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Technico-Economic Analysis of Building Retrofit on Power Systems

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ABSTRACT:

Germany's 2045 climate-neutrality target requires coordinated decarbonisation of electricity supply and residential heating. This thesis quantifies how building-envelope retrofit interacts with heat-pump electrification in Germany using the open-source PyPSA-Eur sector-coupled capacity-expansion model at 5-node, 3-hour resolution under a 2050 net-zero target. Eight scenarios combine retrofit and heat-pump deployment across heat-demand reductions of 15%, 29%, and 45%, with additional smart heat-pump control sensitivities. A post-processing cost-benefit framework combines modelled power-system savings with retrofit investment costs and secondary value streams. For reproducibility, a GitHub repository is included, which provides clean code, scenario outputs, thesis plots, and replication results. The results show that each percentage point of heat-demand reduction lowers German power-system costs by approximately €0.5 bn/yr, with no diminishing returns up to 45%. Under conservative accounting, the campaign-period optimum occurs at 1%/yr renovation, yielding €3.1 bn/yr net benefit and a benefit to cost ratio of 1.37, while the 2%/yr EU target is net-negative during the campaign period but becomes positive under extended lifetime accounting. Retrofit also reduces the grid-flexibility value of heat pumps, with peak smoothing falling from 20.7% at baseline to 1.4% under deep retrofit. Smart heat-pump control cuts system costs by 25% (€17 bn/yr), although benefits diminish after initial thermal-mass smoothing. Heat pumps are cost-optimal at 69–81% share across all scenarios, suggesting that boiler bans reinforce, rather than drive, the main system-cost outcome. The thesis recommends a 2%/yr renovation target combined with retrofit cost-reduction policies and mandatory smart heat-pump control standards.

KEYWORDS: Building retrofit, Energy system modeling, Sector coupling, PyPSA-Eur

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Abbreviations

AGEB	German Working Group on Energy Balances
BBSR	German Federal Institute for Research on Building, Urban Affairs and Spatial Development
BCR	Benefit-Cost Ratio
BEG	German Federal Funding for Efficient Buildings
BMWK	German Federal Ministry for Economic Affairs and Climate Action
BNetzA	German Federal Network Agency
BPIE	Buildings Performance Institute Europe
CAPEX	Capital Expenditure
CBA	Cost-Benefit Analysis
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
COP	Coefficient of Performance (of a heat pump)
DAC	Direct Air Capture
DENA	German Energy Agency
DRI	Direct Reduced Iron
DSO	Distribution System Operator
EBPD	Energy Performance of Buildings Directive (EU)
ENTSO-E	European Network of Transmission System Operators for Electricity
ERA5	ECMWF Reanalysis v5 (weather data)

ETS1	European Union Emissions Trading System (existing, covers power and industry)
ETS2	European Union Emissions Trading System for buildings and road transport (from 2027)
EU	European Union
GEG	German Building Energy Act
GW	Gigawatt
GWh	Gigawatt-hour
HiGHS	High-performance optimization solver (open-source LP)
HP	Heat Pump
HPC	High-Performance Computing
HVDC	High-Voltage Direct Current
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IWU	Institut Wohnen und Umwelt (German Institute for Housing and Environment)
JRC-IDEES	Joint Research Centre Integrated Database of the European Energy System
LP	Linear Program (or Linear Programming)
MILP	Mixed-Integer Linear Program
Mm^2	Million square metres
Mt	Megatonne (10^6 tonnes)
$MtCO_2$	Megatonne of carbon dioxide
MW	Megawatt
MWh	Megawatt-hour
NDP	Network Development Plan

NPV	Net Present Value
OPSD	Open Power System Data
OPEX	Operational Expenditure
PyPSA	Python for Power System Analysis
PyPSA-Eur	PyPSA-Eur (sector-coupled European energy system model)
RQ	Research Question
S0, S1, S2, S3	Scenario labels (defined in Chapter 4)
S3-Low, S3-High	Sensitivity scenarios on retrofit depth
SOC	State of Charge (of storage)
TABULA	Typology Approach for Building Stock Energy Assessment
TTF	Title Transfer Facility (Dutch gas hub, European wholesale gas reference)
TWh	Terawatt-hour (10^{12} watt-hours)
TYNDP	Ten-Year Network Development Plan
UN	United Nations
WSL	Windows Subsystem for Linux

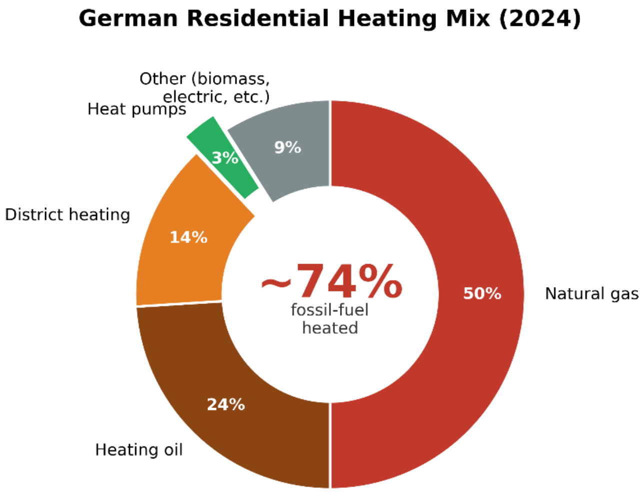
1 Introduction

1.1 Context and Motivation

Climate change driven by anthropogenic CO_2 emissions is now well established as the principal long-term threat to ecological stability and human welfare, and the building sector sits at the centre of any credible response. Carbon dioxide accounts for roughly two-thirds of the radiative forcing from human activity and, owing to its centennial atmospheric lifetime, today's emissions lock in tomorrow's warming [1]. The Intergovernmental Panel on Climate Change has established that limiting warming to 1.5 °C — the central ambition of the Paris Agreement — requires reaching global net-zero CO_2 emissions by around mid-century [1].

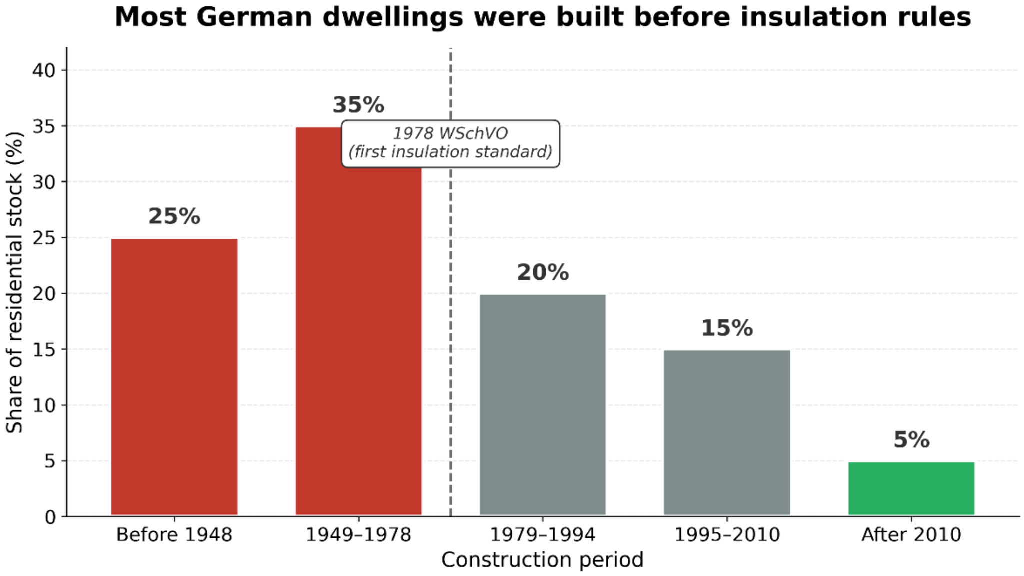
The European Union has translated this scientific imperative into binding law. The European Green Deal [2] and the subsequent European Climate Law [3] commit the Union to climate neutrality by 2050, with an intermediate target of at least 55% net emission reductions by 2030 under the Fit for 55 package. Germany has gone further: the amended Federal Climate Protection Act commits the country to climate neutrality by 2045 [4]. Hitting these targets means restructuring every part of the energy system that today depends on fossil fuels.

