compared to the effects of policy interventions on reductions remains the same for all scenarios. The difference is in the magnitude of these reductions. You could say that

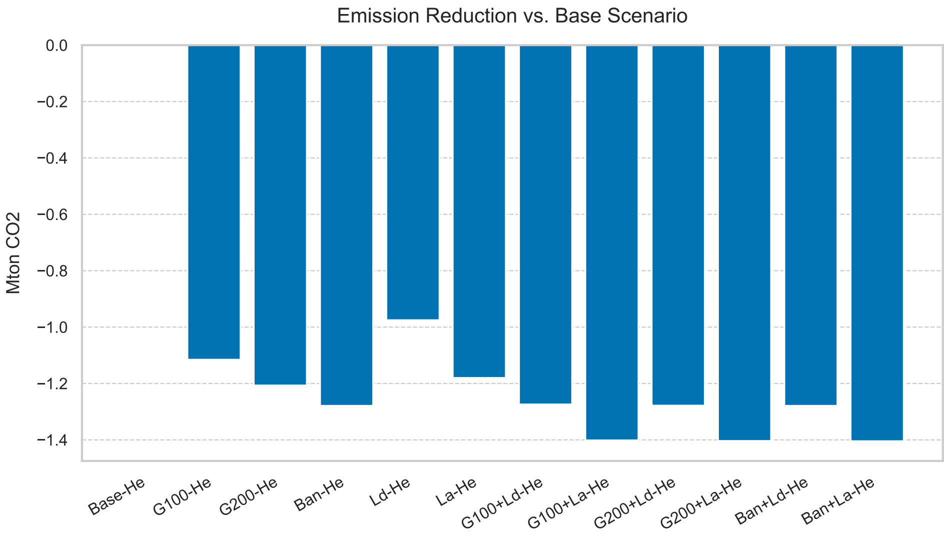

Figure 7.6: Total Annual Emission Reduction Compared to the Base Case (High Electricity Price Scenario)

when electricity prices are high in the future, raising the gas price would already have a significant effect on the cost-attractiveness of gas-based heating solutions and therefore emissions in the sector. In Figure 7.7, the future scenario where electricity prices are 50% lower than the expected electricity price in 2030 can be seen. These emission reductions have been compared with the base case, where

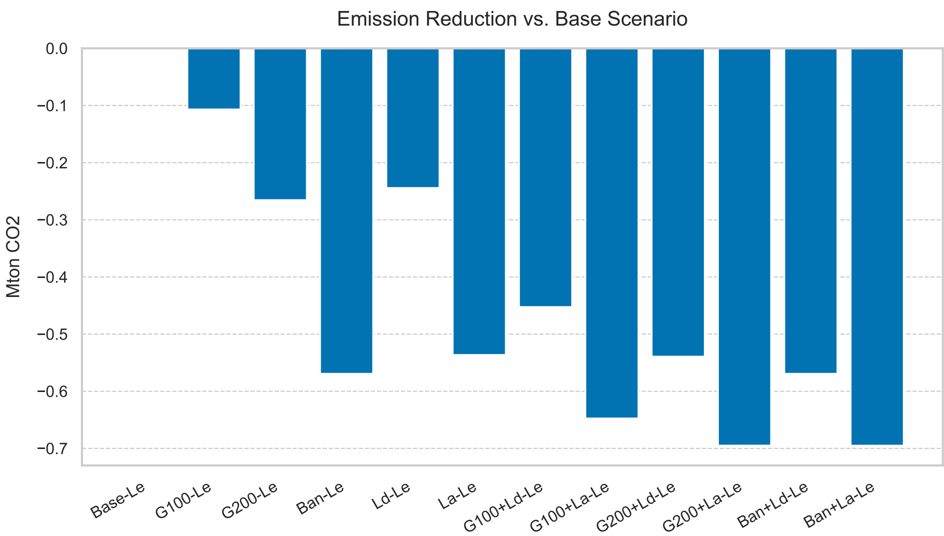

Figure 7.7: Total Annual Emission Reduction Compared to the Base Case (Low Electricity Price Scenario)

the hybrid air heat pump is adopted by 80% of building owners (Section 7.2). This is still a partially gas-based heating technology, but already a lot less polluting than a condensation boiler. This explains why the emission reductions are lower compared to the high electricity price future scenario. Raising the gas price would only increase the emission reduction by 0.1-0.3 Mton of CO_2, compared to 1.1-1.2 Mton in the high electricity price scenario. The same holds true for the standard expected electricity price scenario, where raising the energy price is more effective than in the low electricity price scenario. Combined policy interventions only differ by around 0.05 Mton CO_2, compared to the standard electricity price scenario, meaning that these interventions hold the same effectiveness in different future electricity price scenarios.

Key Insights: Emission Reduction

- **Emission reduction increases with policy ambition:** Scenarios that combine higher gas prices with more stringent energy label mandates (e.g., Label A) result in the highest CO_2 emission reductions. This confirms the additive effect of combining regulatory and economic interventions.
- **Gas price as effective lever:** Raising the gas price proves to be a highly effective policy tool for encouraging the adoption of sustainable heating technologies, especially under conditions where electricity prices are high.
- **Electricity price sensitivity influences baseline behaviour:** In the high electricity price scenario, most building owners default to gas-based solutions, leading to higher emission reduction potential when gas prices are increased. In contrast, when electricity is cheap, cleaner technologies like the hybrid heat pump become attractive by default, reducing the marginal impact of additional policy measures.
- **Consistent relative behaviour across scenarios:** The ranking of policy scenarios in terms of effectiveness remains stable across different electricity price assumptions. While the absolute emission reductions vary, the relative performance of interventions is robust to future energy price uncertainty.
- **Policy robustness under uncertainty:** Combined policy interventions (e.g., Label A + Gas Tax) maintain high effectiveness across all electricity price scenarios. This suggests that such bundles are robust options for long-term planning, irrespective of uncertain energy price developments.

7.4. End-User Costs

In Figure 7.8, the total average yearly costs per square meter are presented. This metric serves as a comparison of the overall costs for all combined end-users in the non-residential service sector, allowing us to evaluate the effects of policy interventions on both CAPEX and OPEX. By standardising these costs (dividing them by the total area in m^2), we can effectively compare the different scenarios.

The yearly costs per square meter are broken down into two categories: OPEX (operational expenditures), which includes energy costs and maintenance expenses, and CAPEX (capital expenditures), which represents the annualized investment cost spread over the technology's lifecycle.

A key observation is that OPEX consistently accounts for a much larger proportion of the total costs compared to CAPEX in all scenarios. Additionally, end-user costs tend to rise when gas prices increase or when stricter energy efficiency standards (higher energy labels) are enforced.

Another interesting insight emerges when we look at the proportional relationship between CAPEX and OPEX. As gas prices rise or higher energy labels are mandated, the relative weight of OPEX decreases, while the weight of CAPEX increases. This shift indicates that energy and maintenance costs (OPEX) are becoming less influential on the overall yearly costs, whereas investment costs (CAPEX) are on the rise, leading to an increase in total combined costs.

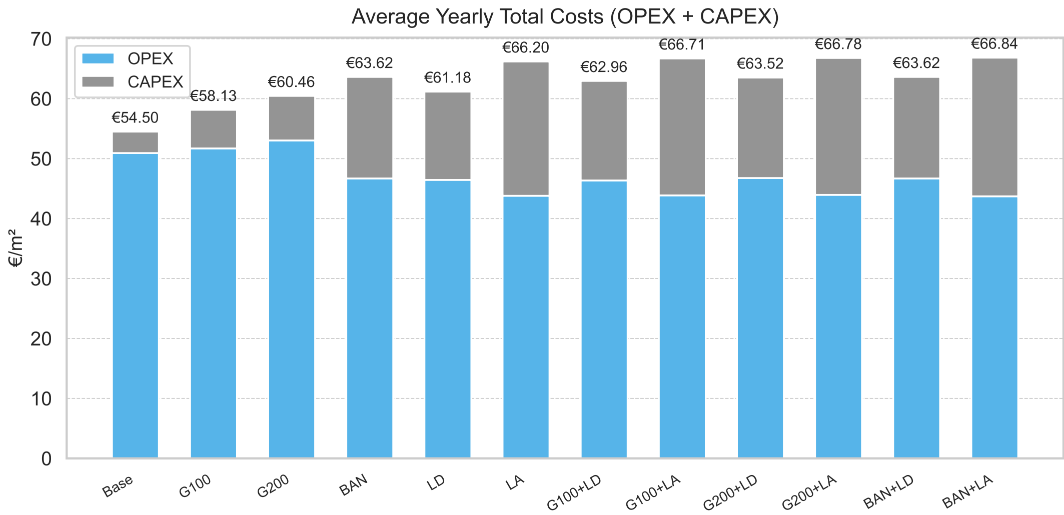

Figure 7.8: Average Yearly Total Costs

For policymakers, this presents a valuable takeaway: energy prices have a more significant impact on overall yearly costs than investment costs (CAPEX). By providing subsidies for specific heating technologies, governments could counterbalance the increasing annual CAPEX costs. This approach could help reduce total and combined end-user costs, making the transition to alternative heating solutions more appealing and accessible for building owners.

High and Low Electricity Price Scenarios

In Figure 7.9, the average yearly costs per square meter for a future scenario where electricity prices are 50% higher than the expected electricity price can be seen.

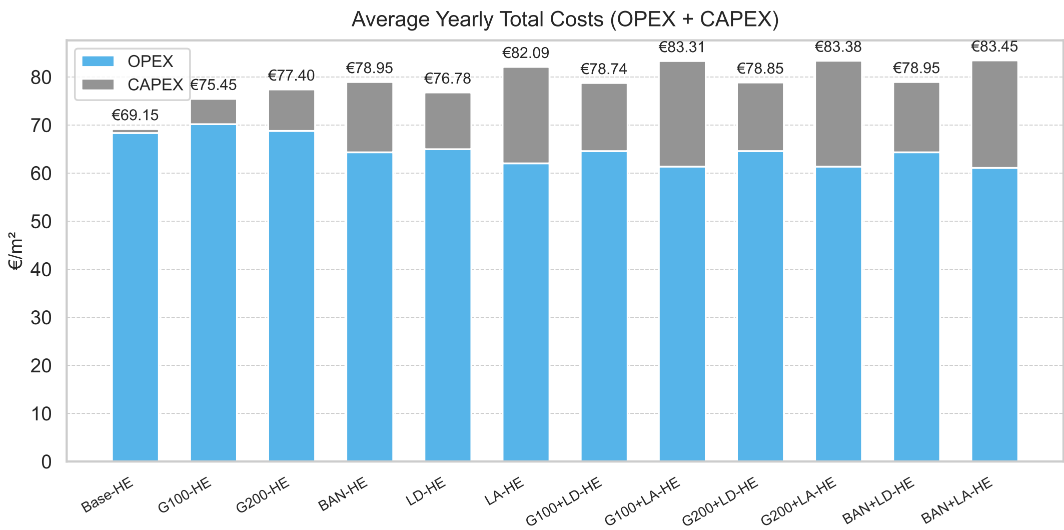

Figure 7.9: Average Yearly Total Costs (High Electricity Price Scenario)

What stands out is that, as was expected beforehand, the OPEX increases in price, while CAPEX stays the same. This increase in OPEX creates a higher overall price for end-users, where the transition to sustainable energy technologies is more expensive than in a lower electricity price scenario. In

Figure 7.10, the average yearly costs per square meter for a future scenario where electricity prices are 50% lower than the expected electricity price, can be seen.

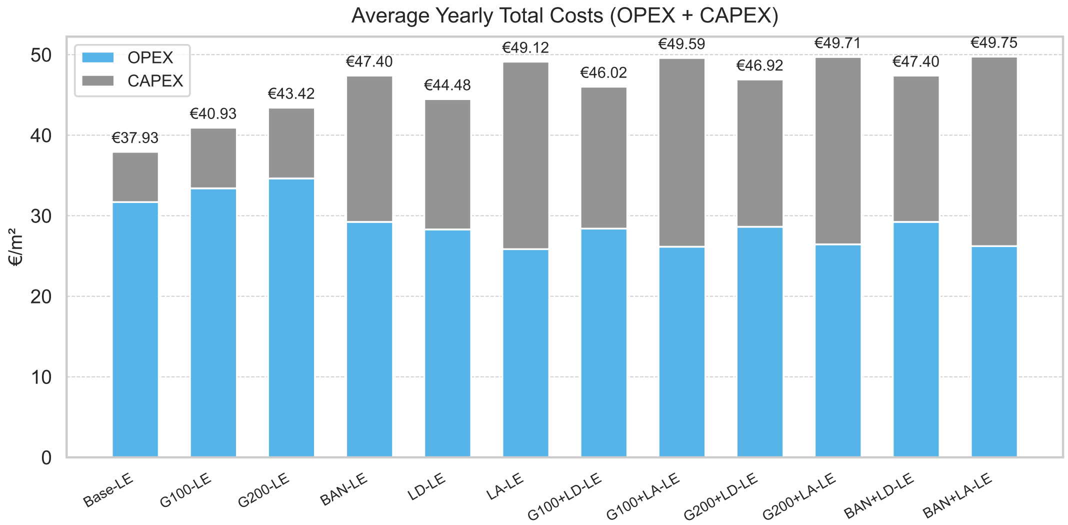

Figure 7.10: Average Yearly Total Costs (Low Electricity Price Scenario)

In some policy scenarios (e.g. G100+LD or G100+LA), annualised CAPEX accounts for half of the total costs the building owner bears. This means that policies that would alleviate annualised CAPEX, such as specific subsidies for heating solutions, could greatly reduce the overall end-user costs of building owners in this sector.

Key Insights: End-User Costs

- **OPEX dominates total yearly costs:** In all scenarios, operational expenditures (including energy costs) account for the majority of total yearly costs. This indicates that policies affecting energy prices can have a substantial effect on affordability.
- **Policy interventions increase total costs:** Stricter energy label mandates and higher gas prices lead to an increase in total yearly costs per m². These policies shift the cost balance from OPEX toward CAPEX, especially in scenarios involving deep retrofits.
- **CAPEX share increases under ambitious policies:** In scenarios with higher ambition levels (e.g., Energy Label A + Gas Tax), CAPEX can make up nearly two-thirds of yearly costs (or half of total yearly costs for low electricity price scenarios). This underlines the importance of addressing upfront investment costs in the decision-making process of building owners, a barrier discussed in Section 2.2
- **Electricity price sensitivity:** High electricity price scenarios result in higher OPEX, especially in scenarios relying on electrification (e.g., heat pumps). This implies that energy price trajectories strongly affect the economic feasibility of decarbonisation strategies.
- **Role for CAPEX-focused policy instruments:** In both high and low electricity price scenarios, targeted financial instruments that reduce annualised CAPEX, such as technology-specific subsidies or low-interest financing, can reduce total end-user costs and enhance the economic attractiveness of sustainable heating solutions.

Cost-Effectiveness

The cost-effectiveness results are seen in Figure 7.11 and expressed in €/ton CO_2, reflecting the additional annual costs and corresponding CO_2 emission reductions relative to the base case. For the detailed methodology and formula, refer to Section 3.5. We observe that:

- The most cost-effective policy intervention is raising the gas price through an energy tax. However, it is the least effective in terms of emissions reduction, achieving only 0̃.2 Mton CO_2 to 0̃.3 Mton CO_2 (as shown in Section 7.3).
- Mandating minimal Energy Labels, when implemented in isolation, proves to be the least cost-effective policy intervention, due to relatively low emission reductions and high associated costs.
- A combination of mandating energy labels alongside raising the energy tax results in significantly higher CO_2 emission reductions, while costs remain moderate. The policy combinations G100+LD, G200+LD, and BAN+LD stand out as the most cost-effective interventions in comparison to others or their combinations.