The building sector is one of those parts. Buildings account for approximately 40 % of final energy consumption and 36 % of energy-related greenhouse gas emissions in the European Union, with around 80 % of household energy use going to space heating, water heating, and cooling [5]. In Germany the picture is sharpened by a structural dependence on natural gas: roughly half of all dwellings are heated by gas boilers (Fig-ure 1), and residential and commercial buildings together account for about 37 % of final energy consumption [6], [7]. The 2022 energy crisis made visible — to households and to policymakers — that this dependence is no longer a stable foundation. Decarbonising heat is therefore simultaneously a climate-policy, security, and affordability question.



Source: BDEW, Heating structure of the German housing stock, 2024.

Figure 1. German Residential Heating Mix



Source: BBSR, Gebäudereport 2022 — Bauen und Wohnen in Deutschland.

Figure 2. Share of Residential Stock in Germany

1.2 Two Levers, One Coupled System

Two decarbonisation levers dominate the policy debate. The first is building-envelope retrofit: insulation, windows, air-tightness - measures that cut useful heat demand at the source. The second is heating electrification, principally through heat pumps that couple residential heating to the electricity grid. The recast Energy Performance of Buildings Directive makes both legally salient by requiring all new buildings to be zero-emission from 2030 and the residential stock to reduce primary energy use by at least 16% by 2030 [8]. Germany's Building Energy Act and Federal Funding for Efficient Buildings subsidy programme push in the same direction [9].

The challenge is that the two levers are not independent. Retrofitting a house reduces the heat-pump load it would otherwise impose; that lower load reduces the wind, solar, and storage capacity the power system needs to build; the cost of those avoided investments is therefore a system-level benefit of retrofit that does not appear on any household's electricity bill. Conversely, electrifying heat without retrofitting first means oversizing every heat pump and every kilowatt of supporting renewable capacity behind it. The two decisions are coupled through the energy system, and the optimal allocation is not obvious from either side alone.

1.3 Literature Review and Research Gap

The challenge of decarbonising the German heating sector has produced two broad streams of research that this thesis sits between. On the supply side, the German energy-system modelling community has built increasingly detailed capacity-expansion models of the German and European electricity systems — initially proprietary models such as Renewable Energy Model (REMod) [15] and Price-Induced Market Equilibrium System (PRIMES) [16], and more recently the open-source Python for Power System Analysis (PyPSA-Eur) framework [11], [12] which has become the dominant academic reference for European decarbonisation modelling. These models capture the supply-side dynamics in fine detail but typically represent the building sector as an aggregated exogenous demand input. On the demand side, bottom-up building-stock studies anchored in the Institute for Housing and Environment (IWU) and Typology Approach for Building Stock Energy Assessment (TABULA) typologies have demonstrated repeatedly that envelope retrofit can reduce heat demand by 40–60 % at the archetype level [17], with the binding constraint not being technical potential but renovation rate — currently around 1 % per year in Germany, well below the 2–3 % needed to align with the 2045 neutrality target [13]. These studies, by contrast, treat the energy supply system as exogenous.

The technical feasibility of the two principal levers is now well established. Recent Fraunhofer Institute for Solar Energy Systems (ISE) field-monitoring of heat pumps in retrofitted German residential buildings reports seasonal performance factors of 2.6 to 4.9 for air-source units and 3.6 to 5.4 for ground-source units, with electric back-up elements contributing only a small fraction of total energy use even in cold winters [14]. The persistent claim that heat pumps cannot work efficiently in older German buildings is, on the evidence, no longer defensible. What remains contested is the system-level economics: given that both levers are technically feasible, how should their depth be set to minimise the total cost of meeting the 2050 climate constraint?

The single most important methodological reference for this thesis is Zeyen, Hagenmeyer and Brown [10], "Mitigating heat demand peaks in buildings in a highly renewable European energy system" (Energy, 2021). This is, to the author's knowledge, the first peer-reviewed study to co-optimise building-envelope retrofit simultaneously with electricity, heat, and transport sectors at hourly resolution within a single sector-coupled net-zero model. The work shows three findings that shape the present thesis. First, the strong seasonal peaks of space-heating demand drive up total system cost by approximately 30 % compared with a heating profile without seasonal variation — meaning the cost of decarbonising heat is mostly the cost of meeting the winter peak. Second, building renovation is the largest single cost-reduction lever among the demand-side options, responsible for the largest share of a possible 17 % system-cost reduction. Third, the cost-optimal renovation level is driven by the peak, not by the total — the model selects the level of retrofit that cuts the winter peak enough to make the residual supply system tractable.

The Zeyen et al. study has limitations that motivate the present work. The analysis is conducted at European aggregate, with each country represented as a single node and the heating sector aggregated to a broad pan-European profile. Germany is not analysed in detail as a separate case. The retrofit decision is made endogenously, which yields a single cost-optimal point but obscures the marginal trade-off that policymakers actually need: how does cost change as renovation ambition is varied? And the analysis stays inside the optimisation — no post-processing cost-benefit accounting is performed that would translate avoided system costs into a policy-actionable benefit figure inclusive of value streams (household bill savings, European Union Emissions Trading System for buildings and road transport (ETS2) revenue, avoided imports, comfort gains) that lie outside the system optimisation but matter for the renovation-policy debate.

This thesis fills three specific gaps. First, it produces a Germany-specific quantification at 5-node resolution of how retrofit depth affects the cost-optimal power-system capacity mix — a level of granularity below the European aggregate at which the existing literature operates. Second, it uses a sensitivity decomposition across three retrofit depths to characterise the marginal system value of retrofit, rather than reporting a single endogenous optimum. Third, it combines the system-cost output with a post-processing cost-benefit framework that brings the four secondary value streams into the analysis, producing net-benefit numbers directly usable by the German renovation-policy debate.

1.4 Research Questions and Objective

The objective is to quantify the techno-economic impact of building envelope retrofit and heat-pump electrification on the German energy system, and to identify the cost-optimal renovation ambition level through scenario analysis and sensitivity testing. Three research questions follow:

Research Question 1 (RQ1) – Technical: How do renovation rates affect the cost-optimal installed capacities of wind, solar, storage, and heat pumps in Germany through 2050?

Research Question 2 (RQ2) – Economic: What is the system-level cost benefit of building retrofit in terms of avoided power-system investment, and how does this benefit scale with renovation ambition?

Research Questio 3 (RQ3) – Policy: Given the technical and economic findings, what concrete actions should the German government take to decarbonise the residential heating sector, and in what order should those actions be sequenced? Specifically: (i) at what annual renovation rate should the Federal Funding for Efficient Buildings (BEG) subsidy programme target the residential stock; (ii) should the Building Energy Act (GEG) fossil-boiler phase-out be implemented in parallel with, or sequenced after, the insulation requirement; and (iii) should the Network Development Plan (NDP) of the Federal Network Agency (BNetzA) build grid capacity for a high-heat-demand future or a low-heat-demand future?

The three questions are nested. RQ1 establishes the physical mechanism: how the system responds to demand reduction. RQ2 monetises that mechanism: what avoided investment is worth. RQ3 translates the answer into specific policy actions and their sequencing — naming the instruments (BEG, GEG, NDP) and the ministries responsible (Federal Ministry for Economic Affairs and Climate Protection, BMWK; and BNetzA), and asking what they should do and in what order. Together the three questions form the spine of this thesis, and each subsequent chapter explicitly returns to one or more of them.

1.5 Approach in Brief

The questions are answered with the open-source PyPSA-Eur sector-coupled capacity-expansion model [11], [12], configured for Germany at 5-node spatial resolution and 3-hour temporal resolution over the 2013 weather year, optimised for the 2050 net-zero end-state.

Eight scenarios isolate and recombine the two policy levers. Six primary scenarios constitute the core analytical design: Scenario 0 (S0) - Baseline; Scenario 1 (S1) - Insulation only; Scenario 2 (S2) - Electrification only; Scenario 3 (S3) - Combined moderate; Scenario 3 with the low retrofit rate (S3-Low) and high retrofit rate (S3-High). Two additional sensitivity scenarios test smart heat-pump control through demand-profile smoothing (12-hour and 24-hour windows representing building thermal mass and buffer storage respectively). The S3-Low / S3 / S3-High triplet is the methodological heart of the work: it generates a system-cost curve as a function of retrofit depth, from which the marginal system value of retrofit is computed.