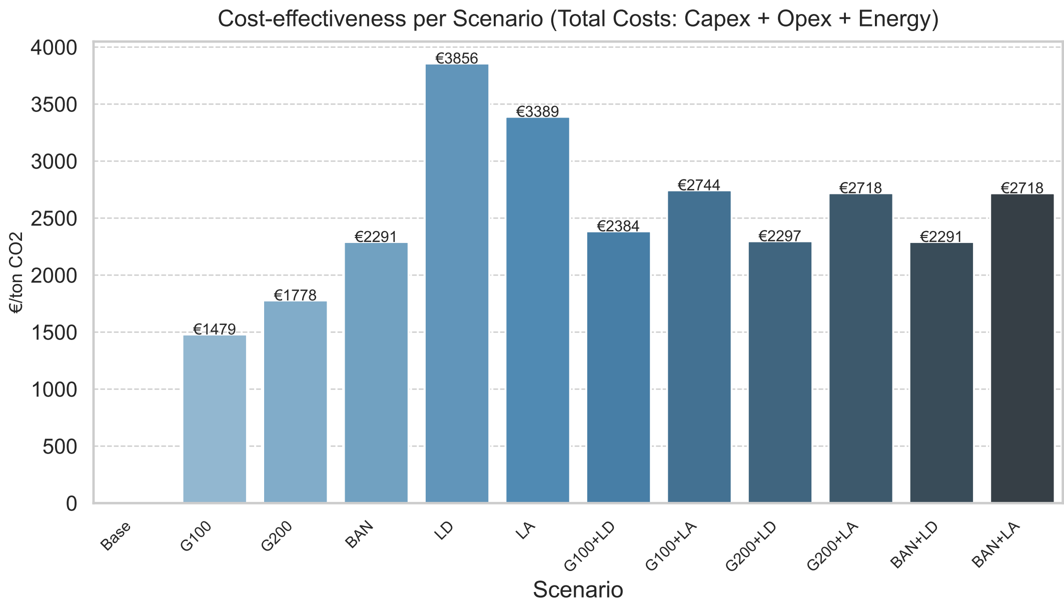

Figure 7.11: Cost-Effectiveness of different Scenarios

Key Insights: Cost-Effectiveness

- Raising the Gas Price through an Energy Tax alone is the most cost-effective intervention in terms of emissions reduction cost per ton.
- Mandating Energy Labels in isolation is the least cost-effective policy, given its relatively high cost per ton of CO_2 reduced.
- Combining policy measures, such as mandating energy labels with an energy tax increase, strikes a balance between increased emission reductions and moderate costs, offering a more cost-effective solution than gas price increases alone.

7.5. Sector-Specific Impact by Building Function

To derive more targeted policy recommendations, we examine the distribution of buildings and their floor area across different user functions and size classes. Understanding this distribution allows for a more precise assessment of where CO_2 emissions and end-user costs are concentrated, which ultimately aids in designing focused policies that address sector-specific challenges and opportunities. Figures 7.12, 7.13, and 7.14 provide a detailed breakdown of the current non-residential building stock in terms of functional use and size class, both in terms of building count and total floor area.

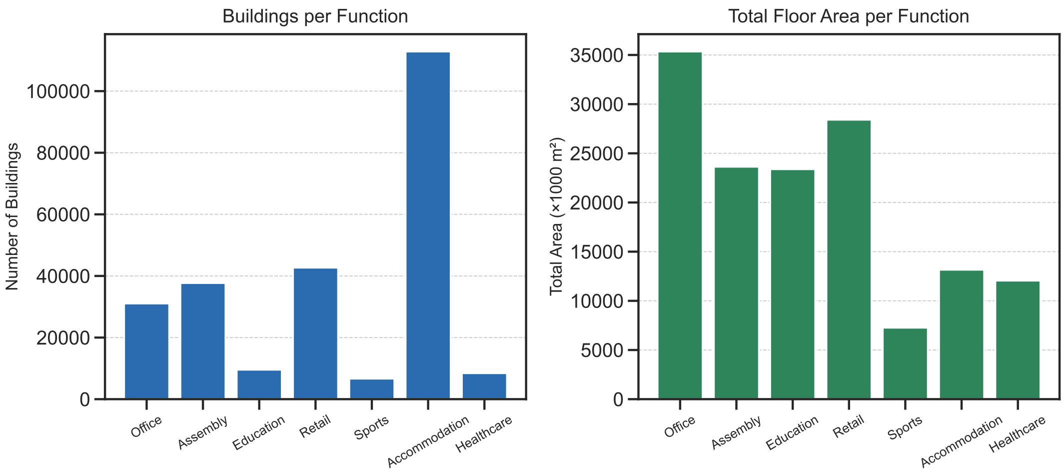

Figure 7.12: Distribution of Buildings and Total Floor Area per User Function

The first set of graphs reveals that the accommodation sector (e.g., hotels, lodging) comprises the highest number of buildings, followed by retail, assembly (e.g., event venues), and offices. However, when measured by floor area, offices dominate the sector, followed by retail and education. This suggests that while accommodation buildings are numerous, their smaller average size means they contribute less to overall energy demand. In contrast, office buildings, due to their larger size, play a disproportionately large role in energy consumption and CO_2 emissions.

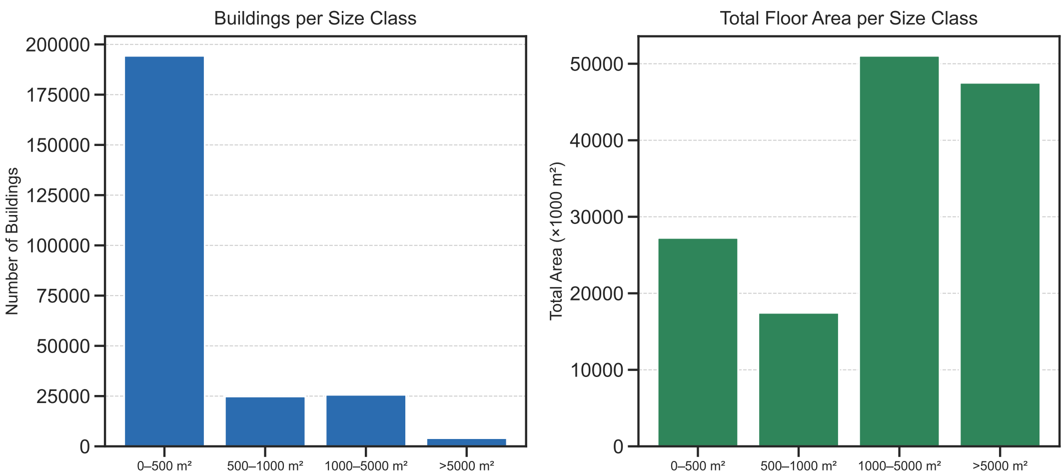

Figure 7.13: Distribution of Buildings and Total Floor Area per Size Class

The second set of graphs confirms that the majority of buildings (over 190,000) fall into the smallest size class (0–500 m²). However, these small buildings contribute less to the total sectoral floor area than mid-sized and large buildings. The majority of floor space is concentrated in the 1,000–5,000 m² and >5,000 m² categories, which together account for the bulk of energy demand and CO_2 emissions. This emphasises the importance of targeting larger buildings with emission reduction strategies, as they are responsible for a significant share of sectoral emissions.

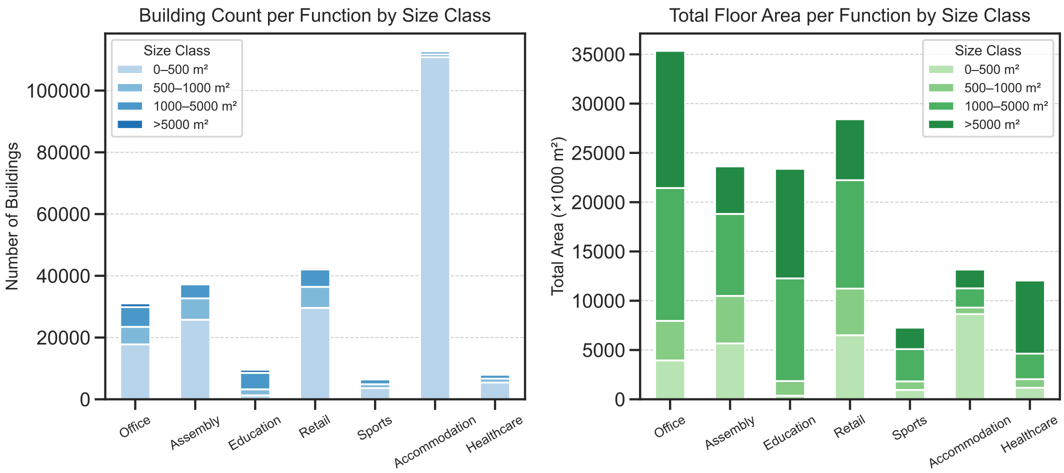

Figure 7.14: Distribution of Size Classes per User Function

The third set of graphs integrates both function and size class, showing that in nearly all building functions, the 0–500 m² category dominates in terms of building count, except for educational buildings. However, the larger size classes (especially 1,000–5,000 m²) account for the majority of the total floor area. This pattern is especially pronounced in offices, where a relatively small number of large buildings account for a significant share of the total energy-related footprint. The opposite is true for accommodation. The education and retail sectors also exhibit a relatively even distribution of building sizes, suggesting that targeted policy instruments may need to be adjusted to the typical scale of buildings within each sector.

These findings have clear implications for policy targeting. Interventions such as subsidies or performance standards may need to differentiate between building functions and size classes, not only for reasons of cost-effectiveness but also to ensure equitable and feasible implementation across the sector. While small buildings are numerous, large buildings disproportionately drive energy demand—and thus present key leverage points for emission reduction. This sectoral heterogeneity should be considered when evaluating the effectiveness, efficiency, and robustness of policy scenarios, and will be further reflected upon in Section 8.2.

7.5.1. Emission Reduction by Building Function

Figure 7.15 illustrates the emission reduction achieved per scenario, differentiated by building function.

A key observation from the figure is that assembly buildings exhibit the highest absolute emission reductions compared to other building functions, indicating that the greatest potential for emission reductions lies within the assembly sector. As discussed in Section 7.5, the assembly sector is one of

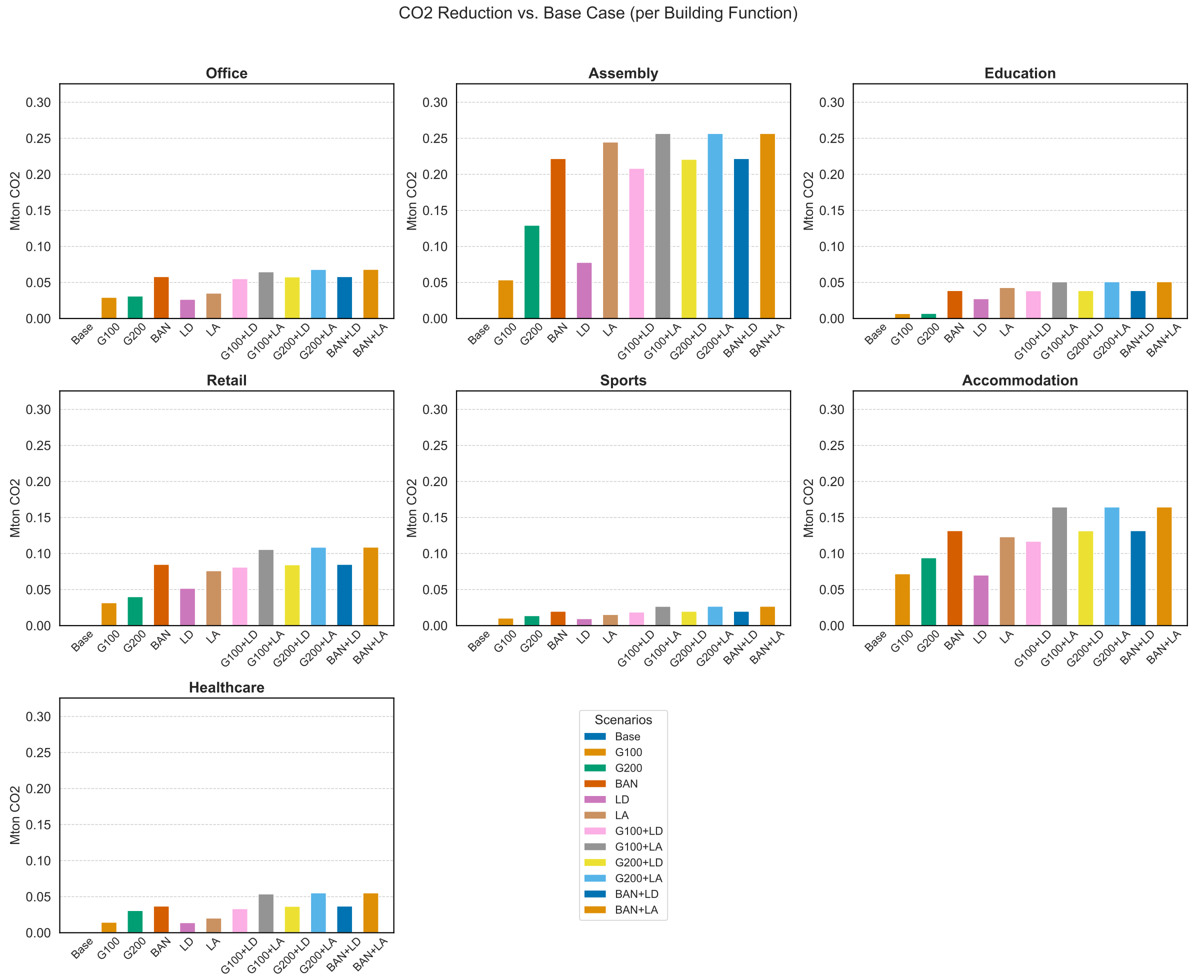

Figure 7.15: Total Annual Emission Reduction per Scenario

the larger contributors to the overall service sector building stock. Despite offices and retail buildings occupying a larger total area, assembly buildings show the highest CO_2 emission reduction potential, outpacing offices, retail, and other functions.

When comparing the effects of different policy scenarios per user function, there are no major differences in terms of overall behaviour relative to the combined building stock. However, an important policy implication arises: mandating Energy Label D results in similar emission reductions for both accommodation and assembly buildings. In contrast, implementing Energy Label A, or a combination of Label D with raising the gas price, leads to much higher reductions for assembly buildings. Specifically, mandating Energy Label A would lead to a 300% increase in emission reductions for assembly buildings (from 0.075 Mton to 0.24 Mton) compared to mandating Energy Label D alone.

This highlights the importance of targeted policy interventions. Mandating more stringent energy performance standards, such as Energy Label A, can lead to significantly higher emission reductions in sectors like assembly, which are particularly sensitive to energy performance improvements. Such policies should be tailored to sector-specific characteristics in order to maximise their impact.

7.5.2. End-User Costs by Building Function

Figure 7.16 presents the average yearly total costs per building function under various policy scenarios.

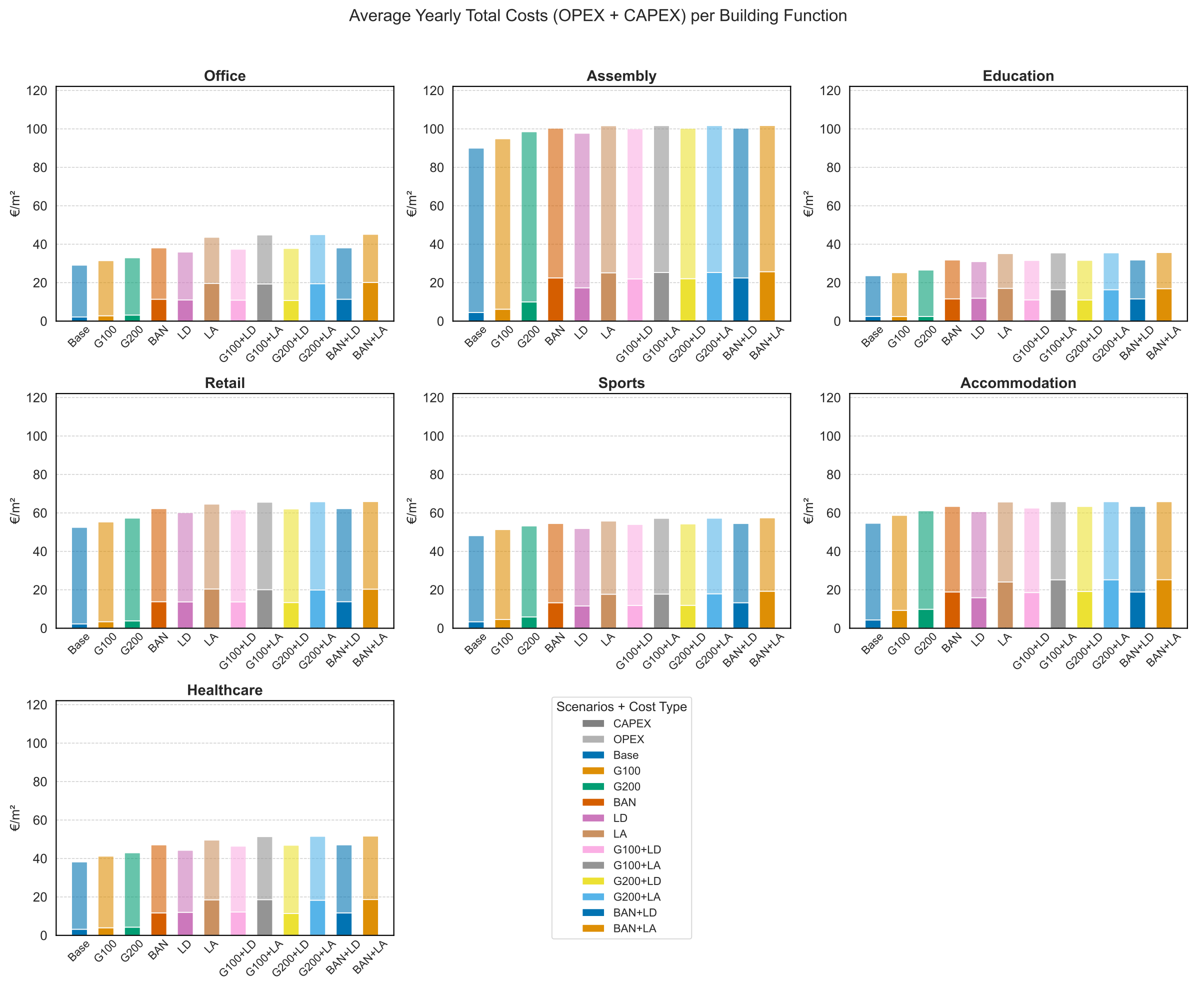

Figure 7.16: Average Yearly Total Costs per Building Function

As with emission reductions, the assembly sector stands out with the highest average annual costs, consistently exceeding €90/m² across all scenarios, and rising above €100/m² under more stringent policy interventions. Retail, sports, and accommodation sectors show moderate costs, hovering around €60/m². In contrast, offices, healthcare, and educational sectors have the lowest annual costs, at approximately €40/m². This highlights that the assembly sector bears roughly twice the costs for the emission reductions achieved in this sector compared to others. While the assembly sector shows the greatest potential for emission reductions, it also incurs the highest costs.