That value is then fed into a post-processing system-level cost-benefit analysis that compares the avoided power-system investment against the cost of the retrofit itself, and adds four additional value streams drawn from secondary literature: direct energy-bill savings to households, CO_2-pricing benefits under the EU ETS2 (projected at €60/tCO_2), avoided fossil-fuel imports valued at wholesale gas prices, and health and comfort co-benefits estimated at €70/m^2 of renovated floor area [13], [14]. Together, the system optimisation and the cost-benefit framework deliver a complete economic picture rather than a single capacity result.

1.6 Contributions

This thesis makes four contributions. First, it develops a reproducible open-source PyPSA-Eur framework for evaluating German building decarbonisation policy, combining 5-node spatial resolution, 3-hour temporal granularity, retrofit modelling, and post-processing cost-benefit analysis. Second, it quantifies the system value of retrofit and heating electrification through a controlled scenario design that isolates and recombines both levers across different renovation depths. Third, it identifies two policy-relevant mechanisms: heat pumps are cost-optimal for roughly 70–80% of heat demand even without explicit mandates, and their grid-flexibility value declines as retrofit depth increases. Fourth, it translates these findings into concrete recommendations for the Federal Ministry for Economic Affairs and Climate Protection (BMWK), the Federal Network Agency (BNetzA), and the implementation of the Building Energy Act (GEG), supporting the EU Renovation Wave and Germany’s 2045 net-zero strategy.

1.7 Outline

Chapter 2 describes the PyPSA-Eur model, the mathematical formulation, the data sources, the scenario design, the cost-benefit framework, and the validation checks performed on the output. Chapter 3 presents the scenario results - installed capacities, system costs, heat-demand peaks, and the retrofit sensitivity curve. Chapter 4 develops the cost-benefit analysis and interprets the findings against German policy targets. Chapter 5 concludes with policy recommendations and identifies priorities for future work.

2 Methodology

The research questions stated in Chapter 1 — technical, economic, and policy — require a methodology that does three things. It must represent the electricity and heating sectors together, since the whole point is to capture how retrofit on the building side ripples back through to capacity investment on the supply side. It must operate at hourly resolution over a full year, because winter heat-demand peaks rather than annual totals are what drive system design [10]. And it must perform endogenous capacity-expansion optimisation, so that the cost-optimal mix of wind, solar, storage, heat pumps, and gas back-up is found by the model rather than assumed by the analyst. No bottom-up building-stock model satisfies the third requirement, and no electricity-only capacity-expansion model satisfies the first. The open-source PyPSA-Eur framework [11], [12] satisfies all three and is therefore adopted as the methodological backbone.

The chapter is organised as follows. Section 2.1 introduces the PyPSA-Eur framework. Section 2.2 explains the optimisation problem in full: the decision variables (2.2.1), the objective function (2.2.2), the constraints (2.2.3), and the parameters and data sources (2.2.4). Section 2.3 describes the configuration choices that focus the model on the German power-system question. Section 2.4 explains the heating-sector representation in detail, including the COP modelling and the retrofit constraint. Section 2.5 presents the scenario design. Section 2.6 describes the system-level cost-benefit framework that sits on top of the optimisation. Section 2.7 reports the validation and quality-assurance checks. Table 1 presents a mapping methodology to research questions, which explains which methodological component is responsible for each research question and why.

Table 1. Mapping methodology to research questions

Research questions	Methodological component	Why it answers the question
RQ1 - Technical: how renovation rates affect cost-optimal capacities	Sector-coupled PyPSA-Eur with orthogonal S0/S1/S2/S3 scenarios	Isolating each lever individually and combined makes the marginal

		contribution to capacities visible
RQ2 - Economic: system-level cost benefit and how it scales	S3-Low / S3 / S3-High retrofit-depth triplet	Three depths give a system-cost curve; differences against S0 are the avoided power-system costs
RQ3 - Policy: cost-minimising ambition and its policy implication	Combined optimisation result + post-processing cost-benefit analysis	The system curve plus retrofit costs plus four secondary value streams yield net benefit per ambition level

2.1 The PyPSA-Eur Framework

PyPSA-Eur is the open-source sector-coupled capacity-expansion model maintained by the Department of Digital Transformation in Energy Systems at Technical University of Berlin [11], [12]. It builds on the more general Python for Power System Analysis (PyPSA) toolbox [29] and implements the linearised optimal power flow (LOPF) formulation that is standard for capacity-expansion studies at annual hourly horizons. The model represents the European energy system as a network of nodes (electricity buses) linked by transmission lines, with each node carrying additional buses for heat, gas, hydrogen, and other carriers as configured. Generators, storage units, and conversion technologies are attached to these buses, and the model optimises both their installed capacities and their hourly dispatch over the full year.

This thesis uses PyPSA-Eur v2025.07. The HiGHS open-source solver is used throughout.

2.2 Mathematical Formulation

The optimisation is a deterministic linear programme under the assumptions of perfect competition and perfect foresight over the modelled year. This section explains each piece in turn.

2.2.1 Set and Indices

The optimization problem is defined over the following sets:

- n$\in N$ — set of nodes (5 spatial clusters within Germany)
- s∈S — set of technologies (wind, solar, and so on)
- t∈T — set of time snapshots (2,920 hours at 3-hourly resolution over the 2013 weather year)
- l∈L — set of transmission lines connecting nodes
- r∈R — set of storage units

These indices define the scope of every variable and parameter in the model.

2.2.2 Decision Variables

The optimiser chooses values for two classes of variable: investment variables, sized once for the planning horizon, and operational variables, dispatched in every snapshot.

The investment variables represent the capacities the system can build:

- $G_{n,s} \geq 0$ in megawatts is the new generation or conversion capacity of technology s at node n - for example, how much onshore wind to build at the north-Germany node, or how much heat-pump capacity to install in urban-decentral heating.
- $E_{n,r} \geq 0$ in megawatt-hours is the new storage energy capacity of storage unit r - for batteries this is the energy that can be stored, separate from the power rating.
- $F_l \geq 0$ in megawatts is the new transmission capacity on line l - relevant within Germany for the north-south corridor, since cross-border lines are not in scope.

The operational variables represent what the system does in each snapshot:

- $g_{n,s,t} \geq 0$ in megawatts is the dispatch of technology $s$at node n in snapshot t - how much each wind turbine, gas boiler, or heat pump produces in each three-hour block.
- $g^{+}_{n,r,t}$ and $g^{-}_{n,r,t} \geq 0$ are the storage charging and discharging powers.
- $e_{n,r,t} \geq 0$ in megawatt-hours is the storage state of charge.
- $f_{l,t}$ in megawatts (signed, since flow can go either direction) is the power flow on line l.

The model is therefore choosing, simultaneously, how big to build each piece of infrastructure and exactly how to operate it in every three-hour block of the year - under the constraint that supply must equal demand everywhere, at all times, and that total annual emissions must not exceed the CO_2 cap.

2.2.3 Parameters and Data Sources

The parameters that feed the optimisation are taken from authoritative public sources. None of the data is synthetic in the sense of being invented - the only "synthetic" element is the fallback construction of electricity demand time series for years not covered by ENTSO-E records, which is documented and not relevant to the 2013 weather year used here.

Table 2. Parameters and Data Sources

Parameter	Symbol	Source
Annualised capital cost per MW of generation	$c_{n,s}$	Danish Energy Agency Technology Catalogue [27]
Annualised capital cost per MWh of storage capacity	$c^{E}_{n,r}$	Danish Energy Agency Technology Catalogue [27]
Annualised capital cost per MW of line capacity	c_{l}	Danish Energy Agency Technology Catalogue [27]
Variable operating cost per MWh	$o_{n,s}$	Danish Energy Agency Technology Catalogue [27]

Capacity-factor time series	$\bar{g}_{n,s,t}$	ERA5 reanalysis [23] via atlite [31]
Baseline electricity demand	$d_{n,t}^{elec}$	ENTSO-E Transparency Platform [25]
Baseline heat demand	$d_{n,t}^{heat,0}$	JRC-IDEES [26] annual totals modulated by BDEW profiles [24]
Heat-pump COP profiles	COPn,t	Derived from ERA5 ambient temperatures using Staffell et al. [32]
Emission factors	ϵ_s	IPCC [1]
Annual CO_2 cap	$\overline{CO_2}$	Configured to net zero for 2050
Existing power plants in MW	$G_{n,s}^0$	Open Power System Data (OPSD) [28]
Pre-existing Transmission Capacity in MW	F_l^0	ENTSO-E Transparency Platform [25]
Network incidence matrix	K_{nl}	ENTSO-E Transparency Platform [25]
Time step weight	w_t	Input

Two points are worth emphasising. First, the Danish Energy Agency catalogue [27] provides projected costs out to 2050 for every technology used in the model, so future cost reductions for heat pumps, electrolysers, and batteries are captured in the optimisation. Second, the ERA5 reanalysis [23] is not a forecast or a simulation — it is a physically consistent reconstruction of past weather built by assimilating real meteorological observations into an atmospheric model, and it is the standard data source for renewable-resource and temperature time series in the European energy-modelling community.

2.2.4 Objective Function

The objective minimises total annualised system cost, comprising the annualised capital costs of new generation, storage, and transmission, plus the annual operating costs of running the dispatched fleet:

$$\min Z = \underbrace{\sum_{n,s} c_{n,s} G_{n,s}}_{\text{Generation CAPEX}} + \underbrace{\sum_{n,r} c^{E}_{n,r} E_{n,r}}_{\text{Storage CAPEX}} + \underbrace{\sum_{l} c_l F_l}_{\text{Transmission CAPEX}} + \underbrace{\sum_{n,s,t} w_t \, o_{n,s} \, g_{n,s,t}}_{\text{Operational \& fuel cost}} \qquad (1)$$

The equation (1) has four terms, and each one has its own interpretation. The first term is *generation CAPEX,* which is the total annualized investment cost of building all generation capacity. For every technology s at every location n, it multiplies $c_{n,s}$, annualised capital cost per MW of generation of a technology, to $G_{n,s}$, the new generation capacity of a technology, and it sums up all the investment cost. The same logic applies to *storage and transmission CAPEX.* Regarding the fourth term, *operational and fuel cost*, it sums variable operating costs across all dispatched units and snapshots, weighted by the snapshot duration w_t (three hours in this study). For example, for a gas boiler the operating cost is the fuel cost. This is the only place where fuel prices enter the optimisation, which is why a CO_2 cap rather than a CO_2 price is used to drive decarbonisation: emissions are constrained directly rather than priced through this term.

2.2.5 Constraints

The objective function is minimised subject to a set of constraints that enforce physical and policy realism. Each constraint is explained in turn.

Energy balance: At every node n and every snapshot t, the total dispatch into the node minus the demand at the node must equal the net flow out across the network. It applies both to heat and electricity:

$$\sum_s g_{n,s,t} - d_{n,t} = \sum_l K_{nl} f_{l,t} \tag{2}$$

where $K_{nl}$is the node-line incidence matrix that maps which lines connect to which node. This is the conservation-of-energy condition: nothing is created and nothing is destroyed; the system must balance, hour by hour, at every node.

Capacity limit: Dispatch is bounded by the available capacity, with renewable generators additionally constrained by the time-varying capacity factor $\bar{g}_{n,s,t}$ that reflects weather conditions:

$$0 \leq g_{n,s,t} \leq \bar{g}_{n,s,t} \cdot \left(G^0_{n,s} + G_{n,s}\right) \tag{3}$$

Existing capacity $G^0_{n,s}$ and new capacity $G_{n,s}$ are added. For a solar panel, $\bar{g}_{n,s,t}$ ranges from 0 at night to roughly 0.5–0.6 at midday in summer; for a gas boiler it is effectively 1.0 at all hours. This is what makes wind and solar fundamentally different from controllable plants in the optimisation: their dispatch is bounded by the weather, not by the operator's choice.

Heat pump: A heat pump consumes electricity and produces heat with a Coefficient of Performance that depends on the temperature lift:

$$g^{\text{heat}}_{n,t} = \text{COP}_{n,t} \cdot g^{\text{elec}}_{n,t} \tag{4}$$

This is the coupling constraint between the electricity bus and the heat bus. The COP varies with ambient temperature (lower in cold weather, higher in mild weather), which means heat-pump performance is worst exactly when heat demand is highest - a key reason why peak winter electricity demand is one of the system-design pinch points and why retrofit, which reduces that peak, is so valuable.

Gas boiler: A gas boiler consumes gas and produces heat with a constant efficiency:

$$g_{n,t}^{\text{heat}} = \eta^{\text{boiler}} \cdot g_{n,t}^{\text{gas}} \tag{5}$$

Typical efficiency $\eta^{\text{boiler}} \approx 0.9$ for a modern condensing boiler. The contrast with (C3) is informative: a heat pump with COP = 3 produces three units of heat per unit of electricity, while a boiler produces 0.9 units of heat per unit of gas. The thermodynamic case for heat pumps is overwhelming on energy grounds; the only thing that complicates the system case is the temporal shape of the resulting electricity demand.

Storage state of the charge: Storage state of charge is updated each snapshot according to charging, discharging, and standing losses:

$$e_{n,r,t} = \eta^0 e_{n,r,t-1} + \eta^+ g_{n,r,t}^+ - \frac{g_{n,r,t}^-}{\eta^-} \tag{6}$$

where η^0 is the standing efficiency (1 minus the standing-loss fraction), η^+ is the charging efficiency, and η^- is the discharging efficiency. The state of charge is also subject to a periodicity condition $e_{n,r,T} = e_{n,r,0}$ that prevents the model from artificially exhausting a reservoir at year-end.

Transmission limit: Power flow on each line is bounded by the line's capacity in both directions:

$$-\left(F_l^0 + F_l\right) \leq f_{l,t} \leq F_l^0 + F_l \tag{7}$$

The line flows themselves are determined by the linearised DC power-flow equations on the meshed network - Kirchhoff's voltage and current laws under the DC approximation.

CO_2 cap: Total annual emissions across all sectors are bounded:

$$\sum_{n,s,t} w_t \epsilon_s g_{n,s,t} \leq \overline{\mathrm{CO}_2} \tag{8}$$

where ϵ_s is the emission factor of technology s (tonnes CO_2 per MWh fuel input, zero for renewables and electricity-driven technologies, positive for fossil-fuelled ones). For the 2050 horizon, $\overline{CO_2}$, enforcing net-zero across all modelled sectors.

Retrofit: The heat demand seen by the rest of the model is scaled by the retrofit factor:

$$d_{n,t}^{\text{heat}} = d_{n,t}^{\text{heat},0} \cdot (1 - \alpha_{DE}) \tag{9}$$

where $d_{n,t}^{\text{heat},0}$ is the un-retrofitted baseline heat and $\alpha_{DE} \in [0,1]$ is the fractional reduction in space-heating demand in Germany. Setting different values of α_{DE} across scenarios is how this thesis isolates the system effects of retrofit. The retrofit cost itself does not enter the LP objective; it is handled in post-processing as part of the cost-benefit analysis described in Section 3.6. This separation is a deliberate methodological choice: it produces a clean system-cost curve from the LP whose marginal value of retrofit can then be compared against any chosen retrofit-cost assumption without re-running the model.

2.3 Heating Sector Representation

The representation of the heating sector is the methodological heart of this thesis and warrants explicit description.

2.3.1 Demand segmentation.

PyPSA-Eur splits residential and commercial heat demand into three categories per country: rural, urban decentral, and urban central (district heating). The split for Germany is determined by population density and current district-heating coverage, yielding approximately an 8 % urban-central share consistent with the roughly 1.5 million dwellings currently on German district heating networks [7].