Examining the distribution between CAPEX and OPEX per user function reveals that OPEX constitutes a significant portion of the total annual costs for assembly buildings, accounting for 5-20% of the total costs. In contrast, for education buildings, OPEX makes up roughly 10-50% of total costs. This difference in the division between CAPEX and OPEX suggests that targeted policy interventions are necessary to address the sector-specific cost structures.

While the assembly sector offers significant potential for emission reductions, it also faces the highest costs. Therefore, policy interventions that alleviate part of this financial burden, while ensuring fair distribution of costs and emissions reductions, are crucial to achieving both environmental and economic objectives in a balanced manner.

Key Insights: per Building Function

- **High emission reduction potential in assembly sector:** The assembly sector shows the highest absolute emission reductions among all building functions, indicating significant potential for emission reductions. This is despite the fact that other sectors, such as offices and retail, occupy larger total areas.
- **Impact of policy interventions:** Mandating Energy Label A leads to a significant increase in emission reductions for assembly buildings (up to 300%) compared to milder interventions, such as Energy Label D. This suggests that stricter energy performance standards have a more substantial impact in sectors like assembly, where energy performance improvements can drive large emission reductions.
- **High costs in the assembly sector:** While the assembly sector offers the greatest emission reduction potential, it also incurs the highest costs, consistently exceeding €90/m^2. This suggests that assembly buildings bear disproportionately high costs relative to other building functions.
- **Distribution between CAPEX and OPEX:** The distribution of CAPEX and OPEX varies across sectors, with OPEX constituting a significant portion of the total costs for assembly buildings (5-20%). In contrast, OPEX in education buildings represents a larger share (10-50%). This indicates the need for sector-specific policy interventions that account for these cost structures.
- **Need for financial support in the assembly sector:** Given the high costs in the assembly sector, targeted policy interventions (e.g., subsidies or financial incentives) are necessary to alleviate the financial burden while still achieving significant emission reductions. Such measures are crucial for maintaining a balance between environmental goals and economic feasibility.

7.6. Sector Specific Impact by Building Size

As outlined in Section 7.5, building size influences the distribution of energy demand and CO_2 emissions in the non-residential sector. This section analyses emission reductions and associated end-user costs across building size classes. The results provide insights into the relative effectiveness and cost-efficiency of policy interventions per size class.

7.6.1. Emission Reduction by Size Class

Figure 7.17 presents the emission reductions achieved per scenario, broken down by building size class. The analysis of CO_2 reductions by size class reveals that smaller buildings (0-500 m^2) achieve higher reductions per square meter compared to medium-sized (500-1000 m^2, 1000-5000 m^2) and large buildings (>5000 m^2). Despite larger buildings occupying a larger share of the total building stock (Figure 7.13), small buildings yield the highest emission reductions. This indicates that smaller buildings present a significant opportunity for emission reductions within the sector.

In terms of policy implications, targeting smaller buildings with interventions such as mandating Energy Label A, or combining energy label mandates with raising the gas price, proves to be particularly

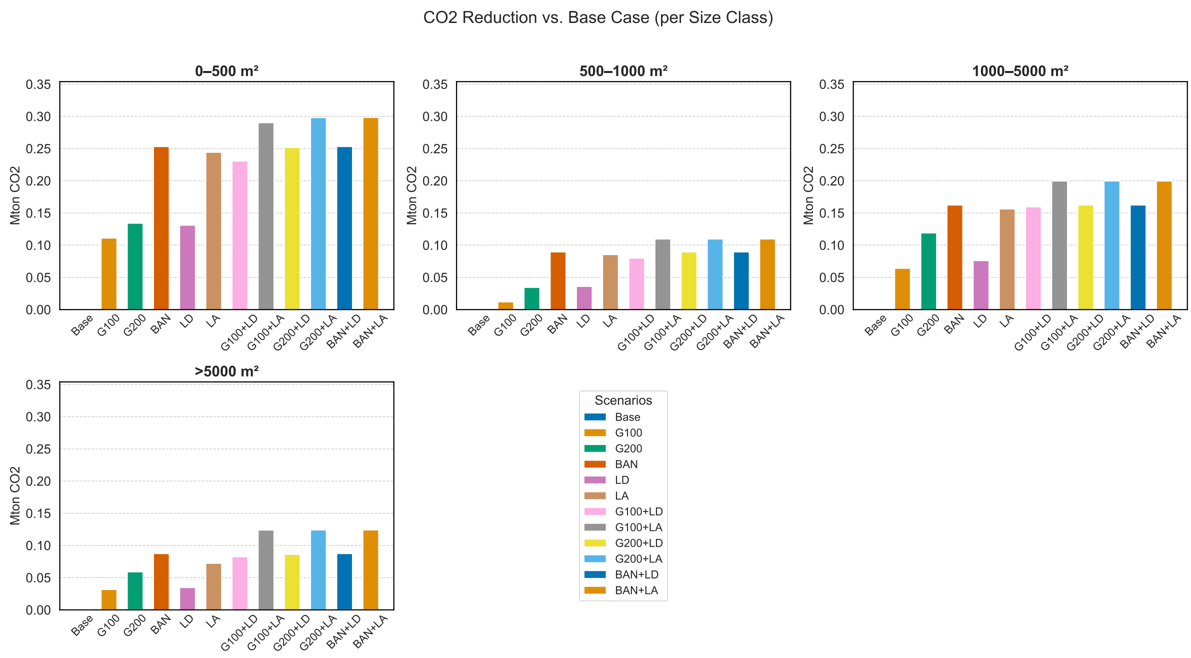

Figure 7.17: Annual Emission Reduction per Size Class

effective. These interventions can unlock substantial CO_2 reductions in the smaller building segment, which aids into targeted policy design.

7.6.2. End-User Costs by Size Class

Figure 7.18 displays the division of end-user costs (CAPEX + OPEX per m²), differentiated among the different building size classes.

The figure reveals that smaller buildings incur the highest average total costs per square meter. Despite achieving the highest emission reductions per square meter, smaller buildings also bear the highest costs, similar to the pattern observed in assembly buildings (Section 7.5.2). Notably, medium-sized buildings (500–1000 m²) show relatively high costs for the low emission reductions achieved within this size class (Figure 7.17).

An important observation is that, across different policy scenarios, CAPEX tends to increase more than OPEX, especially with more stringent policy interventions. For example, in smaller buildings, CAPEX accounts for approximately 30% of the total costs. If financial support were provided through targeted policy interventions, these upfront costs could be alleviated, significantly reducing the overall costs and making the transition to more sustainable heating technologies more cost-attractive, thereby unlocking the high emission reduction potential of smaller buildings.

In terms of policy recommendations, interventions should be focused on smaller-sized buildings, as they offer the highest emission reduction potential. However, it is crucial to acknowledge that these buildings also face the highest costs. Targeted policies that reduce CAPEX through subsidies or financial support could make these interventions more feasible, ensuring that smaller buildings contribute significantly to the overall emissions reduction goals while maintaining economic feasibility.

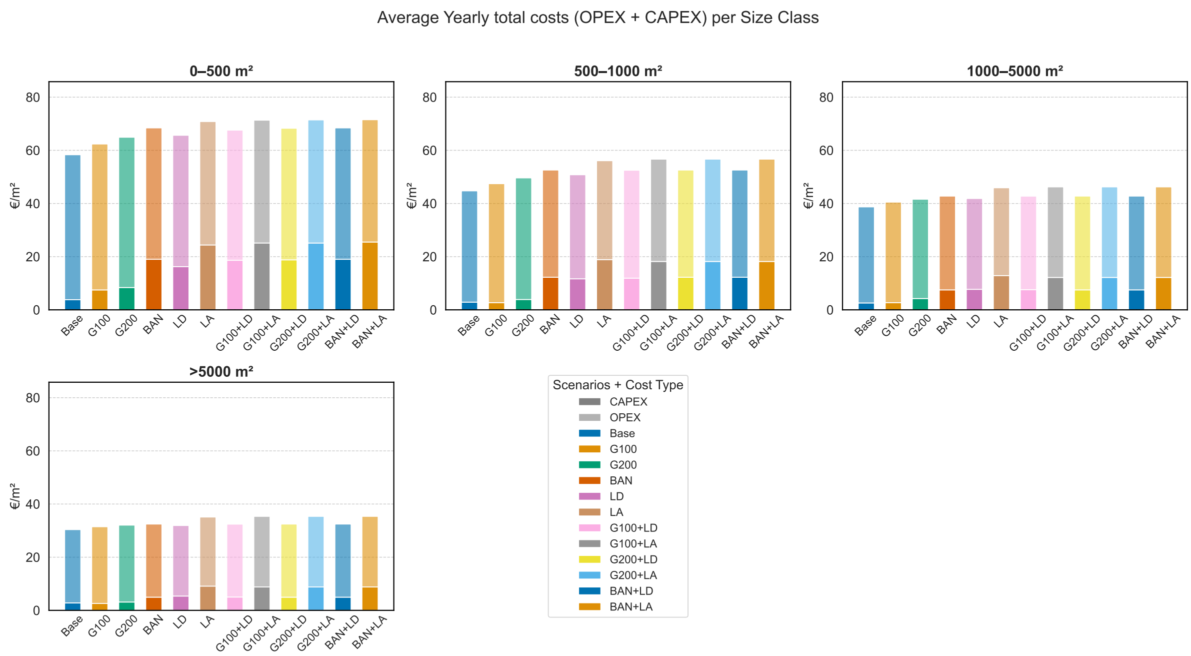

Figure 7.18: Total Annual Costs per Size Class

Key Insights: per Size Class

- **Smaller buildings lead in CO_2 reductions**: Despite representing a smaller share of the total building stock, smaller buildings (0-500 m²) achieve the highest CO_2 reductions per square meter. This suggests that they hold significant potential for emission reductions within the non-residential sector.
- **Targeted policy interventions for smaller buildings**: Policy measures such as mandating Energy Label A, or a combination of energy label mandates with raising the gas price, are particularly effective in driving substantial CO_2 reductions in smaller buildings.
- **High Costs for Smaller Buildings**: Smaller buildings, while yielding the highest CO_2 reductions, also bear the highest costs per square meter. This reflects the higher upfront capital expenditures (CAPEX) in smaller buildings, which need attention when designing cost-effective interventions.
- **Medium-Sized buildings show relatively high costs for low reductions**: Medium-sized buildings (500–1000 m²) exhibit relatively high costs, but the emissions reductions achieved in this category are comparatively low.
- **Importance of Reducing CAPEX**: For smaller buildings, CAPEX makes up a significant portion of total costs (about 30%). Targeted policy interventions, such as subsidies or financial support for CAPEX, can alleviate these upfront costs and improve the feasibility of transitioning to sustainable heating solutions, unlocking their full emission reduction potential.

8

Discussion and Recommendations

8.1. Introduction

This chapter interprets the model outcomes in relation to the existing literature, providing an integrated analysis of how various policy interventions influence the transition towards sustainable heating solutions in the non-residential built environment. The analysis presents a techno-economic upper bound based on the assumption that building owners make cost-optimal decisions, while also acknowledging that real-world investment decisions are influenced by behavioural, organizational and other factors. This discussion addresses the research question:

> *How do policy interventions improve CO_2 emission reductions in the Dutch non-residential service building stock, in terms of their effectiveness, cost-effectiveness and distributional effects?*

In doing so, this chapter is structured as follows. First, it provides an interpretation of the key findings, evaluating the effectiveness, cost-effectiveness, and distributional impacts of different policy interventions across building types and size classes. Where relevant, findings are compared with insights from the broader academic literature to assess the consistency and significance of the results.

Second, based on the findings and identified patterns, the chapter presents a set of policy recommendations. Practical implications for policy design are drawn, paying particular attention to how policymakers can effectively balance effectiveness, cost-effectiveness and fairness when shaping the decarbonisation strategy for the non-residential building sector.

Finally, the chapter reflects on the limitations of the study and proposes directions for future research that could address current gaps, improve model realism, and improve future policymaking.

8.2. Interpretation of Findings and Academic Context

This section interprets the main model outcomes in light of existing literature and theoretical frameworks, evaluating how the findings align with broader knowledge on investment behaviour, barriers to energy efficiency, and the effectiveness of policy instruments in the non-residential building sector.

8.2.1. Technology Preferences and Investment Behaviour

The model results show that gas-based heating solutions, particularly condensation boilers and hybrid heat pumps, remain dominant in baseline scenarios. This finding is consistent with empirical observations that, in many cases, climate-neutral heating remains more expensive than natural gas alternatives, even with subsidies (Hoogervorst, 2024). As a result, gas-based heating continues to be the dominant choice in practice, confirming the persistence of natural gas as the default option despite current policy efforts (Tollenaar et al., 2024; van den Bergh et al., 2021). The preference for familiar technologies at low upfront cost is consistent with rational investment behaviour under Rational Choice Theory (RCT), where actors select the least-cost option given current market conditions (Becker, 1976).

Economic interventions that increase gas prices (through the Energy Tax) are shown in the model to shift technology adoption towards sustainable alternatives such as air-water heat pumps and district heating. This result aligns with empirical studies demonstrating that energy price signals influence investment decisions and improve the business case for sustainable heating solutions (Anczewska et al., 2025; Koster et al., 2022).

The results of this study are in line with findings by Özer et al. (2024), who analysed policy impacts on heat pump adoption across the EU27 (the current 27 EU member states, post-Brexit). In our model, heat pump adoption reaches between 45–75% of buildings under more stringent policy packages combining economic and regulatory measures, whereas adoption rates remain between 10–60% under standalone interventions such as an energy tax or a mandatory energy label. Similarly, Özer et al. (2024) found that in high-efficiency scenarios with stringent regulation, heat pump shares reached 47–86%, while more moderate policies led to a broader price sensitivity and lower uptake, between 15–55%. Although their study considers the European Union as a whole, and therefore includes different national contexts and starting points, the parallel with the Dutch non-residential sector is striking. Both studies show that ambitious policy combinations not only drive higher overall adoption rates of sustainable heating technologies but also reduce the elasticity of technology choice to energy price signals, as regulatory requirements force upgrades regardless of short-term price fluctuations.

8.2.2. Effectiveness of Policy Instruments

The model demonstrates that combining regulatory measures (e.g., energy label mandates) with economic instruments (e.g., gas taxes) is the most effective strategy for achieving large-scale emission reductions. This supports the theoretical expectation that mixed policy packages can simultaneously address multiple barriers (Section 2.2). Regulatory standards create trigger points for investment (Eichholtz et al., 2024; RICS, 2024; Sebi et al., 2019), while economic incentives improve the financial attractiveness of sustainable options (Akhatova & Kranzl, 2024; Sebi et al., 2019).