2.3.2 Hourly heat-demand profiles

Profiles ($d_{n,t}^{\text{heat},0}$) are constructed by combining annual sectoral totals from JRC-IDEES [26] with intra-day BDEW load profiles ($p_{n,t}^{BDEW}$) [24] and modulating with the heating-degree-day signal ($\text{HDD}_{n,t}$) derived from ERA5 ambient temperatures [23]. The reference annual residential heat demand for Germany is approximately **739 TWh** ($D_n^{heat,0}$) in the un-retrofitted baseline, in line with national statistics.

$$d_{n,t}^{\text{heat},0} = D_n^{\text{heat},0} \cdot \frac{p_{n,t}^{\text{BDEW}} \cdot HDD_{n,t}}{\sum_{t \in T} p_{n,t}^{\text{BDEW}} \cdot HDD_{n,t}} \tag{10}$$

2.3.3 Heat-pump COP

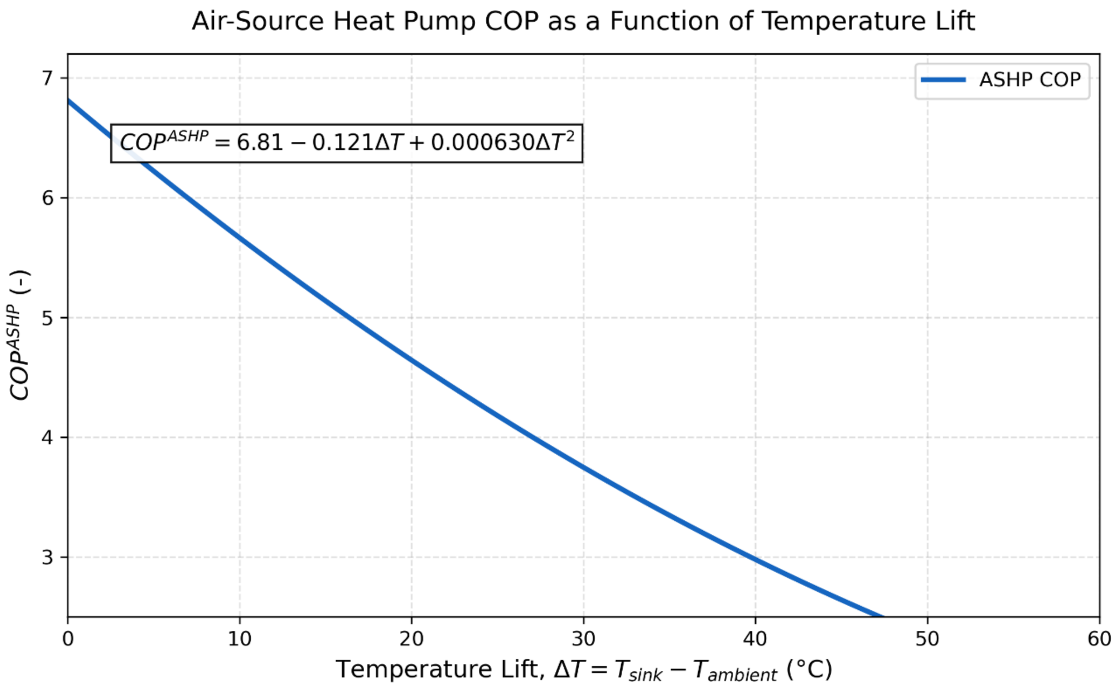


Figure 3. Air-Source Heat Pump (ASHP) COP as a Function of Temperature Lift

ASHP COP is a temperature-dependent quadratic of the temperature lift, calibrated against manufacturer specification curves, which is shown in Figure 1 [32]. The sink temperature is set to 55 °C in the configuration, representing radiator-based systems typical of the existing German residential stock. Ground-source heat pumps use an analogous formulation with the source temperature replaced by the soil temperature, yielding consistently higher seasonal COP. These formulations reproduce the seasonal performance factors of 2.6 to 4.9 (air source) and 3.6 to 5.4 (ground source) reported by Fraunhofer ISE for retrofitted German residential buildings [15].

2.4 Scenario Design

Eight scenarios are constructed to isolate and combine the principal policy levers governing the German residential heating transition. Six primary scenarios constitute the controlled-comparison analytical design, addressing the technical and economic research questions (RQ1 and RQ2). Two additional sensitivity scenarios test the methodological substance of smart heat-pump control as a demand-side flexibility mechanism. The eight scenarios share the same net-zero CO_2 constraint, weather year, spatial resolution, and technology cost assumptions; differences in system cost or capacity expansion are therefore attributable solely to the experimental levers under test.

Table 3. Scenario assumptions and policy interpretations

Element	**S0**	**S1**	**S2**	**S3**	**S3-Low**	**S3-High**
Retrofit factor α_{DE}	0	0.29	0	0.29	0.15	0.45
Heat demand seen by model	d^0	$\mathbf{0.71\,d^0}$	d^0	$\mathbf{0.71\,d^0}$	$0.85\,d^0$	$0.55\,d^0$
Gas boiler new-build	extendable	extendable	**banned**	**banned**	**banned**	**banned**
Heat pumps	extendable	extendable	extendable	extendable	extendable	extendable
CO_2 cap	net-zero	net-zero	net-zero	net-zero	net-zero	net-zero
Real-world meaning	no intervention	renovation only	electrification only	combined moderate	low ambition	deep renovation

2.4.1 Primary Scenarios (Core Analytical Design)

The six primary scenarios employ a controlled-comparison logic. S0 establishes the reference system without policy intervention. S1 isolates the system-level value of building envelope retrofit alone (29% heat-demand reduction, gas boilers remain available). S2 isolates the system-level cost of forced electrification without demand reduction (gas boilers banned, no retrofit). S3 tests the realistic German policy pathway of parallel retrofit and electrification (29% retrofit, gas boiler ban). The differences S0−S1, S0−S2, S1−S3, and S2−S3 systematically attribute observed system effects to the underlying policy levers.

The triplet S3-Low / S3 / S3-High provides the sensitivity curve on retrofit depth (15%, 29%, 45% cumulative heat-demand reduction) that drives RQ2 and RQ3. The slope of this curve directly answers the economic question of the system value of additional retrofit ambition, while informing the policy pathway analysis.

2.4.2 Smart Control Sensitivity Scenarios

PyPSA-Eur optimizes capacity expansion and dispatch at three-hour resolution but does not endogenously model dispatch-level smart control strategies for heat pumps. In practice, heat pumps with modulating compressors, building thermal mass, and buffer storage tanks provide significant demand-side flexibility — they can shift heat production in time, smoothing peaks and reducing required infrastructure. To quantify the system-level value of this flexibility, a shape modifier was applied in pre-processing to the heat demand profile of the S3 scenario.

The shape modifier applies a centered moving-average filter to the original heat demand profile, $D_{n,t}^{heat}$, smoothing temporal peaks while preserving the annual heat demand total:

$$D_{n,t}^{\mathrm{smooth}} = \frac{1}{W} \sum_{i=-W/2}^{W/2-1} D_{n,t+i}^{\mathrm{heat}} \tag{11}$$

Where, W is the window size, which controls the degree of smoothing. And, to preserve the annual heat demand total, the smoothed profile is rescaled:

$$D_{n,t}^{\text{final}} = D_{n,t}^{\text{smooth}} \cdot \frac{\sum_t D_{n,t}^{\text{heat}}}{\sum_t D_{n,t}^{\text{smooth}}} \tag{12}$$

Two window sizes were tested to bracket realistic smart-control deployment:

- S3-Smoothed-12h applies a 12-hour rolling average, representing the smoothing achievable through building thermal mass alone. This corresponds to the inherent flexibility of typical German residential buildings (medium-mass masonry construction with thermal time constants of 6-24 hours) when controlled by smart heat-pump dispatch algorithms. This level of smoothing requires only software-based control logic; no additional hardware infrastructure is needed.
- S3-Smoothed-24h applies a 24-hour rolling average, representing additional smoothing from external buffer storage tanks installed alongside heat pumps. This level requires both software control logic and physical buffer storage infrastructure. The two scenarios together bracket the realistic smart-control deployment spectrum, from conservative (thermal mass alone) to aggressive (thermal mass plus buffer storage), enabling quantification of the system-cost savings from each tier and the diminishing returns between them.

2.4.3 Common Scenario Specifications

The configuration choices made for the model below is a trade-off between accuracy and keeping the computational burden low enough so that the optimization problem could be solved on the personal computer. All eight scenarios share the following specifications:

- Optimization horizon: single representative year 2050
- Temporal resolution: 2,920 snapshots (3-hourly)
- Spatial resolution: 5 nodes covering Germany

- CO_2 constraint: 0 $MtCO_2$/yr (hard cap, binding net-zero by design)
- CO_2 sequestration limit: 250 $MtCO_2$/yr (allowing CCS-equipped technologies and DAC)
- Weather year: 2013 (ERA5 reanalysis)
- Technology costs: Danish Energy Agency Technology Catalogue 2050 projections
- Available heating technologies: heat pumps (air-source, round-source), resistive heaters, thermal storage (water anks, water pits), gas CHP with carbon capture
- All capacity decisions extendable (greenfield optimization)
- Solver: Highs

The retrofit factor α_{DE} is applied as an exogenous demand multiplier — PyPSA-Eur does not optimize the retrofit decision itself but accepts it as an input parameter representing the policy outcome of the renovation rate over the 2025-2050 period.