Empirical research confirms this interaction. Studies show that performance standards (such as the Dutch label C obligation for offices) successfully create mandatory investment moments (Arnoldussen et al., 2016; Eichholtz et al., 2024), while price signals drive efficiency in cases where voluntary uptake is feasible (Vringer et al., 2016). Relying solely on economic instruments risks leaving hard-to-reach segments untouched due to non-economic barriers (Olsthoorn et al., 2017; Rosenow et al., 2017).

The model's finding that gas taxation alone is more cost-effective per tonne of CO_2 than stand-alone energy label mandates is consistent with literature showing that market-based instruments generally achieve higher efficiency by allowing actors to choose least-cost abatement options (Goulder & Parry, 2008). Although, as stated by (ürge-Vorsatz et al., 2007), *"The direct effectiveness as well as cost-effectiveness of taxes is often limited."* Supporting the model's conclusion that a combination of regulatory instruments is necessary for a more effective policy strategy.

8.2.3. Cost Structures and Cost-Effectiveness under Different Policy Scenarios

Across all scenarios, the model shows that operational expenditures (OPEX) currently dominate total yearly costs in the non-residential sector, particularly under fossil fuel-based heating systems. This finding is consistent with previous research highlighting that energy bills constitute the largest component of building operating expenses (Bleyl et al., 2019).

Under stricter policy interventions, such as mandatory energy labels combined with higher gas prices or a gas ban, the model predicts a shift towards a cost structure where capital expenditures (CAPEX) account for a substantially larger share of total costs. Specifically, CAPEX shares rise to between 20% and 50% of annualised costs, depending on the future energy price scenario. Although this is somewhat lower than reported in deep retrofit case studies (where CAPEX shares of up to 70% have been observed post-renovation (Bleyl et al., 2019)), the model captures the same underlying behaviour: higher upfront investments lead to lower long-term operating expenses.

From a Rational Choice Theory perspective, such investments are economically rational if future energy savings sufficiently outweigh the initial outlay when discounted over time (Gillingham & Palmer, 2014). Recent empirical work further suggests that as energy prices rise, such as during the 2021–2022 energy crisis, the payoff for CAPEX investments increases, strengthening the case for upfront interventions (Koster et al., 2022). This dynamic reinforces the model's findings: scenarios with higher gas prices show greater adoption of sustainable heating technologies, as higher expected OPEX motivates owners to accept higher CAPEX.

However, barriers such as limited access to capital, short payback expectations, and competing investment priorities can inhibit real-world uptake (Kapur et al., 2011; Olsthoorn et al., 2017). To mitigate these barriers, supportive financing mechanisms such as targeted subsidies or low-interest loans can help policymakers (Akhatova & Kranzl, 2024; Sebi et al., 2019). Notably, the model shows that if CAPEX is lowered through for example subsidies, in stringent policy scenarios, the total annualised costs after deep retrofits can be comparable to, or even lower than, those in the base case, despite higher upfront investment. This underscores that strict policy interventions, although capital-intensive, can ultimately be cost-effective for end-users if combined with financial support measures that lower effective CAPEX and facilitate the transition to a lower-OPEX future.

8.2.4. Differences by Building Type and Size

The model identifies that smaller buildings achieve greater CO_2 reductions per square metre but face higher retrofit costs per square metre. Assembly buildings exhibit large abatement potentials but incur disproportionately high costs. These patterns are consistent with empirical evidence showing that smaller buildings suffer from higher operational costs and less favourable economies of scale (de Clerck, 2024).

Compared to literature on energy label improvements across the sector, such as the Niessink et al. (2017) 'Exploration of Non-Residential Buildings' (In Dutch: "Verkenning Utiliteitsbouw"), the model takes a different perspective. While earlier studies identified hospitality, retail, and healthcare buildings as having high emission-saving potentials based on floor area, the present study evaluates actual CO_2 abatement potential in relation to sustainable investment decisions. This methodological distinction could explain why assembly buildings emerge as the largest abatement contributors in this study.

Future policies may need to differentiate more explicitly by building size segment, providing targeted financial support to smaller buildings to unlock their emission reduction potential. Such support would not only facilitate investment decisions in sustainable heating solutions but also promote equitable policies through a fair distribution of cost burdens across different types of building owners. Similarly, owners of assembly buildings will require specific support measures to enable their transition towards sustainable heating technologies and to realise their full abatement potential within the sector.

8.2.5. Policy Robustness under Energy Price Uncertainty

The model indicates that combined policy interventions remain highly effective across a range of future electricity price scenarios. This robustness is important for future policy design given the volatility in energy markets, particularly since 2022. Literature supports that hybrid approaches—mixing economic incentives with regulatory obligations— are less sensitive to changes in electricity prices and could be a stable option for achieving emission reduction objectives in the sector (Anczewska et al., 2025; Özer et al., 2024).

In line with theoretical perspectives on risk management in public policy (Hood, 1983), ensuring redundancy through policy layering helps maintain decarbonisation trajectories even under adverse external conditions. As energy price trajectories are inherently uncertain, robust policy design remains a core principle for effective long-term climate governance.

8.2.6. Synthesis: Evaluation of Policy Interventions

This section synthesises the main findings by explicitly assessing the policy interventions on three key criteria: effectiveness, cost-effectiveness, and distributional effects. It reflects on how specific policy combinations perform and how these results compare to insights from existing literature.

Effectiveness

The model shows that combined policy interventions—particularly scenarios combining gas tax increases with mandatory energy label upgrades (e.g., G100+LD, G200+LD, BAN+LD)—are the most effective in achieving large-scale CO_2 emission reductions. These interventions consistently outperform standalone measures, confirming the theoretical and empirical expectation that mixed policy packages address a broader range of barriers (Sebi et al., 2019). Economic interventions alone, such as raising the gas price by 100% or 200%, are effective in shifting technology adoption but achieve relatively lower absolute CO_2 reductions compared to combined interventions.

Cost-Effectiveness

In terms of cost-effectiveness, raising the gas price emerges as the most cost-effective stand-alone intervention, with the lowest cost per tonne of CO_2 reduced. This finding aligns with broader policy analyses showing that pricing instruments typically achieve higher cost-effectiveness (ürge-Vorsatz et al., 2007). However, this strategy is less effective overall in absolute emission reductions compared to mixed interventions.

Purely regulatory approaches, such as mandating Energy Label A or D without accompanying price signals, are less cost-effective. This mirrors findings from retrofit literature that highlight the high marginal cost of achieving deep energy savings through standards alone (ürge-Vorsatz et al., 2007).

Combining economic and regulatory measures (e.g., G100+LD, G200+LD) strikes a favourable balance: achieving high CO_2 reductions at moderate additional costs. These results support the conclusion from Goulder and Parry (2008) and ürge-Vorsatz et al. (2007) that carefully designed policy packages are more effective and efficient than isolated instruments.

Distributional Effects

Distributional analysis shows that smaller buildings, despite delivering higher CO_2 reductions per square metre, face disproportionately high retrofit costs relative to larger buildings. Similarly, assembly buildings demonstrate high emission reduction potential but at high overall costs. Smaller and assembly buildings require targeted support to unlock their abatement potential without imposing inequitable financial burdens.

Policy recommendations should therefore incorporate differentiated support mechanisms:

- Targeted CAPEX subsidies or low-interest loans for smaller buildings and assembly venues.
- Policy interventions that recognise sector-specific cost structures to maintain affordability and fairness.

Reflections on Cost Structure Shifts

The model also captures the shift towards higher CAPEX shares under ambitious policy interventions, reaching 20–50% of total annual costs. This reinforces policy strategies that focus on reducing upfront CAPEX barriers through financial support, especially under volatile energy price conditions. If successful, such strategies can ensure that total annualised costs after deep retrofits remain comparable to, or even lower than, the base case, improving the economic rationale for sustainable investments.

8.3. Methodological Reflection

As discussed in Section 2.2.3 and 3.5, this study relies on a techno-economic modelling approach that assumes rational, cost-optimising behaviour by building owners. While this abstraction omits behavioural barriers and organisational constraints, it enables a transparent and comparable assessment of what could be achieved under idealised economic conditions. This section reflects not on the limitations themselves (see Section 8.4.1), but on the methodological implications and added value of this approach for policy and research.

The core strength of this method lies in its internal consistency and transparency. Each model outcome is directly traceable to a defined set of assumptions and input values. This enables reproducible comparisons across policy scenarios and supports clear attribution of effects to specific interventions. For policymakers, such consistency is crucial: it allows for the isolation of specific policy effects and the identification of cost drivers, helping to inform policy design and prioritisation in a controlled and analytically transparent setting.

The model assumes that building owners make economically rational choices at natural replacement moments, always selecting the heating solution with the lowest projected total cost (CAPEX + OPEX). This creates a stylised benchmark: it reflects what could happen if financial considerations were the sole driver of decision-making, and if all adoption barriers were absent. It does *not* represent the absolute technical or behavioural maximum of what could be achieved—some actors in the real world choose more sustainable but less financially optimal options, driven by reputational goals, internal sustainability targets, or normative motivations. Conversely, others may fail to act even when an investment is cost-effective due to short payback expectations, capital constraints, or split incentives.

As such, the model defines a specific type of upper bound: the upper limit of emission reductions under idealised economic rationality, not the theoretical maximum of technical or voluntary ambition. This distinction matters. If a policy intervention proves *ineffective* even under these favourable assumptions, it is unlikely to perform better in reality. This makes the model a conservative stress test for structural policy viability: it highlights which measures could work *if* key barriers (Section 2.2.2) were addressed, and which are structurally weak regardless of implementation context.

In a domain where empirical investment data is limited and behavioural dynamics are diverse, such models serve a practical role. They do not predict what will happen, but help clarify what *could* happen under defined conditions, and what is required to bridge the gap between potential and practice. They make structural trade-offs visible—between short-term cost and long-term benefit, between efficiency and fairness, and between incentives and obligations. This enables ex-ante screening of policy options before committing to more resource-intensive pilot programmes or behavioural studies.

Finally, adapting CEKER to the non-residential sector expands its policy relevance. While the model was originally designed for residential contexts, this study extends its use to more heterogeneous and less-studied building types such as offices, schools, and assembly buildings. This improves the applicability of the model to real-world policy questions in the heat transition.

In sum, the model offers no forecast but a normative benchmark. It is not designed to predict reality, but to inform it—by showing where policy could be effective, and where it likely will not be, even under the best possible conditions.

Limitations of CEKER and Recommended Extensions

The model abstracts from behavioural, organisational, and spatial complexity. It treats building owners as a homogeneous group, applies static energy prices and emission factors, and assumes full policy implementation by a fixed target year. These simplifications, while methodologically necessary, limit its applicability for modelling transitional dynamics or capturing non-economic barriers. A more detailed discussion of these and other limitations is provided in Section 8.4.

Based on this, several targeted extensions are recommended:

- Introduce spatial differentiation by linking BAG building data with CBS neighbourhood statistics, using population density as a proxy to assess the regional feasibility of district heating.
- Extend the investment logic with payback thresholds or agent-based behaviour to better reflect real-world decision-making, acknowledging that owners in the non-residential sector typically apply payback criteria of 3–5 years.
- Incorporating policy roll-out trajectories into the model would create a more realistic representation of how investment decisions and emissions evolve over time. Compliance tends to increase gradually due to market readiness and alignment with natural investment cycles.
- Model the typical replacement cycles of heating systems currently present in the building stock, based on estimated technical lifetimes, to identify when investment decisions are most likely to occur.
- Model split incentives in rental settings for the non-residential sector, including rent-pass-through or tenure-specific barriers, as was done in the original CEKER model for the residential sector.

Together, these extensions would improve the model's ability to inform policy design by bridging the gap between theoretical potential and implementation reality. For CE Delft, this would enhance its capacity to evaluate the effects of policy interventions on the non-residential sector more accurately, thereby strengthening the quality of advice provided to public and private clients.

8.4. Limitations of the Study and Real-World Relevance

This section discusses key limitations of the CEKER model, organised around methodological assumptions, scope choices, and implementation simplifications. While these limitations are partly due to data availability, time constraints, or modelling tractability, they also reveal important tensions between theoretical modelling and the messy reality of policy implementation. Where relevant, we reflect on how these constraints shape the model's real-world applicability.

In Section 8.6, these limitations are revisited through reflections on how additional time or resources could have allowed for further research and model development.

8.4.1. Modelling Assumptions and Behavioural Gaps

Economic Decision Logic

Investment behaviour is modelled using Rational Choice Theory (Section 2.2.3), which captures cost-driven decision-making but overlooks real-world deviations such as strict payback requirements (no longer than 3 to 5 years) or investment trigger points (Section 2.2.1 and 2.2.2). In practice, many firms impose even stricter internal thresholds, prioritising core business investments over energy efficiency measures, even when these are cost-effective over their lifetime. This means that in reality actual adoption rates could lag behind the modelled results.

Immediate Policy Implementation Assumption

Policy interventions are assumed to be fully implemented by 2030 without transition phases. In reality, policy rollouts are often gradual and subject to political delays, administrative preparation, or market readiness. These temporal dynamics can postpone investment responses and therefore delay emission reductions, even when measures are cost-effective.

Emission Factor Assumptions

Scope 1 and Scope 2 emissions are considered, but dynamic developments such as grid decarbonisation or changes in district heat supply are not modelled. In particular, district heating scenarios assume static emission factors and do not distinguish between sustainable and fossil-based heat sources under increased demand. In reality, limited availability of residual heat may require supplemental fossil-based production, which could increase both CO_2 emissions and heat prices. These simplifications affect the accuracy of emissions estimates and may overstate the climate benefits of district heating.

Tenant Influence Not Captured

The model assumes that investment and operational decisions are made by a single actor, typically the building owner. In leased properties, however, decision-making is often split between owners and tenants, which can reduce the incentive to invest in energy-saving measures. This may result in an overestimation of retrofit adoption rates and energy savings in tenant-occupied buildings.

Lack of Regional Differentiation in Feasibility

The model does not distinguish between urban and rural areas. In practice, spatial differences in infrastructure and building density strongly influence the feasibility of certain heating technologies. For instance, district heating networks are often not viable in rural or low-density areas, yet the model treats them as universally applicable. This could result in an overestimation of the applicability and cost-effectiveness of district heating in rural areas, and underestimation of grid-related constraints in high-density areas.

8.4.2. Scope and Data Limitations

Fixed Technology Applicability

The model assumes that all heating technologies are technically feasible for all buildings. In practice, technical barriers—such as space constraints, heritage status, or network limitations—may prevent certain solutions from being implemented, especially in older or complex buildings. As a result, the model may overstate the feasibility of certain low-carbon technologies in specific segments of the building stock.

Uniform Treatment of Real Estate Types

Due to limited data availability, the model treats all buildings and owners as a homogeneous group, without distinguishing between commercial real estate (e.g., offices, retail) and societal real estate (e.g., schools, healthcare). In practice, these segments have different ownership structures, investment incentives, and budgetary constraints, which could influence responsiveness to policy interventions.

8.4.3. Bridging Model Outcomes and Implementation Realities

Even where technical feasibility and cost-effectiveness are assumed, the real-world uptake of sustainable measures depends on broader enabling conditions. Investment decisions rarely occur in isolation and often coincide with lifecycle "trigger points" such as renovations, equipment replacement, or changes in ownership (Section 2.2.1). Outside these moments, owners are unlikely to act, regardless of economic rationale.

Moreover, decisions are embedded in complex organisational and institutional settings. Beyond financial support, effective implementation requires:

- **Policy alignment with decision timelines**, ensuring that regulations and incentives coincide with or create natural investment cycles
- **Credible and stable policy frameworks**, avoiding stop–start subsidies or inconsistent targets that create uncertainty and delay.
- **Infrastructure readiness**, particularly grid capacity, which is a prerequisite for electrification pathways.
- **Organisational and technical capacity**, including in-house expertise and project management resources to plan and execute building upgrades.

Multiple actors must contribute to creating these conditions. Municipalities can steer transitions through local heat plans and enforcement of label requirements. National authorities set financial and legal frameworks and ensure long-term coherence. Grid operators must invest in infrastructure, and building owners ultimately bear responsibility for action. Without coordination and active participation across these levels, the modelled potential is unlikely to be realised in full.