2.5 System-Level Cost-Benefit Analysis

The PyPSA-Eur optimisation gives each scenario a total annualised system cost. The difference between baseline S0 and each alternative scenario is interpreted as either system savings or dissavings. To make these results policy-relevant, the analysis adds three post-processing components: retrofit investment costs, secondary value streams outside the power-system model, and a net-benefit calculation comparing total benefits with total costs.

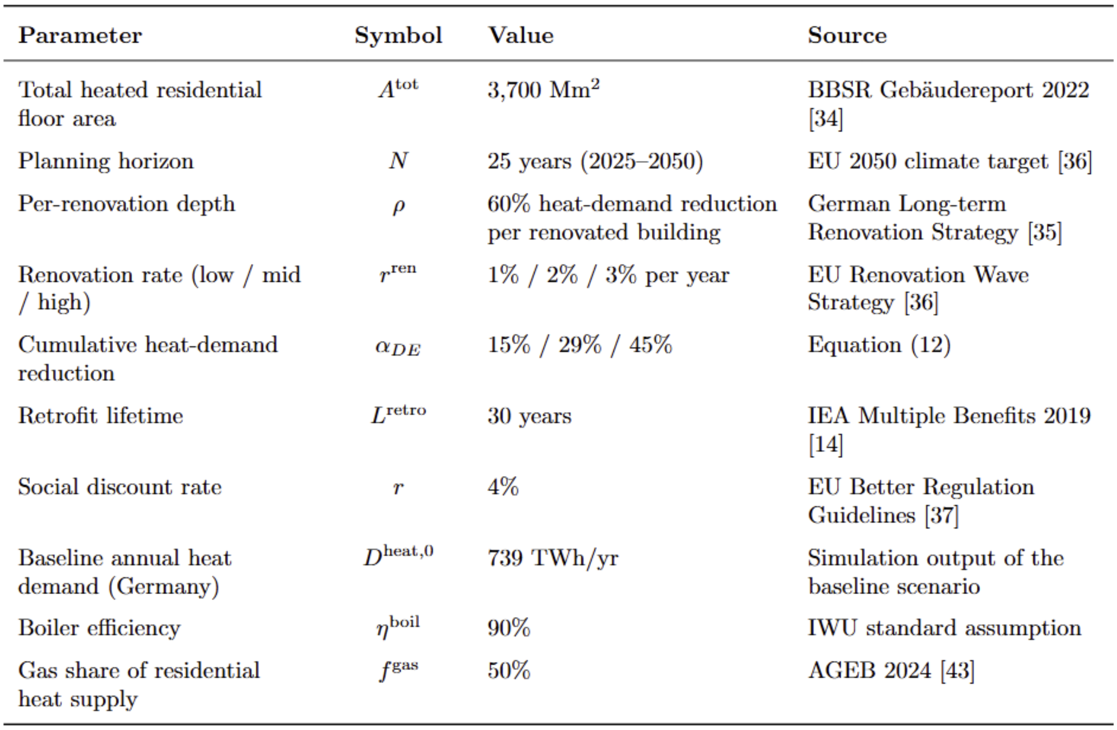
This cost-benefit analysis is conducted in Python using the optimization outputs and documented parameter values. It is kept outside the PyPSA-Eur objective for methodological clarity: the model first produces a clean system-cost curve, which can then be tested against different retrofit-cost assumptions without re-running the optimisation. This also makes the framework transparent, since individual secondary benefits can be removed or adjusted while the system-cost result remains unchanged.

Two calibration choices are important. First, the gas-share factor $f^{\text{gas}} = 0.50$ (the AGEB 2024 figure for the share of German residential heat supplied by natural gas) is applied consistently to both the CO_2 pricing benefit and the avoided-imports benefit, since only the gas-supplied portion of heating demand translates directly to avoided gas consumption, its associated emissions, and its associated imports. Second, avoided imports are valued only at the energy-security premium of €10/MWh, not the full gas price, because wholesale gas costs are already included in the PyPSA-Eur objective. This avoids double-counting and captures only the additional security value of reduced import exposure.

2.5.1 Common Parameters

All cost-benefit calculations use the consistent parameter set in Table 4.

Table 4.Parameters common to all cost-benefit components.



Parameter	Symbol	Value	Source
Total heated residential floor area	A^{tot}	3,700 Mm^2	BBSR Gebäudereport 2022 [34]
Planning horizon	N	25 years (2025–2050)	EU 2050 climate target [36]
Per-renovation depth	ρ	60% heat-demand reduction per renovated building	German Long-term Renovation Strategy [35]
Renovation rate (low / mid / high)	r^{ren}	1% / 2% / 3% per year	EU Renovation Wave Strategy [36]
Cumulative heat-demand reduction	α_{DE}	15% / 29% / 45%	Equation (12)
Retrofit lifetime	L^{retro}	30 years	IEA Multiple Benefits 2019 [14]
Social discount rate	r	4%	EU Better Regulation Guidelines [37]
Baseline annual heat demand (Germany)	$D^{\text{heat},0}$	739 TWh/yr	Simulation output of the baseline scenario
Boiler efficiency	η^{boil}	90%	IWU standard assumption
Gas share of residential heat supply	f^{gas}	50%	AGEB 2024 [43]

2.5.2 Renovation Rate to Heat-Demand Reduction

The mapping between annual renovation rates and cumulative heat-demand reductions deserves explicit justification because it underpins the policy interpretation in Chapter 5:

$$\alpha_{DE} = r^{\text{ren}} \cdot N \cdot \rho \tag{13}$$

The per-renovation depth $\rho = 0.60$ corresponds to substantial - though not passive-house grade — envelope refurbishment, and is the central assumption in the German Federal Government's Long-term Renovation Strategy [35].

Table 5.Mapping from renovation rate to cumulative heat-demand reduction under the central depth assumption.

Renovation rate r^{ren}	Cumulative renovated area	Per-renovation depth ρ	Cumulative reduction α_{DE}	Mid cost (€/m^2)
1%/yr	25% of stock	60%	**15%**	225
2%/yr	50% of stock	60%	**29%**	500
3%/yr	75% of stock	60%	**45%**	900

2.5.3 Retrofit Investment Cost

For each retrofit depth, the total annual retrofit investment cost during the 2025–2050 campaign period is the annual renovated rate multiplied by the total heated residential floor area multiplied by the per-square-metre cost:

$$C_{\alpha}^{\text{retro}} = r_{\alpha}^{\text{ren}} \, A^{\text{tot}} \, c_{\alpha}^{\text{retro}} \tag{14}$$

Per-square-metre costs are taken from the mid estimates of IWU 2024 cost study [38] and the dena Gebäudereport [39], which are shown in Table 5:

2.5.4 CO$_2$ Pricing Benefit

The EU ETS2 mechanism, operational from 2027, places a direct carbon price on fossil fuels burned in heating boilers [3], [42]. Only the gas-supplied portion of the German heat demand is directly exposed to ETS2: electrified heat (heat pumps, resistive), district heating, and biomass-fueled heat are subject to different regulatory mechanisms.

Approximately 50 % of German residential heat is currently supplied from natural gas [43], so the avoided ETS2 cost is computed against that share:

$$B_{\alpha}^{\mathrm{ETS2}} = f^{\mathrm{gas}} \cdot \left(\alpha_{DE} \cdot D^{\mathrm{heat},0}\right) \cdot \epsilon^{\mathrm{gas}} \cdot p^{\mathrm{ETS2}} \tag{15}$$

The emission factor is $\epsilon^{\mathrm{gas}} = 0.275$ $\mathrm{tCO_2}$/MWh of heat delivered, derived from the IPCC gas-combustion factor of 0.247 $\mathrm{tCO_2}$/MWh of fuel input divided by the 90 % boiler efficiency [41]. The ETS2 price is set at the €60/$\mathrm{tCO_2}$ price cap that the European Commission targets between 2027 and 2030 (equivalent to €45/$\mathrm{tCO_2}$ in 2020 prices) [3], [42].

Applying the ETS2 price uniformly to all avoided heat demand — rather than only to the gas-supplied share — would over-state the benefit by a factor of two. The 50 % adjustment used here reflects how the ETS2 mechanism actually operates in Germany and is the conservative choice.