In sum, while the CEKER model provides valuable insights into policy trade-offs under idealised assumptions (Section 8.3), real-world impact depends on the alignment of investment incentives, institutional capacity, and infrastructure readiness. Effective policy design must therefore go beyond techno-economic optimisation and account for the behavioural, organisational, and technical realities of the built environment.

8.5. Policy Recommendation and Societal Relevance

To effectively accelerate the decarbonisation of the Dutch non-residential service sector, this study recommends a combination of economic instruments and regulatory interventions, carefully sequenced to create natural investment moments while improving the financial attractiveness of sustainable heating technologies.

First, the findings confirm that economic incentives, such as a gradual increase of the energy tax on natural gas, improve the business case for alternative heating solutions. Higher gas prices discourage reinvestment in fossil-based systems and stimulate the adoption of heat pumps and district heating, consistent with rational investment behaviour (Akhatova & Kranzl, 2024; Sebi et al., 2019).

Second, regulatory standards such as mandatory minimum energy labels create clear trigger points for building owners to undertake renovations. Evidence from the label C requirement for office buildings in the Netherlands shows that such obligations successfully induce investment decisions (Arnoldussen et al., 2016; Eichholtz et al., 2024; RICS, 2024). This study's model results confirm that mandatory label upgrades significantly increase the likelihood of transitioning to low-carbon heating systems, particularly when combined with economic incentives.

The recommendation is therefore to implement a two-step policy package:

- Gradually raise the natural gas energy tax to signal increasing future operating costs.

- Mandate a minimum energy label D for all non-residential service buildings by a clearly defined target year (e.g., 2030–2035), allowing owners time to plan and finance upgrades.

This staged approach ensures that owners first experience rising operational costs (improving the business case for action) and then face a mandatory trigger point, pushing those who would otherwise postpone action to invest.

This would result in stretching the potential emission reduction under purely rational investment decisions (techno-economic upper bound) to 0̃.5 Mton CO2 under low and moderate future electricity prices and to 1̃.2 Mton under high future electricity prices (Section 7.3).

In the longer term, as the Netherlands moves towards a net-zero building stock by 2050, a subsequent obligation for energy label A should be introduced. This higher performance standard would drive deeper renovations and maximise CO_2 reductions, while giving sufficient lead time for the market to adapt.

It is not recommended to implement a full gas ban at this stage. A blanket prohibition would severely restrict choice and could impose disproportionate costs on buildings with technical limitations (e.g., heritage buildings). If considered in the future, gas bans should include carefully designed exemptions or a green gas obligation (e.g., biomethane), although further research is required to assess feasibility.

Although this study does not include targeted insulation subsidies as a core policy scenario, it is worth considering the role of insulation as a complementary policy lever. While this study does not model targeted subsidies for building envelope improvements, the results indicate that higher energy labels, representing better insulation, reduce total heating costs and improve the financial viability of sustainable heating systems. Supporting insulation measures through subsidies may therefore lower the threshold for switching to non-fossil heating technologies. Moreover, insulation upgrades often coincide with broader renovation activities, creating natural investment moments during which owners may also replace or upgrade their heating systems. Future policy packages could benefit from explicitly incorporating envelope-focused support, although the relative effectiveness of such support compared to other interventions requires further research.

In addition, these recommendations are based on modelled outcomes under the assumption of rational, cost-optimising investment behaviour. As discussed in Section 8.3, this approach defines an economic upper bound: it indicates what could be achieved if financial incentives were fully effective and behavioural barriers were absent. While this enables clear comparison of policy options, real-world uptake may lag due to practical constraints such as short payback expectations, limited access to capital, or split incentives. Translating modelled potential into impact therefore requires not only regulation and pricing, but also supporting conditions that lower implementation barriers—such as accessible financing instruments, clear and stable long-term policy frameworks, and sufficient technical and organisational capacity among building owners.

Ensuring Fairness and Societal Acceptability

The success of any transition policy depends not only on technical and economic efficiency, but also on fairness and public acceptance. This study highlights that smaller buildings and assembly venues, despite their high abatement potential, face disproportionately high retrofit costs. Lowering CAPEX through grants or low-interest financing can make deep retrofits economically viable, ensuring that these high-impact segments can fully participate in the transition.

As discussed in Section 2.3, theories of policy design emphasise that legitimacy and effectiveness are shaped by the perceived fairness of cost and responsibility allocation. The model's disaggregated results help identify which segments need additional support, enabling both public authorities and representative organisations to advocate for equitable policy designs.

In sum, combining economic and regulatory instruments with targeted financial support for smaller and assembly buildings ensures that climate policy is not only effective and cost-efficient, but also just and politically feasible across all segments of the non-residential building stock.

8.6. Suggestions for Further Research

This study identifies several areas where further research could refine the modelling approach and improve the applicability of its findings to real-world policy design. Building on the limitations outlined in Section 8.4, future work can strengthen both the empirical realism and policy relevance of the model.

Although the model includes differences in building size and function, it does not distinguish between types of ownership. Differentiating between private and public real estate, such as office buildings versus schools, would allow future studies to account for variation in investment capacity, planning horizons, and responsiveness to financial incentives. This segmentation could be implemented by linking BAG data to external property or ownership registries. Additionally, empirical studies—such as Jonker et al. (2024) provide insight into the investment preferences of different owner types. These findings could inform more realistic behavioural assumptions or be used to parameterise differentiated decision rules per ownership category.

District heating is typically only feasible in densely built areas with existing or planned networks. Future work could include regional variation by using CBS neighbourhood statistics in combination with BAG data. This would allow for a more realistic assessment of where heat networks are practically applicable.

The model assumes fixed energy prices and emission factors for 2030, while in reality these variables change over time due to supply-side developments such as grid decarbonisation or shifts in the energy mix. Integrating the model with external projections of electricity prices and emission factors, such as those from national energy outlooks or scenario studies, could improve the accuracy of cost and emission estimates, especially for electrification strategies. For district heating in particular, rising demand for sustainable heat sources may exceed available residual or renewable supply. In such cases, additional demand may be met through gas-fired generation or other carbon-intensive sources, leading to higher-than-expected emissions. Including this dynamic supply response in future modelling could provide a more realistic assessment of the climate impact of large-scale heat network deployment.

Policy implementation in practice rarely happens all at once. The model currently assumes that all policies are fully effective by 2030, but in reality, roll-out is gradual due to administrative lead times and political decision-making. Future research could simulate policy adoption over time by modelling a gradual increase in compliance rates or investment uptake. This would allow for a more realistic estimation of how quickly policies deliver results.

The current model includes limited uncertainty analysis. While some scenario variation is explored, a more systematic approach using probabilistic methods—such as Monte Carlo simulation—could help assess the robustness of results under a wider range of assumptions.

Tenant-landlord dynamics are also not explicitly modelled. In leased properties, owners often bear the investment cost, while tenants benefit from lower energy bills. This split incentive reduces the likelihood of energy efficiency investments. Future research could model these relationships more explicitly, for instance by including the possibility for owners to recover part of the investment via rent increases.

Lastly, the model assumes that investment choices are based on minimising total cost over time. In reality, payback periods play a more central role in decision-making. Many building owners will reject cost-effective measures if the payback exceeds internal thresholds. Future work could integrate these behavioural thresholds directly into the investment logic or use agent-based modelling to simulate how different types of owners respond to the same policy signals.

Incorporating these elements would improve the model's ability to reflect real-world investment decisions, allowing for more targeted and reliable policy analysis.

9
Conclusion

9.1. Introduction

This chapter answers the central research question and sub-questions of this thesis. Each sub-question is addressed individually, based on the methods and results presented in the previous chapters. Together, the answers provide a coherent response to the main research question:

> *How do policy interventions improve CO_2 emission reductions in the Dutch non-residential service building stock, in terms of their effectiveness, cost-effectiveness, and distributional effects?*

This study investigated how policy interventions can improve CO_2 emission reductions in the Dutch non-residential service building stock, evaluated through their effectiveness, cost-effectiveness, and distributional effects. To answer the main research question, the study was structured around four sub-questions, each addressing a key aspect of the transition towards sustainable heating solutions in this sector. Below, each sub-question is briefly answered, after which an overarching conclusion is drawn.

9.2. Sub-question 1

What are the key components in the non-residential service building system, and how do they interact?

The Dutch non-residential service building system consists of several key components that jointly determine the energy and emission profile of the sector. First, the **actors** include building owners — both owner-users and owner-lessors — who make investment decisions regarding heating solutions, and *policymakers*, who influence these decisions through taxes, subsidies, and regulations. Although tenants indirectly affect energy use, they are not the primary decision-makers modelled in this study.

Second, the **buildings** themselves are heterogeneous. Smaller buildings (0–500 m^2) make up the majority of the building stock by number but contribute a smaller share to the total floor area. Larger buildings dominate in total floor area and therefore have significant aggregate energy demand. Building types included are offices, education, healthcare, accommodation, sports, assembly, and retail.

Third, the **heating solutions** available vary in technology (e.g., gas boilers, hybrid heat pumps, all-electric heat pumps, district heating) and are linked to *insulation levels* represented by energy labels. Heating system selection is influenced by both technical feasibility (e.g., insulation requirements) and economic attractiveness (CAPEX and OPEX).

Fourth, **cost structures** play a crucial role. Investment costs (CAPEX) and operational costs (OPEX) vary widely by technology and building type, influencing the cost-optimal choices available to owners. Policies such as the energy tax on gas and mandatory energy label requirements alter these relative costs.

These components interact dynamically: policy interventions influence the financial attractiveness of certain heating solutions; building owners respond by selecting the most attractive option based on lifecycle costs; and building characteristics determine the feasible technology options and the resulting CO_2 reductions. Mapping these interactions provided the basis for adapting the CEKER model to the non-residential sector and designing relevant policy scenarios.

9.3. Sub-question 2

Which policy interventions show promise for reducing CO_2 emissions in the non-residential service sector, and will therefore be selected for analysis in this study?

Based on a review of the current policy landscape and relevant barriers in investment decision-making, three types of policy interventions were identified as promising and selected for analysis in this study.

First, **increasing the energy tax on natural gas** was selected. Higher gas prices improve the business case for sustainable heating alternatives such as heat pumps and district heating, directly addressing the upfront economic barrier identified in both theory and recent empirical studies (e.g., during the European energy crisis 2021–2022).

Second, **mandatory minimum energy label requirements** were chosen. Regulatory standards such as the Dutch Energy Label C obligation for offices have been shown to create 'trigger points' for investment decisions, overcoming behavioural and organisational inertia that often prevent voluntary retrofitting. Extending such mandatory label requirements to the broader service sector is expected to significantly accelerate building upgrades.

Third, **a gas ban for existing buildings** was included as a more extreme policy scenario. Although politically sensitive and less feasible in the short term, a complete prohibition on gas-based heating provides insight into the upper limits of emission reductions that could be achieved if gas-based options are entirely phased out.

In addition to evaluating these instruments individually, the study also considers **policy packages**, combining economic and regulatory measures. Literature suggests that such combinations perform better than standalone interventions, especially under conditions of market uncertainty and behavioural barriers.

9.4. Sub-question 3

Through which modifications can the CEKER model be adapted to capture the heterogeneity of non-residential service buildings?

The CEKER model was originally designed for the residential sector. To accurately capture the heterogeneity of non-residential service buildings, the following key adaptations were implemented:

- **Building categorisation:** Buildings were classified based on dominant use functions (e.g., offices, healthcare, retail), enabling tailored energy demand and technology suitability profiles.
- **Size scaling:** Surface area and energy intensity were explicitly incorporated into system sizing and cost calculations, acknowledging the greater variability in building size and energy demand.
- **Adapted CAPEX and OPEX parameters:** Technology investment and operational costs were recalibrated using non-residential sector-specific data sources, recognising different scaling effects and installation complexities.
- **Energy demand adjustment:** Space heating demands were adapted based on non-residential energy label structures and typical operational patterns, ensuring realistic baseline and post-insulation scenarios.
- **Energy cost modelling:** Non-residential tiered energy tariffs and taxes were incorporated, differentiating cost structures from residential customers.
- **Insulation cost modelling:** Insulation upgrade costs were parameterised to reflect non-residential building envelope improvement requirements, linked to energy label improvements.
- **Subsidy and financial incentives:** Non-residential subsidy schemes (e.g., DUMAVA) and financial conditions, including a sector-typical discount rate of 4.5%, were integrated into the investment decision framework.

Through these targeted modifications, the CEKER model was successfully adapted to account for the functional, structural, and economic heterogeneity of the non-residential service sector. The adapted model enables realistic techno-economic assessments of heating transitions at the building level, forming a robust basis for policy scenario evaluation.

9.5. Sub-question 4

How do the policy interventions affect CO_2 emission reduction and end-user costs, and how do those impacts vary by building type and size?

The model results show that policy interventions significantly influence both technology adoption patterns and emission reduction outcomes.

Raising the gas price through an energy tax shifts building owners away from gas-based heating technologies towards more sustainable options, such as air-water heat pumps and district heating, resulting in substantial CO_2 emission reductions. Regulatory interventions, such as mandating a minimum energy label (Label D or A), further accelerate this transition. Combining economic and regulatory measures achieves the highest emission reductions, with the policy mix of raising gas taxes and mandating Label A achieving the largest emission reductions.

However, these more ambitious policy combinations also lead to the highest total end-user costs, driven mainly by increased capital expenditures (CAPEX) for deep retrofits. A milder intervention, such as a moderate gas price increase combined with a minimum Energy Label D requirement, already delivers significant CO_2 reductions while keeping end-user costs at a more moderate level, making it a more cost-effective and politically feasible option.

In terms of end-user costs, operational expenditures (OPEX) dominate yearly costs in all scenarios, but stricter policies shift a larger share towards CAPEX. Targeted financial support could help mitigate these upfront investment costs, especially for vulnerable segments.

Sector-specific analysis reveals that the assembly sector has the highest emission reduction potential but also incurs the highest yearly costs. By building size, small buildings (0–500 m^2) offer the greatest CO_2 reduction potential but face higher relative costs compared to larger buildings.

9.6. Answer to the Main Research Question

How do policy interventions improve CO_2 emission reductions in the Dutch non-residential service building stock, in terms of their effectiveness, cost-effectiveness, and distributional effects?

This study finds that policy interventions improve CO_2 emission reductions primarily by altering investment choices at natural replacement moments of heating systems. Policy measures change the cost-optimal options available to building owners, either by raising the operational costs of fossil fuel systems or by enforcing minimum insulation standards that enable low-carbon technologies to become economically attractive.

The adapted CEKER model, extended to represent the heterogeneity of non-residential buildings (Sub-question 3), shows that different interventions affect technology choices, building costs, and emission outcomes in predictable ways. The key findings from the sub-questions connect directly to the answer to the central research question:

- The system mapping (Sub-question 1) showed that decision-making is dominated by lifecycle cost considerations, with investment barriers such as upfront costs or investment inertia being important.
- The policy review (Sub-question 2) identified gas taxes, mandatory energy labels, and gas bans as promising interventions to influence these investment decisions.
- The model adaptations (Sub-question 3) ensured that building size, use function, and cost structure differences were reflected realistically.
- The scenario analysis (Sub-question 4) demonstrated how these interventions shift heating technology adoption and change emission outcomes across different building types and sizes.

9.6.1. Effectiveness

Combined interventions, particularly the combination of a gas tax increase and a mandatory minimum energy label A, lead to the highest CO_2 reductions. A moderate gas price increase (+100%) already shifts a substantial share of owners away from gas-based heating towards heat pumps and district heating. Mandatory label improvements reinforce this effect: by requiring insulation upgrades, they not only make all-electric systems technically feasible, but also improve their business case. Buildings that are obligated to invest in insulation find it more attractive to adopt a sustainable heating system, since the marginal cost difference with gas-based systems shrinks after the envelope upgrade. This shows that policy interventions influence emission reductions not only by making fossil options more expensive, but also by reducing the relative cost of sustainable alternatives at a trigger point for investment.

9.6.2. Cost-Effectiveness

Gas price increases are the most cost-effective intervention when evaluated purely by costs per tonne of CO_2 abated. Regulatory standards alone, such as a mandatory Energy Label D or A, are less cost-effective because they impose capital costs on all buildings, including those where sustainable heating would have been adopted voluntarily at a later stage. However, standalone gas price increases achieve lower total emission reductions compared to combined interventions.

The most balanced outcome is achieved by combining gas price increases with label requirements: this ensures deep emission reductions without excessive costs per tonne of CO_2.

9.6.3. Distributional Effects

Distributional effects are clear:

- Smaller buildings (0–500 m^2) and assembly buildings achieve relatively high CO_2 reductions per square metre, but face higher retrofit costs both in relative and absolute terms.

Without additional support, owners of these buildings would bear a disproportionate financial burden in the transition. To avoid this, financial support measures such as targeted investment subsidies or low-interest loans are necessary, focusing specifically on small and assembly buildings.

9.6.4. Policy Recommendations

Based on the findings, the following policy approach is recommended:

1. Gradually increase the energy tax on natural gas to make fossil heating systems less attractive.
2. Introduce a mandatory minimum energy label D requirement by 2030–2035 to create natural investment moments and make sustainable heating technologies financially viable after insulation upgrades.
3. Provide targeted financial support to small buildings and assembly buildings to lower effective retrofit costs.

This combination of measures addresses both cost barriers and timing barriers, ensuring that the sector moves towards lower emissions without imposing disproportionate burdens on vulnerable groups.

9.6.5. Robustness under Energy Price Uncertainty

The model shows that combined interventions perform well under both high and low future electricity price scenarios. Even if electricity prices rise or fall by 50%, the adoption of heat pumps and district heating systems remains strong when supported by label mandates. This indicates that a layered policy design combining economic and regulatory instruments is better able to maintain emission reduction trajectories under uncertain future energy conditions.

9.6.6. Conclusion

In conclusion, policy interventions improve CO_2 emission reductions in the Dutch non-residential service sector by shifting investment decisions towards sustainable heating options. Combining economic incentives (gas taxes) with regulatory trigger points (mandatory insulation levels) is the most effective and cost-efficient approach. However, targeted support for smaller and assembly buildings is necessary to ensure a fair and balanced transition across the sector.

10 Reflection

Writing this thesis marks the end of my student life—a chapter in my life can look back on with a lot of joy and gratitude. Allow me to briefly guide you through my student years before reflecting more deeply on the final stage of this life phase: my Master's thesis.

As an eighteen-year-old, I arrived in Delft without knowing that Delft initially was the ”wrong” choice for me. Early in my Industrial Design studies, I quickly realized that drawing was not my strongest skill, and the program didn't resonate with me. Despite earning sufficient credits, I decided to trust my gut and quit early. It was back to the drawing board: What did I truly want to study? Where did my interests lie? What did I want to improve at? And what do I want to contribute to society? After carefully reconsidering my options, I ended up back in Delft—ironically, the place that initially didn't meet my expectations. But this time, it had to be the right choice.

Systems Engineering, Policy Analysis & Management (or just simply 'Technische Bestuurskunde' in Dutch) soon proved to be exactly that. Complex issues at the intersection of technology and governance fascinated me, and thankfully, they suited me well. I quickly found many friends and a warm home where I lived for five wonderful years, a place I still love visiting. Choosing to restart my academic journey in Delft with a different program turned out to be one of the best decisions I've ever made.

I view my time in Delft as a period during which I matured, from a naive young boy into someone who now believes he understands more about how the world works (although that's certainly debatable). During my Bachelor's in Engineering and Policy Management, I discovered my passion for data analysis and modelling combined with policy analysis. At the start of my fifth year, I logically transitioned to the Master's program in Engineering & Policy Analysis, perfectly aligning with my interests.

This intersection of interests is clearly reflected in my thesis topic, where I attempted to map out the complex system of the non-residential built environment and adapt a model to extract actionable policy insights. CE Delft was the ideal place for this endeavour, providing valuable internal expertise and support whenever needed. As described in my foreword, my weekly conversations with Florian, who patiently answered nearly every question I had, were incredibly helpful. Additionally, Katja's sharp insights consistently challenged me to think deeper and from different perspectives, despite her busy schedule.

If I had to summarise my thesis-writing experience in one word, I would describe it as a roller coaster. You start slowly, trying to familiarise yourself with the topic, and suddenly, two months have flown by. The initial phase was particularly challenging for me. With a limited background in energy and virtually none in the built environment, it sometimes felt overwhelming to grasp exactly what problem I was investigating. My direction changed weekly, and when I finally thought I had clarity, feedback would steer me elsewhere. This iterative struggle is something every thesis writer encounters, and it's a huge relief when you finally define a solid scope and research question.

My first official meeting with my examination committee, my two supervisors, Laurens and Aad, didn't go smoothly and marked my first dip in this roller coaster. Underprepared, I mistakenly assumed it would be a brief, informal conversation, unaware that I was expected to deliver a presentation. This could have been avoided by better managing expectations beforehand, a lesson I immediately applied to future meetings.

When I finally began modelling, it felt liberating. Initially, I hesitated, feeling uncertain about whether I had sufficiently prepared to expand the model step-by-step methodically. Although I had created a conceptual model, my deeper understanding only came through actual practice. I've learned you sometimes just need to start, even when you feel unprepared, because you never fully are. You learn as you go, adjusting your focus and refining your research questions accordingly. The modelling phase was indeed the longest and had many ups and downs, but it was also the most enjoyable part, bringing the research to life.

A particularly learning moment during modelling occurred when I accidentally lost the entire model. Sometimes you hear these kinds of things happen, but I never imagined it could happen to me. Due to my misunderstanding of GitHub and Visual Studio Code functionalities, I erased months of work with a single click. Panic set in, realising I'd potentially lost two months' worth of effort. Thankfully, there was a chance to recover it through GitHub support, enabled by the Pro subscription I'd just acquired via TU Delft's license. After an agonizing half-hour, the model was restored. Lesson learned: Saving something in Visual Studio Code is not the same as pushing it to GitHub.

Planning tasks, processes, and deadlines during my thesis was another challenge. I've never been naturally strong at planning, often overestimating my capabilities within timeframes and underestimating the duration of tasks. During this process, I became more conscious and proficient at task prioritisation. Katja and Laurens advised me to maintain short and long lists to prioritize tasks effectively. Occasionally, I became overly fixated on minor details that retrospectively didn't justify the time invested. Active prioritisation creates clarity and focus, which is crucial in research since a model or project is never truly finished. There always remains scope for expansion and deeper exploration. You must set boundaries at some point, focusing strictly on what's achievable within the given timeframe.

In the final phase, I found myself needing more frequent contact with my examination committee. Keeping communication lines open ensured alignment with my supervisors, crucial for successfully completing the thesis. Here again, managing expectations and showing initiative made a difference. Initially hesitant, worrying about burdening Laurens and Aad given their demanding workloads, I eventually realized that open, proactive communication was key. If they were too busy, they would let me know—another valuable insight and lesson in self-discovery.

All these moments, experiences, setbacks, and triumphs have come together in a feeling of satisfaction and gratitude. Besides the invaluable support from Florian, Katja, Laurens, and Aad, I've learned a lot about myself. I discovered I sometimes found working alone challenging, missing the collaborative energy of teamwork. In my professional career, I intend to actively seek team-oriented environments that energize me. Although I don't yet know exactly where my next step will lead, I plan to take some time to clear my head, reflecting calmly and preparing for the exciting start of my professional journey.

References

Acciai, C., & Capano, G. (2018). Climbing down the ladder: A metaanalysis of policy instruments applications. https://www.ippapublicpolicy.org/file/paper/5b28e4eeaa3d0.pdf

Akhatova, A., & Kranzl, L. (2024). Agent-based modelling of building retrofit adoption in neighborhoods. https://doi.org/10.2139/ssrn.4884153

Anczewska, M., Newitała-Rej, M., & Śniegocki, A. (2025). *Opening a new chapter for heat pumps* (tech. rep.). Reform Institute. https://ireform.eu/s/uploads/POLICY_BRIEF_HEAT_PUMPS_final.pdf

Arnoldussen, J., van Zwet, R., Koning, M., & Menkveld, M. (2016, November). *Verplicht energielabel voor kantoren* (tech. rep.). EIB.

Becker, G. S. (1976). *The economic approach to human behavior*. University of Chicago Press. https://doi.org/10.7208/chicago/9780226217062.001.0001

Benson, A., Vargas, E., Bunts, J., Ong, J., Hammond, K., Reeves, L., Chaplin, M., & Duan, P. (2011). *Retrofitting commercial real estate: Current trends and challenges in increasing building energy efficiency* (tech. rep.). Institute of the Environment Sustainability. https://www.ioes.ucla.edu/project/retrofitting-commercial-real-estate-current-trends-and-challenges-in-increasing-building-energy-efficiency/

Bleyl, J. W., Bareit, M., Casas, M. A., Coolen, J., Hulsthoff, A., Mitchell, S., & Robertson, M. (2019). Building deep energy retrofit: Using dynamic cash flow analysis and multiple benefits to convince investors. *UsersTCP*. https://userstcp.org/wp-content/uploads/2019/11/6-369_Bleyl-etal._DER-MB_170319.pdf

BPIE. (2017, May). *Trigger points as a "must" in national renovation strategies* (tech. rep.). Buildings Performance Institute Europe. https://bpie.eu/wp-content/uploads/2017/05/Factsheet_B-170511_v4.pdf

Bremer, L., den Nijs, S., & de Groot, H. L. (2024). The energy efficiency gap and barriers to investments: Evidence from a firm survey in the netherlands. *Energy Economics*, *133*, 107498. https://doi.org/10.1016/j.eneco.2024.107498

Burgering, C. (2025, March). Esg economist - gas consumption structurally lower since energy crisis. https://www.abnamro.com/research/en/our-research/esg-economist-gas-consumption-structurally-lower-since-energy-crisis

CBS. (2022). Which sectors emit greenhouse gases? Which % 20sectors % 20emit % 20greenhouse % 20gases?

de Clerck, S. (2024). *Marktrapportage benchmark gemeentelijk vastgoed* (tech. rep.). Republiq. https://bouwstenen.nl/sites/default/files/uploads/Marktrapportage-Benchmark-Gemeentelijk-Vastgoed-2024.pdf

Dehens, J., Koster, E., & Kruit, K. (2021, June). *Ceker achtergrondnotitie* (tech. rep.). CE Delft. https://ce.nl/method/ceker/

Directorate-General for Energy. (2024). In focus: Energy efficient buildings - delivering energy and cost savings for eu citizens. https://energy.ec.europa.eu/news/focus-energy-efficient-buildings-2024-04-16_en

Dutchphoto. (2020, June). Luchtfoto van de torens aan de zuidas in zuid van amsterdam. https://www.anpfoto.nl/search.pp?pictureid=413139146

Eichholtz, P., Kok, N., & Sun, X. (2024, January). *Plicht voor energielabel c voor kantoren lijkt gewenst effect te hebben* (tech. rep.). ESB.

European Commission. (2024). Revised energy performance of buildings directive. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en

Garcia-Teruel, R. M. (2024). Overcoming the "tenant-owner dilemma" to foster energy efficiency in residential private rented housing. *Journal of Property, Planning and Environmental Law*, *16*, 185–200. https://doi.org/10.1108/JPPEL-02-2023-0006

Gillingham, K., & Palmer, K. (2014). Bridging the energy efficiency gap: Policy insights from economic theory and empirical evidence. *Review of Environmental Economics and Policy*, *8*, 18–38. https://doi.org/10.1093/reep/ret021

Goulder, L. H., & Parry, I. W. H. (2008). Instrument choice in environmental policy. *Review of Environmental Economics and Policy*, *2*, 152–174. https://doi.org/10.1093/reep/ren005

Government of the Netherlands. (2009). Mandatory epcs for buildings. https://www.government.nl/topics/energy-performance-certificates-for-homes-and-buildings/mandatory-epcs-for-buildings

Gysen, J., Bruyninckx, H., & Bachus, K. (2006). The modus narrandi. *Evaluation*, *12*, 95–118. https://doi.org/10.1177/1356389006064176

Hartnett, M. (2023). Effectiveness, efficiency, and equity: The three "e"s of policy analysis.

Hood, C. C. (1983). *The tools of government*. Macmillan Education UK. https://doi.org/10.1007/978-1-349-17169-9

Hoogervorst, N. (2024, April). *Hoe naar een aardgasvrije gebouwde omgeving in 2050?* (Tech. rep.). PBL. https://www.pbl.nl/system/files/document/2024-04/pbl-2024-hoe-naar-een-aardgasvrije-gebouwde-omgeving-in-2050_5504.pdf

Howlett, M. (2000). Managing the 'hollow state': Procedural policy instruments and modern governance. *Canadian Public Administration*, *43*, 412–431.

IEA. (2022). The global energy crisis. *World Energy Outlook 2022*. https://www.iea.org/reports/world-energy-outlook-2022/the-global-energy-crisis

Jaffe, A. B., & Stavins, R. N. (1994). The energy-efficiency gap what does it mean? *Energy Policy*, *22*, 804–810. https://doi.org/10.1016/0301-4215(94)90138-4

Jonker, H., Bakker, J., Zweers, N., Klösters, M., Kooger, R., & van Diemen, J. (2024, October). *Investeringsbeslissingen voor verregaande verduurzaming binnen de utiliteitsbouw tno publiek* (tech. rep.). www.tno.nl

Kapur, N., Hiller, J., Langdon, R., & Abramson, A. (2011, July). *Show me the money: Energy efficiency financing barriers and opportunities* (tech. rep.). Environmental Defense Fund. https://nicholasinstitute.duke.edu/sites/default/files/publications/show-me-the-money-energy-efficiency-financing-barriers-and-opportunities-paper.pdf

Kim, A. A., & Medal, L. (2024). Factors influencing energy-efficiency retrofits in commercial and institutional buildings: A systematic literature review. *Journal of Facility Management Education and Research*, *7*, 42–63. https://doi.org/10.22361/jfmer/181200

Klimaatwet. (2023). https://wetten.overheid.nl/BWBR0042394/2023-07-22

Komorowska, A., & Surma, T. (2024). Comparative analysis of district heating markets: Examining recent prices, regulatory frameworks, and pricing control mechanisms in poland and selected neighbouring countries. *Polityka Energetyczna – Energy Policy Journal*, *27*, 95–118. https://doi.org/10.33223/epj/175328

Koster, E., Kruit, K., Teng, M., & Hesselink, F. (2022, February). *The natural gas phase-out in the netherlands* (tech. rep.). CE Delft. https://ce.nl/wp-content/uploads/2022/04/CE_Delft_210381_The_natural_gas_phase-out_in_the_Netherlands_DEF.pdf

Kraft, M., & Scott, F. (2020, January). *Public policy: Politics, analysis, and alternatives, 7th edition* (7th ed.). CQ Press/Sage.