2.5.5 Avoided Fossil-Fuel Imports

Germany imports approximately 95% of the natural gas it consumes [43]. Avoided residential gas demand therefore translates almost directly into avoided imports. A methodological clarification matters here. The wholesale cost of avoided gas is already captured inside the PyPSA-Eur operational cost term, because the LP charges the system for every MWh of gas consumed at the wholesale gas price. Adding the wholesale price again as an "avoided imports" benefit in the post-processing would double-count exactly the same physical avoided gas flow. The only economically additional value not already captured by the LP is the option value of reduced exposure to import-disruption price spikes - the energy-security premium that markets do not price in routinely but that has clear economic value (made visible during the 2022 crisis when TTF reached €300/MWh). The avoided-imports stream is therefore valued at the security premium only:

$$B_{\alpha}^{\mathrm{imp}} = f^{\mathrm{gas}} \cdot \frac{\alpha_{DE} \cdot D^{\mathrm{heat},0}}{\eta^{\mathrm{boil}}} \cdot p^{\mathrm{sec}} \tag{16}$$

where $p^{\mathrm{sec}} = €10/\mathrm{MWh}$ is the security premium (an author assumption reflecting the volatility hedge value; no specific citation). The gas-share factor $f^{\mathrm{gas}} = 0.50$ is applied consistently with Section 3.7.5, and the division by boiler efficiency (η^{boil}) converts avoided heat demand ($\alpha_{DE}D^{heat,0}$) to avoided gas demand.

2.5.6 Health and Comfort Co-Benefits

Retrofitted buildings deliver indoor environments that reduce respiratory illness, improve thermal comfort, and increase occupant productivity. The literature has attempted to monetise these benefits through contingent-valuation surveys and willingness-to-pay studies; the BPIE 2018 review [13] reports a range of €30–€200 per square metre of renovated floor area per year, and the IEA Multiple Benefits study [14] reports a comparable range of €40–€150 per square metre per year.

A central value of €70 per square metre per year is used, applied to the annual renovation flow:

$$B_{\alpha}^{\mathrm{HC}} = \left(r_{\alpha}^{\mathrm{ren}} \cdot A^{\mathrm{tot}}\right) \cdot c^{\mathrm{HC}} \tag{17}$$

This formulation captures the ongoing flow of health, comfort, and asset-value benefits accruing to occupants of buildings renovated in each year.

2.5.7 Net benefit

Combining all above equations, the following equation for the net annual benefit for each scenario is computed as shown in the Equation 18:

$$\begin{aligned} \text{Net benefit} = {} & \text{System savings} + \text{CO}_2 \text{ pricing benefit} \\ & + \text{Avoided imports} + \text{Co-benefits} - \text{Retrofit cost} \end{aligned} \tag{18}$$

The system savings come from the PyPSA-Eur optimisation; the other four positive terms come from the secondary literature; the retrofit cost is from the construction-cost literature. This decomposition makes the analysis transparent: any reader who disagrees with one of the secondary value streams can drop it and re-evaluate. The system-level component — the avoided power-system investment that this thesis quantifies rigorously — is the largest single component and is the part the LP delivers.

The Chapter 5 results report net benefit under all combinations of retrofit depth (15 %, 29 %, 45 %), and identify the ambition level that maximises net benefit. This answers RQ3.

2.6 Model Simulation and Validation

All six scenarios solved to optimality using HiGHS in interior-point mode with crossover disabled and an optimality tolerance of 1e-4. The hardware platform was a laptop running Windows Subsystem for Linux (Ubuntu 24.04) with 4 CPU cores and 11 GB of RAM augmented by 8 GB of swap space. Wall-clock solve times per scenario ranged from approximately 13 hours (S3 series) to 20 hours (S2 with simplex cycling issues, ultimately resolved via interior-point method). Below in Table 7 the simulation details presented more in detail:

Table 6. Model details

Scenario	# of variables	# of constraints	Solving time
S0	2,117,369	315,361	16.2 hours
S1	2,117,369	315,361	16.4 hours
S2	2,029,754	315,361	20.5 hours
S3	2,029,754	315,361	13.1 hours
S3-High	2,029,754	315,361	12.8 hours
S3-Low	2,029,754	315,361	13.1 hours
S3-Smooth12h	2,029,754	315,361	10.5 hours
S3-Smooth24h	2,029,754	315,361	11.2 hours

2.6.1 Cross-scenario directional consistency

The scenario results were checked for directional consistency with the experimental design:

- **System costs** decrease with higher retrofit ambition (€84.5 bn/yr in S0 → €60.5 bn/yr in S3-High).
- **Heat demand** declines proportionally to the retrofit factor α_{DE}.
- **Electricity demand** increases when gas boilers are banned without retrofit (S2: 1,065 TWh vs. S0: 1,050 TWh), reflecting heating-load electrification.
- **Transmission expansion** decreases with retrofit ambition (10.9 GW in S0 → 0 GW in S3-High), indicating reduced grid reinforcement needs.

These checks confirm that the scenarios behave as expected and remain physically consistent with the German energy system.

2.7 Summary

This chapter has described the methodology: a Germany-only PyPSA-Eur configuration at 5-node spatial resolution, 3-hour temporal resolution, 2013 weather year, single-shot 2050 net-zero optimisation, with heating represented at three segment levels and retrofit imposed exogenously through the parameter α_{DE}. Six scenarios isolate and combine the two principal decarbonisation levers, with three of them (S3-Low / S3 / S3-High) forming a sensitivity triplet on retrofit depth that supports both the system-cost curve (RQ1, RQ2) and the post-processing cost-benefit analysis (RQ3). All scenarios solved to optimality and the baseline reproduces principal aggregate features of the German energy system within validation tolerances. The next chapter presents the scenario results.

3 Results

This chapter presents the results of the primary six scenario and additional two sensitivity runs and answers the technical and economic research questions from Chapter 1. Section 3.1 reports total system costs, providing the headline result. Sections 3.2, 3.3 and 3.4 decompose these costs into optimiser decisions for the power sector — wind, solar, and transmission — and the heating and storage sectors — heat pumps, gas CHP, batteries, and thermal storage — thereby answering RQ1. Section 3.5 uses the S3-Low / S3 / S3-High scenarios to build the retrofit sensitivity curve and estimate the marginal system value of retrofit, answering RQ2. Section 3.6 analyses demand profiles and identifies the flexibility-retrofit substitution mechanism, where the grid-side value of heat-pump flexibility depends on retrofit context. Section 3.7 analyses smart control sensitivity scenarios results, while Section 3.8 summarises the findings and prepares the cost-benefit interpretation developed in Chapter 4. All numerical results are direct PyPSA-Eur outputs, with no post-processing. The broader cost-benefit aggregation, which combines these optimisation outputs with secondary-literature value streams, is presented in Section 4.

3.1 Total System Cost across Scenarios

As discussed in Chapter 2, the objective of the optimization is to identify minimized total system cost under the constraints, and Figure 1 shows the ouput of this optimization for the primary six scenarios. The vertical axis is annualised system cost in billion euros per year; the dashed horizontal reference line marks the S0 baseline at €84.5 bn/yr.

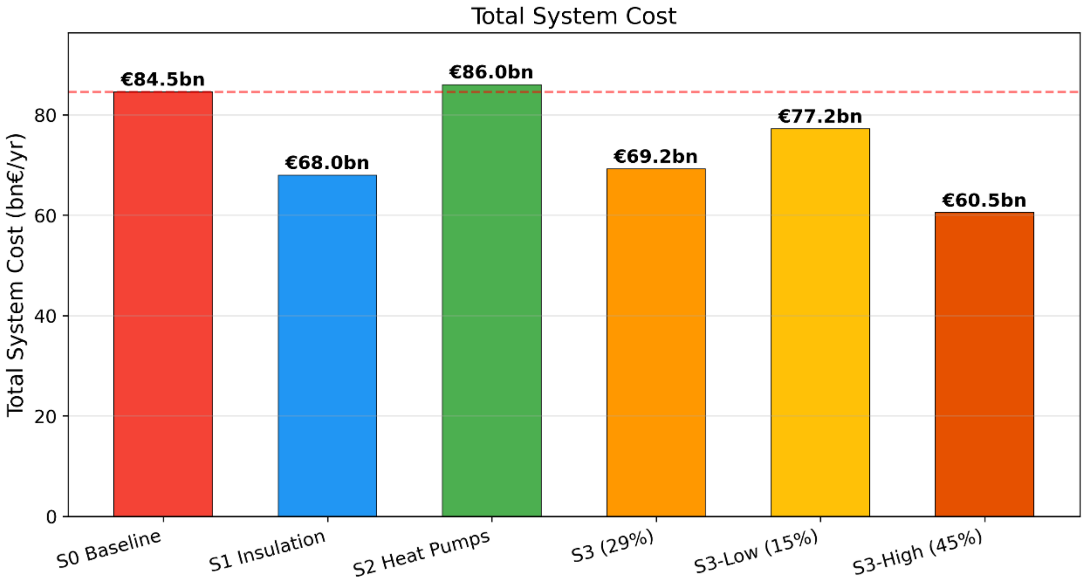


Figure 4. Total annualised system cost for the primary six scenarios.