Kruit, K. (2021). Ceker kosten voor eindgebruikers rekenmodel. https://ce.nl/method/ceker/

Kruit, K. (2023). Decarbonizing the dutch buildings sector. *Oxford Energy Forum*. https://cedelft.eu/wp-content/uploads/sites/2/2023/02/Katja-Kruit_OEF-Issue-135_DECARBONISING-THE-DUTH-BUILDINGS-SECTOR.pdf

Kruit, K., Vendrik, J., van Berkel, P., van der Poll, F., Rooijer, F., Jossen, Q., de Meulemeester, H., Bruel, R., Carton, S., Rochet, A., & Zhang, T. (2020, July). *Zero carbon buildings 2050* (tech. rep.). www.noble.studio

KVK. (2022). Overview standard business categories (sbi codes). https://www.kvk.nl/en/about-the-business-register/overview-standard-business-categories-sbi-codes/

Maduta, C., Melica, G., D'Agostino, D., & Bertoldi, P. (2022). Towards a decarbonised building stock by 2050: The meaning and the role of zero emission buildings (zebs) in europe. *Energy Strategy Reviews*, *44*, 101009. https://doi.org/10.1016/j.esr.2022.101009

Mavrot, C., Potluka, O., Balzer, L., Eicher, V., Haunberger, S., Heuer, C., & Viallon, F.-X. (2025). What evaluation criteria are used in policy evaluation research: A cross-field literature review. *Evaluation and Program Planning*, *108*, 102512. https://doi.org/10.1016/j.evalprogplan.2024.102512

Milieu Centraal. (2025). Energiebelasting 2025. https://www.milieucentraal.nl/energie-besparen/inzicht-in-je-energierekening/energiebelasting-2025/

Munda, G., Albrecht, D., Becker, W., Havari, E., Listorti, G., Ostlaender, N., Paruolo, P., & Saisana, M. (2020). The use of quantitative methods in the policy cycle. In *Science for policy handbook* (pp. 206–222). Elsevier. https://doi.org/10.1016/B978-0-12-822596-7.00018-8

Mundaca, L., Neij, L., Worrell, E., & McNeil, M. (2010). Evaluating energy efficiency policies with energy-economy models. *Annual Review of Environment and Resources*, *35*, 305–344. https://doi.org/10.1146/annurev-environ-052810-164840

Nägeli, C., Jakob, M., Catenazzi, G., & Ostermeyer, Y. (2020). Towards agent-based building stock modeling: Bottom-up modeling of long-term stock dynamics affecting the energy and climate impact of building stocks. *Energy and Buildings*, *211*, 109763. https://doi.org/10.1016/j.enbuild.2020.109763

Niessink, R., Menkveld, M., & Sipma, J. (2017, November). *Verkenning utiliteitsbouw* (tech. rep.). ECN. https://www.bouwstenen.nl/sites/bouwstenen.nl/files/uploads/Verkenning%20Utiliteitsbouw.pdf

Olsthoorn, M., Schleich, J., & Hirzel, S. (2017). Adoption of energy efficiency measures for non-residential buildings: Technological and organizational heterogeneity in the trade, commerce and services sector. *Ecological Economics*, *136*, 240–254. https://doi.org/10.1016/j.ecolecon.2017.02.022

Özer, E., Kranzl, L., Müller, A., & Zakeri, B. (2024). The impact of energy prices in decarbonizing buildings' energy use in the eu27. *Energy and Buildings*, *323*, 114814. https://doi.org/10.1016/j.enbuild.2024.114814

Paris agreement. (2015). https://unfccc.int/sites/default/files/english_paris_agreement.pdf

PBL. (2024a, October). *Beleidsoverzicht en factsheets beleidsinstrumenten. achtergronddocument bij de klimaat- en energieverkenning 2024* (tech. rep.). Planbureau voor de Leefomgeving. www.pbl.nl/kev

PBL. (2024b, October). *Klimaat- en energieverkenning 2024* (tech. rep.) (Gebruik voor beleid of cijfers mbt klimaatdoelen gebouwde omgeving. Klein deel van dit grote rapport.). Planbureau voor de Leefomgeving. www.pbl.nl/kev

RICS. (2024, April). *Energy performance of buildings directive (epbd): Overview* (tech. rep.). Royal Institution of Chartered Surveyors (RICS). https://www.rics.org/content/dam/ricsglobal/documents/latest-news/RICS-EPBD-oveview.pdf

Rijksoverheid. (2019). Rijksbegroting: Wet fiscale maatregelen klimaatakkoord. *35304 C MEMORIE VAN ANTWOORD*. https://archief.rijksbegroting.nl/2020/kamerstukken,2019/11/29/kst269003.html

Rijksoverheid. (2024). Steeds meer kantoren met minimaal energielabel c. https://www.rijksoverheid.nl/actueel/nieuws/2024/10/02/steeds-meer-kantoren-met-minimaal-energielabel-c

Rosenow, J., Cowart, R., Bayer, E., & Fabbri, M. (2017). Assessing the european union's energy efficiency policy: Will the winter package deliver on 'efficiency first'? *Energy Research Social Science*, *26*, 72–79. https://doi.org/10.1016/j.erss.2017.01.022

RVO. (2017a, May). Energielabel utiliteitsgebouwen. https://www.rvo.nl/onderwerpen/wetten-en-regels-gebouwen/energielabel-utiliteitsgebouwen

RVO. (2017b). Energieprestatie indicatoren - beng. https://www.rvo.nl/onderwerpen/wetten-en-regels-gebouwen/beng/indicatoren

RVO. (2017c). Investeringssubsidie duurzame energie en energiebesparing voor zakelijke gebruikers (isde). https://www.rvo.nl/subsidies-financiering/isde/zakelijke-gebruikers

RVO. (2018). Energielabel c kantoren. https://www.rvo.nl/onderwerpen/wetten-en-regels-gebouwen/energielabel-c-kantoren

RVO. (2021). Hernieuwbare energie bij ingrijpende renovatie. https://www.rvo.nl/onderwerpen/wetten-en-regels-gebouwen/energieprestatie-eisen-verbouw-renovatie/hernieuwbare-energie

RVO. (2022a). Erkende maatregelenlijsten (eml). https://www.rvo.nl/onderwerpen/energiebesparingsplicht/eml

RVO. (2022b). Over de energiebesparingsplicht. https://www.rvo.nl/onderwerpen/energiebesparingsplicht/over-de-energiebesparingplicht

RVO. (2023a, January). Verschillen en overgang tussen de nen 7120 en nta 8800 voor nieuwbouwwoningen. https://www.rvo.nl/onderwerpen/wetten-en-regels-gebouwen/energielabel-woningen/verschillen-overgang-tussen-nen-7120-en

RVO. (2023b). Subsidieregeling duurzaam maatschappelijk vastgoed (dumava). https://www.rvo.nl/subsidies-financiering/dumava

RVO. (2025a). Energy investment allowance (eia). https://business.gov.nl/subsidy/energy-investment-allowance/

RVO. (2025b). Sme-credit scheme green (bmkb-groen). https://business.gov.nl/subsidy/sme-credit-green/

RVO. (2025c). Tax schemes for environmentally-friendly investments (mia and vamil). https://business.gov.nl/subsidy/mia-vamil/

Salamon, L. M. (2002, January). *The tools of government: A guide to the new governance*. https://www.researchgate.net/publication/248037530_The_Tools_of_Government_A_Guide_to_the_New_Governance

Schepers, B. (2020). *Cegoia* (tech. rep.). CE Delft. https://ce.nl/method/cegoia/

Sebi, C., Nadel, S., Schlomann, B., & Steinbach, J. (2019). Policy strategies for achieving large long-term savings from retrofitting existing buildings. *Energy Efficiency*, *12*, 89–105. https://doi.org/10.1007/s12053-018-9661-5

Sipma, J. (2023, November). *Verrijkte bag ter ondersteuning van lokale energetische vraagstukken* (tech. rep.). TNO. https://energy.nl/publications/verrijkte-bag-energetische-vraagstukken/

Sipma, J., Kremer, A., & Niessink, R. (2024, August). Energiekengetallen utiliteitsgebouwen. https://energy.nl/publications/energiekengetallen-utiliteitsgebouwen/

Smith-Spangler, C. M. (2012). Transparency and reproducible research in modeling. *Medical Decision Making*, *32*, 663–666. https://doi.org/10.1177/0272989X12458977

Szekeres, A., & Jeswiet, J. (2018). Effects of technological development and electricity price reductions on adoption of residential heat pumps in ontario, canada. *International Journal of Energy and Environmental Engineering*, *9*, 201–213. https://doi.org/10.1007/s40095-018-0263-y

Tollenaar, S., Verhulst, L., & van Marwijk, M. (2024, December). *Renovaties in de utiliteit* (tech. rep.). Panteia.

Trading Economics. (2022). Eu natural gas ttf. https://tradingeconomics.com/commodity/eu-natural-gas

Trein, P. (2024, July). Policy instruments and their implementation. In *Handbook of public policy implementation* (pp. 204–215). Edward Elgar Publishing. https://doi.org/10.4337/9781800885905.00025

Tweede Kamer der Staten-Generaal. (2019). Kamerstuk internationale klimaatafspraken [31793 nr. 191]. https://zoek.officielebekendmakingen.nl/kst-31793-191.html?

ürge-Vorsatz, D., Koeppel, S., & Mirasgedis, S. (2007). Appraisal of policy instruments for reducing buildings' co2 emissions. *Building Research Information*, *35*, 458–477. https://doi.org/10.1080/09613210701327384

van den Bergh, P. D. J., Biesmeijer, P. D. K., Davidson, P. D. M., Erisman, P. D. I. J. W., van Hal, P. D. A., Renes, D. R. J., van Soest, I. J. P., van Tilburg, D. R., de Vries, D. G., van Wee, P. D. B., Worrel, P. D. E., & Rooijer, I. F. (2021, April). *Kimaatbeleid gebouwde omgeving advies 2: Kbt klimaatcrisis beleid team* (tech. rep.). Klimaatcrisis Beleid Team.

Vattenfall. (2025). Tarieven energiebelasting. https://www.vattenfall.nl/grootzakelijk/energiebelasting/tarieven/

Vedung, E. (1998). Policy instruments: Typologies and theories. In M.-L. Bemelmans-Videc, R. C. Rist, & E. Vedung (Eds.), *Carrots, sticks sermons* (pp. 21–58). Routledge. https://doi.org/10.4324/9781315081748-2

Vringer, K., van Middelkoop, M., & Hoogervorst, N. (2016). Saving energy is not easy: An impact assessment of dutch policy to reduce the energy requirements of buildings. *Energy Policy*, *93*, 23–32. https://doi.org/10.1016/j.enpol.2016.02.047

A

System Analysis

A.1. Actor Overview

The non-residential built environment involves a variety of actors, each with distinct roles, goals, and levels of influence. Understanding these actors is important for interpreting the effects of policy interventions and their implementation strategies. The most prominent actors in the system include building owners, tenants, policymakers, grid operators, energy suppliers, technology/service providers, and financial institutions.

- **Building Owners (Owner-Users and Owner-Lessors)**: Building owners, including both owner-users (those who occupy and own the building) and owner-lessors (those who lease buildings to tenants), are the primary decision-makers in terms of investments in heating technologies and energy efficiency measures. Owner-users are responsible for all aspects of the building, including energy decisions, while owner-lessors are more focused on the financial aspects, as they invest in the building but do not bear the operational energy costs.
- **Tenants (Users)**: Tenants occupy and use the building but generally have little control over energy-related decisions. Their interests often conflict with those of building owners, especially in cases where the owner is responsible for the upfront investment, but tenants benefit from reduced energy costs, a dynamic known as the split incentive dilemma.
- **Policymakers and Regulators**: These actors are responsible for designing and enforcing policies and regulations that affect building owners' decisions. They implement standards, energy performance regulations, and financial instruments (such as taxes or subsidies) to encourage the adoption of sustainable heating technologies.
- **Grid Operators**: These actors manage the energy infrastructure, ensuring a reliable supply of energy for buildings. They also play a role in the integration of district heating systems and managing the capacity needed to support the energy transition.
- **Energy Suppliers**: Energy suppliers provide gas, electricity, or district heating to buildings, and are integral to the energy market. Their role in providing clean energy options and the

pricing of energy carriers impacts the financial feasibility of energy transitions for building owners.

- **Technology/Service Providers**: These actors supply and install energy-efficient heating systems and other energy technologies. They also offer advisory services to building owners on suitable heating solutions based on the building's specific needs.
- **Financial Institutions**: These institutions offer the capital and financial products (e.g., loans, grants) that enable building owners to invest in energy-efficient technologies and improve their buildings' energy performance.

Each of these actors has a varying degree of influence on the decision-making process and their interests and goals often overlap or conflict. For example, building owners are primarily interested in minimizing costs, while policymakers are focused on achieving environmental goals. In contrast, tenants might prioritize comfort and cost savings but have limited influence over investment decisions.

Table A.1: Actor analysis in the non-residential built environment

Actor	Role in the System	Interest / Goal	Influence
Building owner-user	Owns and occupies the building; responsible for investment and operation decisions.	Reduce operational costs, improve comfort, comply with regulations.	High
Building owner-lessor	Owns the building and leases it to third parties; decides on renovations.	Maximize return, maintain asset value, attract/retain tenants.	Medium
Tenant (user)	Occupies and uses the building; pays for energy but has little control over systems.	Minimize costs, improve comfort, continuity of operations.	Low
Grid operator	Manages connection to energy infrastructure; responsible for capacity and reliability.	Ensure stable supply, prevent congestion, coordinate network expansion.	Medium
Policymaker / Regulator	Designs and enforces policies, standards, and financial instruments.	Achieve climate targets, safeguard fairness and feasibility.	High
Technology / Service provider	Delivers and installs energy technologies; advises on solutions.	Increase sales, promote technologies, build long-term relationships.	Low
Financial institution	Provides capital or financial products for energy-efficiency investments.	Manage risk, support ESG-compliant investments, earn returns.	Medium
Energy supplier	Supplies gas, electricity or district heat; interacts with customers and tariffs.	Secure market share, promote carriers, comply with regulation.	Medium

A.2. Power-Interest Grid

The Power–Interest Grid (Figure A.1) visualises how different stakeholders in the non-residential building sector relate to decarbonisation efforts, by mapping their ability to influence outcomes (power) against their stake in those outcomes (interest).

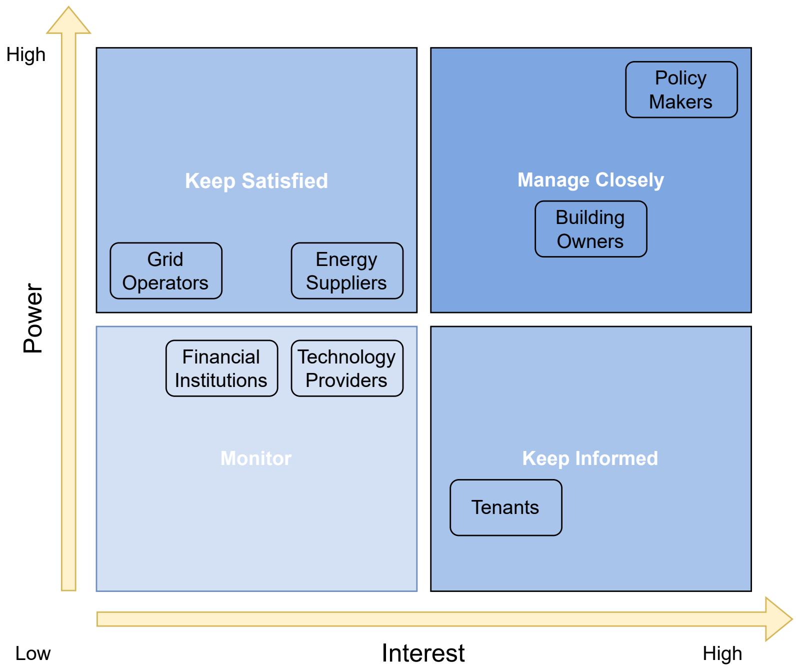

Figure A.1: Power–Interest Grid for stakeholders in building decarbonisation

Power: the capacity of an actor to shape investment decisions, policy implementation or technology adoption. **Interest:** the degree to which an actor is invested in the success of decarbonisation.

Grid Placement and Rationale

- **Policymakers** (High Power, High Interest): set regulations, incentives and targets; directly accountable for meeting climate goals.
- **Building Owners** (Medium–High Power, High Interest): decide on heating upgrades; motivated by cost savings, asset value and compliance.
- **Tenants** (Low Power, Medium Interest): benefit from comfort and lower bills; limited authority to change systems but can pressure owners.
- **Grid Operators** (Medium Power, Low Interest): manage energy distribution and grid stability; less directly concerned with individual building decarbonisation.
- **Energy Suppliers** (High Power, Medium Interest): control energy mix and pricing; respond to market and regulatory drivers.
- **Technology Providers** (Medium Power, Medium Interest): supply heat pumps, insulation, etc.; profit from market growth but do not set policy.
- **Financial Institutions** (Medium Power, Medium Interest): enable financing (green loans, grants); their engagement depends on risk–return profiles.

This analysis highlights which actors policy packages must engage (e.g. high-power/high-interest) and where additional outreach or incentives may be needed (e.g. low-power but high-interest groups) to ensure effective, equitable decarbonisation.

A.3. Buildings

Classification of Buildings

Table A.2: SBI classification and its relation to energy sectors

SBI-letter	SBI description	Energy sector for classification
A	Agriculture, forestry and fishing	agriculture
B	Mining of resources	industry
C	Industry	industry
D	Electricity, gas, steam and cooled air supply	production
E	Water supply; waste management and remediation	industry
F	Construction	industry
G	Wholesale and retail trade; repair of motor vehicles	services
H	Transportation and storage	services
I	Accommodation and food service activities	services
J	Information and communication	services
K	Financial institutions	services
L	Real estate activities	services
M	Professional, scientific and technical activities	services
N	Administrative and support service activities	services
O	Public administration and social security	services
P	Education	services
Q	Human health and social work activities	services
R	Arts, entertainment and recreation	services
S	Other service activities	services
T	Households as employers	services
U	Extraterritorial organizations and bodies	services
	No economic activity	residential

A.4. Active Policy Interventions in the Dutch Non-Residential Built Environment

The Dutch government employs various **policy interventions** to drive the sustainability of the non-residential building sector (service-oriented buildings such as assembly halls, healthcare facilities, offices, educational institutions, accommodations, sports venues, and retail). Below, the key national measures are discussed by intervention type. All measures are supported by official sources from the Ministry of the Interior and Kingdom Relations, RVO, or relevant legislation.

Taxes as an Incentive for Energy Savings

- **Energy Tax on Natural Gas and Electricity:**

  An important financial instrument is the energy tax. Reformed under the 2019 Climate Agreement, the tax structure now makes natural gas more expensive and electricity relatively cheaper, thereby providing a **strong incentive** to pursue sustainable alternatives (Rijksoverheid, 2019).

- **Renewable Energy Surcharge (ODE):**

  Until 2023, the Renewable Energy Surcharge (ODE) was a separate levy on energy consumption to fund renewable energy projects. In 2023, the surcharge was reduced to zero and has been fully integrated into the energy tax as of 2024. Due to the degressive structure of the energy tax and the fixed tax reduction per electricity connection, non-residential buildings with high energy consumption benefit relatively less from tax relief compared to small-scale users.

Subsidies for Sustainable Investments

The government directly supports non-residential buildings with **subsidies** that lower the investment threshold for insulation, sustainable installations, and renewable energy:

- **Subsidy Scheme for Sustainable Social Real Estate (DUMAVA):** This subsidy assists owners of *social real estate* (e.g., schools, government buildings, healthcare institutions, museums, and monuments) with the costs of making their buildings sustainable (for insulation, installations, etc.). DUMAVA covers a portion of investments in measures such as insulation, solar panels, and heat pumps (RVO, 2023b).

  (Status: Active; application period reopens in mid-2025.)

- **Investment Subsidy for Sustainable Energy (ISDE) – Business:** Under ISDE, business users receive subsidies when investing in sustainable heat generation and small-scale renewable energy systems. This covers installations such as (hybrid) heat pumps, solar water heaters, or small wind turbines. The subsidy helps reduce payback periods for technologies like heat pumps deployed in non-residential buildings (RVO, 2017b).

  (Status: Active, application ongoing.)

- **Stimulation of Renewable Energy Production (SDE++):** SDE++ is an operating subsidy for large-scale renewable energy production or CO_2 reduction projects. Companies and non-profit organizations receive support to make projects profitable, for instance, installing large photovoltaic systems on roofs or deploying innovative climate technologies in hospitals or data centers (RVO, 2023a).

(Status: Active, with annual rounds.)

Fiscal Arrangements and Green Financing

In addition to direct subsidies, fiscal incentives and financing measures make sustainable investments in non-residential buildings more attractive:

- **Energy Investment Allowance (EIA):** The EIA provides a fiscal allowance for investments in energy-efficient technologies or renewable energy, allowing companies to deduct 40% of the investment cost from their taxable profit (RVO, 2025b). This significantly shortens the payback period for investments in building-related energy savings, as listed on the annual Energy List.

  (Status: Active; the allowance stands at 40% for 2024 (Belastingdienst, 2025).)

- **Environmental Investment Allowance (MIA) and Vamil:** These measures stimulate eco-friendly investments by granting additional tax deductions (MIA) of up to 27%, 36%, or 45% on certain sustainable investments, and the possibility to depreciate 75% of the investment cost at the entrepreneur's discretion (Vamil)(RVO, 2025c). Together, they lower both liquidity and tax burdens for green investments, making projects (such as green roofs or efficient ventilation systems) financially attractive.

  (Status: Active; percentages depend on the category defined in the Environmental List.)

- **BMKB-Groen (SME Guarantee Scheme – Green):** This scheme extends the existing guarantee arrangement for SME loans to support **green investments** (RVO, 2025c). The government guarantees up to 75% of a green loan, making it easier for banks to lend to SMEs for sustainability improvements in buildings (e.g., bringing a building up to at least energy label C).

  (Status: Active; applications accepted until June 30, 2027.)

Regulations and Obligations

Stricter regulations have been established in recent years to improve the energy performance of non-residential buildings:

- **Mandatory Energy Savings (Environmental Management Act / Environmental Planning Act):** Organisations with an annual energy consumption of over 50,000 kWh electricity or 25,000 m³ natural gas (or equivalent) are required to implement *all energy-saving measures with a payback period of 5 years or less (RVO, 2022a).*

  Compliance: Organisations must submit an energy-saving report every 4 years. A reporting round was due by December 1, 2023. For very large users, an Energy Audit obligation every 4 years also applies. Oversight is provided by municipalities and environmental agencies. This regulation ensures that even without direct economic incentives, the most viable energy-saving steps are taken.

- **Energy Label C Requirement for Offices:** As of January 1, 2023, office buildings larger than 100 m² must have at least an energy label C (a maximum of 225 kWh primary fossil energy per

m^2 per year, or an energy index of ≤1.3) (Rijksoverheid, 2024). Offices that do not comply cannot be used as offices. This requirement, embedded in the Building Decree (formerly the Building Code), compels owners to invest in better insulation, more efficient systems, and sustainable energy production (RVO, 2018). Exceptions exist for monuments, temporary structures, and small offices (<100 m^2). Compliance is supported by initiatives with large property owners aiming at portfolio-wide sustainability by 2030.

- **Mandatory Energy Label for Sale or Rent:** In addition to the office-specific requirement, non-residential buildings must display a valid energy label when sold, rented, or delivered (RVO, 2017b). This is an implementation of the European EPBD directive (European Commission, 2024b). The requirement applies to a broad range of use functions such as offices, educational buildings, assembly venues, healthcare facilities, accommodations, sports venues, and retail. Failure to provide an energy label may result in fines, thereby encouraging owners to maintain or improve their building's rating.
- **Natural Gas Ban in New Construction:** Since July 1, 2018, new buildings are in principle banned from connecting to the gas grid (RVO, 2022b). This legislative change ensures that new construction (residential or non-residential) is carried out with electric (or alternative) systems to meet the nearly-zero energy demand requirements (BENG standard as described below). The ban generally obliges projects to employ all-electric installations (e.g., heat pumps) or connect to a sustainable heat network, with very few exceptions.
- **Nearly Zero-Energy Building (BENG) Requirements for New Construction:** As of January 1, 2021, all new buildings in the Netherlands must comply with the Nearly Zero-Energy Building (BENG) requirements, which replace the former EPC standard (RVO, 2017a). BENG specifies three indicators: maximum energy demand per m^2, maximum primary fossil energy use per m^2, and a minimum share of renewable energy. This approach ensures new non-residential buildings—such as offices and schools—are built to a high energy-performance standard. BENG is closely linked with the natural gas prohibition, effectively making new buildings fossil-free.
- **Minimum Renewable Energy Requirements for Major Renovations:** Since February 1, 2022, major renovations (where more than 25% of the building envelope is replaced and the heating/cooling systems are updated) must incorporate a minimum share of renewable energy (RVO, 2021). In practice, for example, a major office renovation that replaces the HVAC system may be required to install solar panels or integrate a (hybrid) heat pump. The exact minimum requirement is determined based on the ratio of roof area to usable floor area and can be met by various renewable systems.

B

CEKER Model

B.1. Data Preprocessing for the Adapted CEKER Model

This appendix outlines the main data preprocessing steps performed on the enriched BAG dataset to prepare it for use in the adapted CEKER model.

B.1.1. Selection of Buildings

Only buildings with a single dominant non-residential use function (covering more than 50% of the usable floor area) were included. Buildings with mixed or unknown dominant functions were excluded for consistency.

B.1.2. Assignment of Primary Heating Systems

Since the enriched BAG dataset does not contain information on the installed heating systems, primary heating systems were inferred based on:

- Buildings constructed from 2021 onwards were assumed to have electric heat pumps, unless connected to a district heating network.
- Buildings constructed before 2021:
    - With energy label A+ or higher: electric heat pump.
    - With energy label A or lower: condensing gas boiler.
- District heating connections were identified using the `warmtenet_pbl1` variable.

B.1.3. Handling of Energy Consumption Data

Indicative gas, electricity, and heat consumption values provided in the dataset (in kWh/m²/year) were used directly without recalculation (Sipma, 2023).

B.1.4. Summary of Key Assumptions

- Dominant use function represents the building's primary energy use characteristics.

- Heating system type is inferred based on construction year, energy label, and district heating connection.
- Provided energy consumption intensities are sufficiently accurate for aggregate-level analysis, despite possible variation at the individual building level.

C Results

C.1. Absolute Annual Emission Reduction

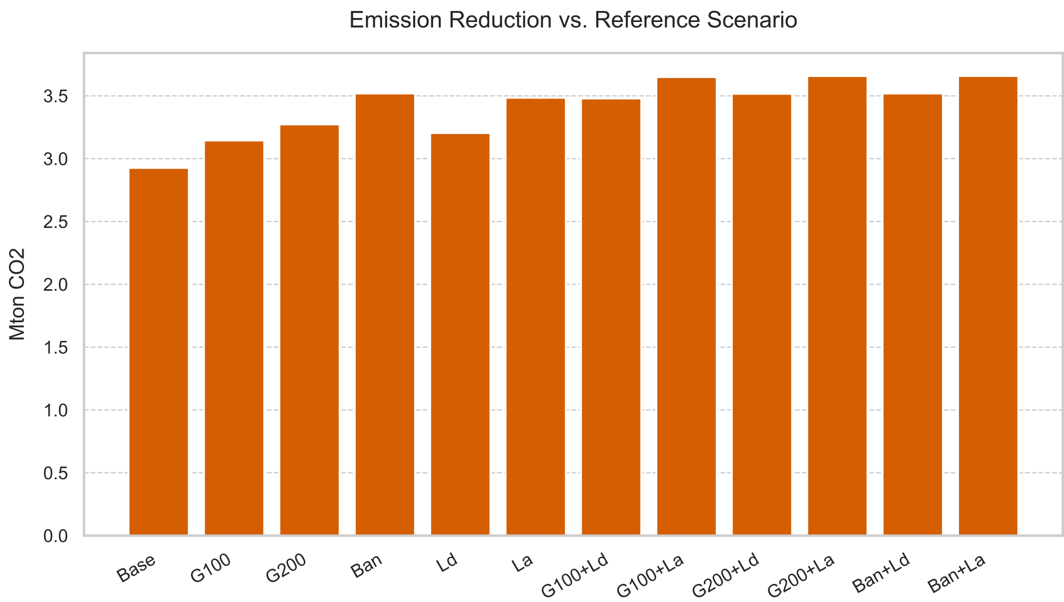

Figure C.1: Total Annual Emission Reduction Compared to Reference Scenario

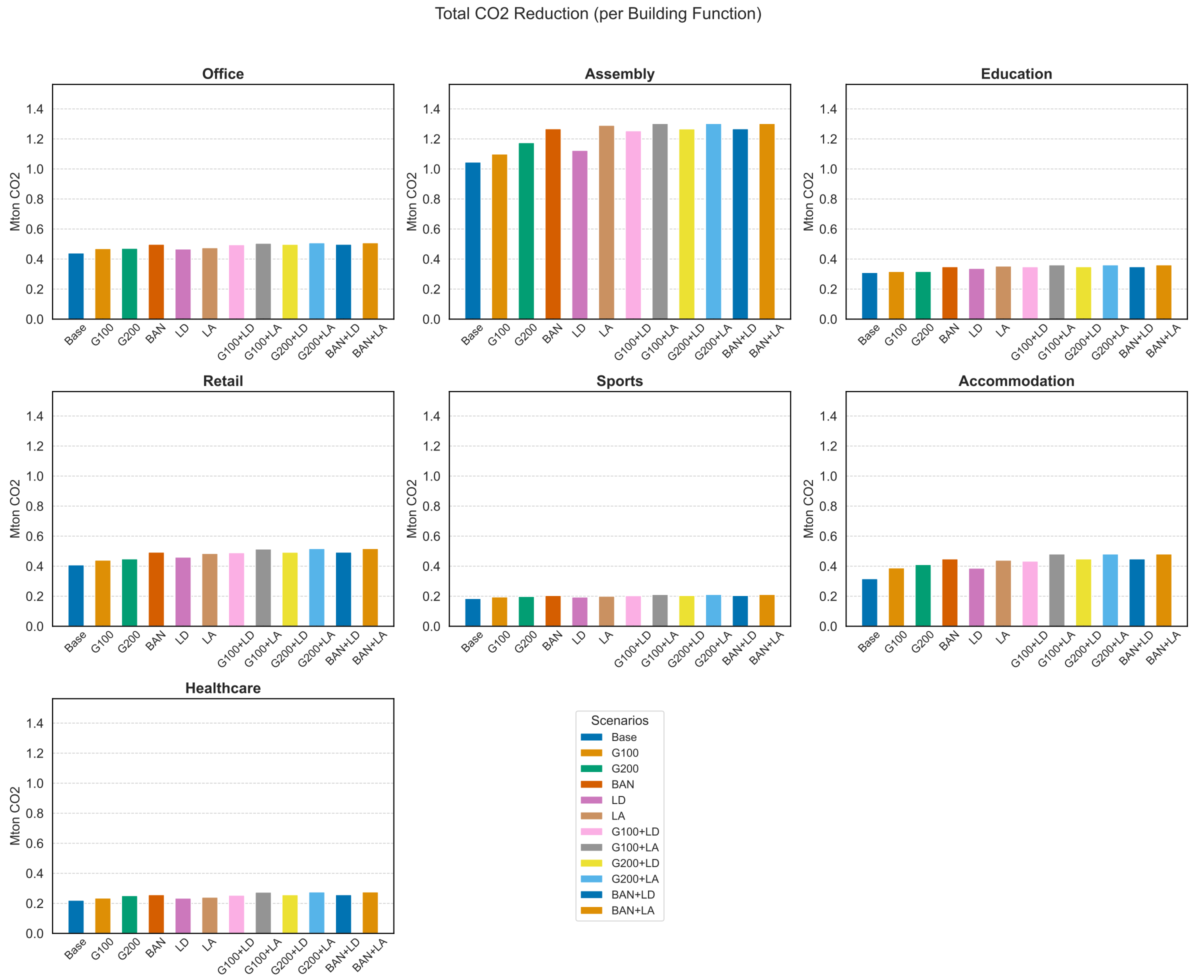

Figure C.2: Total Annual Emission Reduction per Scenario

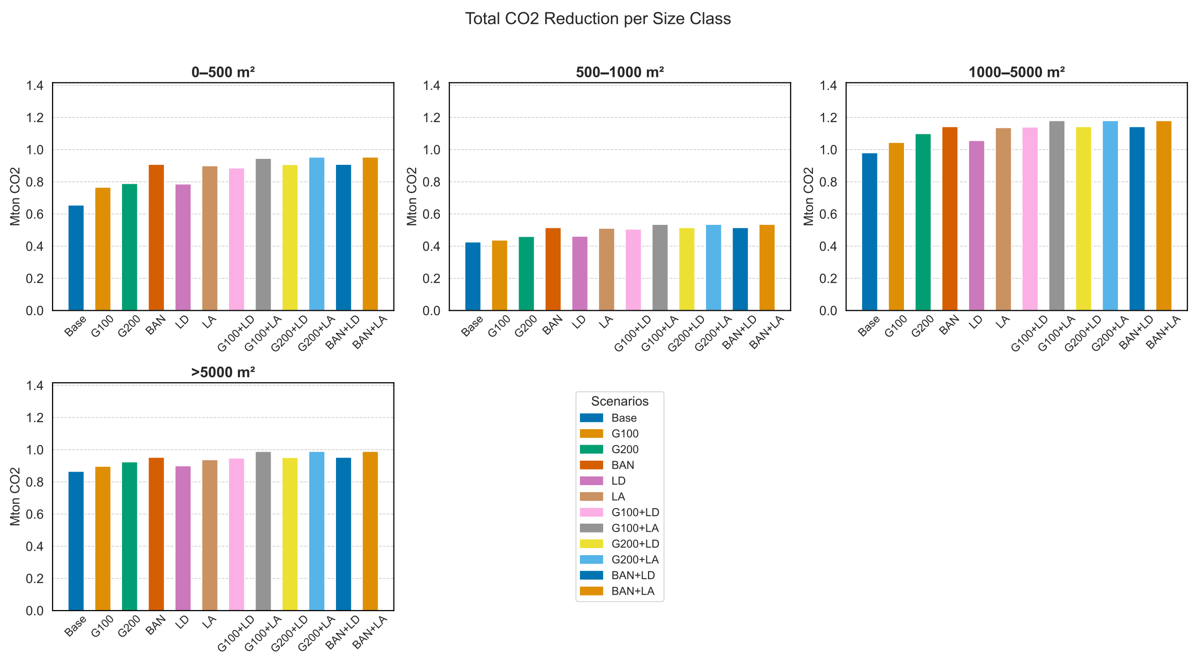

Figure C.3: Average Yearly Total Costs per Size Class