Three observations follow directly from the figure. First, insulation alone (S1) is the largest single cost-reducing intervention among the baseline-comparator scenarios: it cuts system cost from €84.5 bn/yr to €68.0 bn/yr, a reduction of €16.5 bn/yr or roughly 20 %. Second, heating electrification alone (S2) does not reduce system cost - it slightly increases it, from €84.5 bn/yr to €86.0 bn/yr. Banning gas boilers without first reducing heat demand simply shifts the fossil dependence from boilers to gas-fired CHP and forces oversized heat-pump and renewable capacity build-out to serve a still-unreduced winter peak. Third, the combined scenario S3 at moderate ambition (29 % retrofit + boiler ban) comes in at €69.2 bn/yr, marginally higher than S1 - a result that on its own would seem to argue against pursuing the boiler ban. But the S3-High sensitivity (45 % retrofit + boiler ban) overturns that reading: at €60.5 bn/yr it is the cheapest scenario in the entire run, undercutting S1 by €7.5 bn/yr and the baseline by €24.0 bn/yr.

The pattern is therefore not "insulation is cheaper than insulation-plus-electrification" but rather "the combination is cheaper than insulation alone if the retrofit ambition is deep enough." Section 4.5 unpacks why.

3.2 Power-Sector Capacity Decisions

Figure 2 reports the new generation and transmission capacity built by the optimiser in each scenario. These are the decision variables $G_{n,s}$ for onshore wind and solar HSAT (horizontal single-axis tracking), and F_l for transmission, as defined in Section 2.2.2.

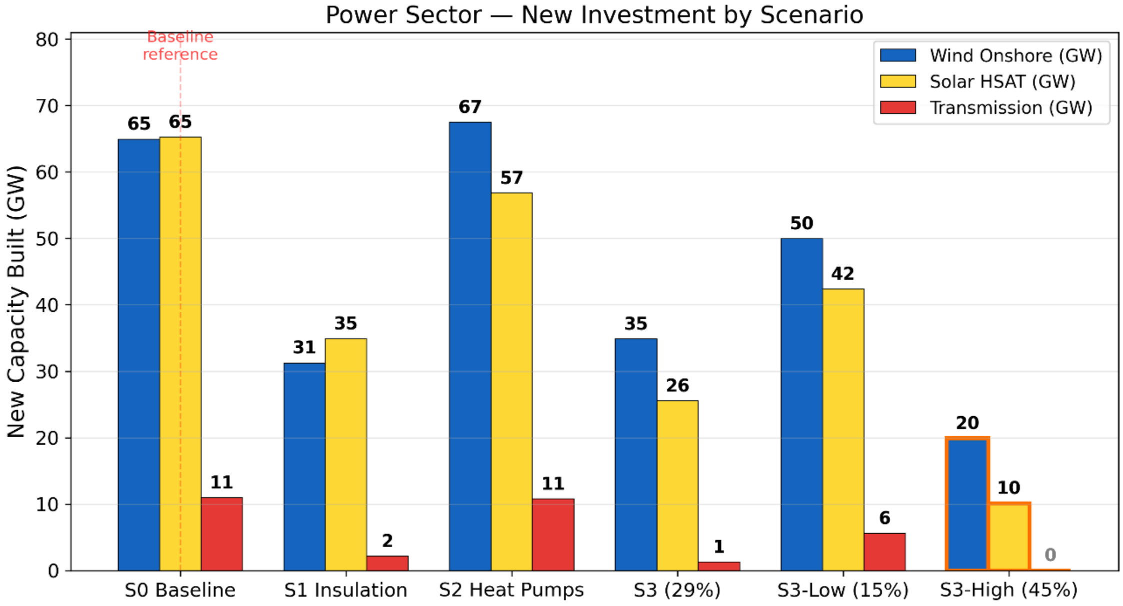


Figure 5. New capacity built in the power sector by scenario.

The scenario pattern is internally consistent and physically intuitive. In the baseline S0, the system builds 65 GW of onshore wind, 65 GW of solar HSAT, and 11 GW of new transmission. Insulation alone (S1) reduces heat demand and therefore cuts all infrastructure needs: wind falls to 31 GW, solar to 35 GW, and transmission to 2 GW. Electrification alone (S2) shifts heating demand onto the power system, raising wind slightly above baseline to 67 GW while leaving transmission unchanged at 11 GW, because the system must cover a higher winter peak without demand reduction. The combined moderate scenario S3 reduces wind to 35 GW, solar to 26 GW, and transmission to 1 GW.

The strongest effect appears in S3-High. Deep retrofit at 45% combined with the boiler ban cuts new onshore wind to 20 GW, 69% below baseline, solar to 10 GW, 84% below baseline, and new transmission to essentially zero. This explains the cost result in Figure

1: deep envelope retrofit lowers the winter heat-demand peak enough to shrink the entire coupled system. Lower heat demand reduces heat-pump capacity, peak electricity demand, generation capacity, and transmission needs. This cascade shows why retrofit is not only a building-sector measure, but also a power-system planning variable. Transmission illustrates the mechanism clearly: it remains at 11 GW without retrofit, falls to 6 GW under 15% retrofit, 2 GW under insulation alone, 1 GW under moderate combined retrofit, and zero under deep retrofit. This makes deep renovation policy-significant because, in this configuration, it eliminates the need for new transmission expansion.

3.3 Heating Technology Installed Capacity

Figure 3 reports the new heating technology capacity built by the optimiser in each scenario:

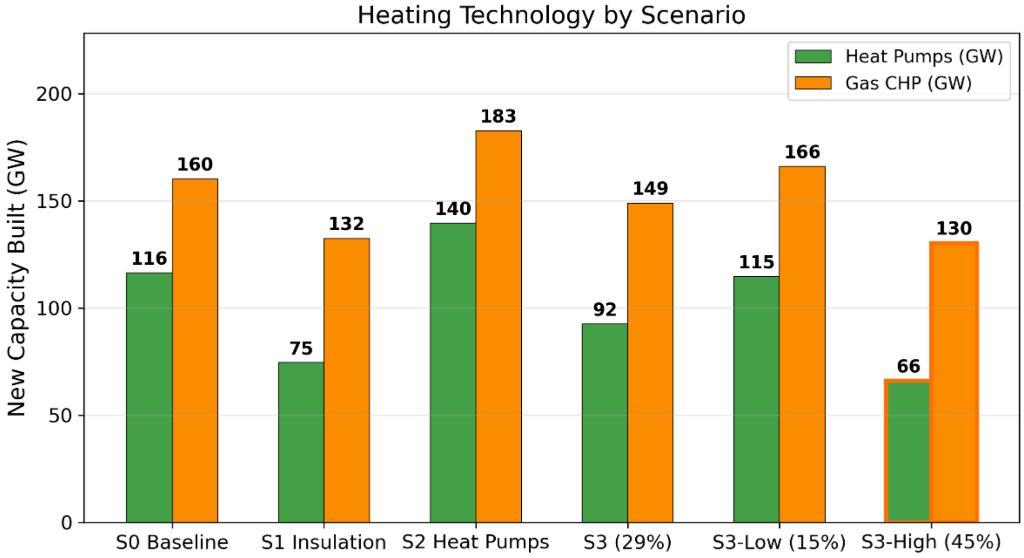


Figure 6. Heating Technology Installed Capacity

The baseline S0 installs 116 GW of heat pumps. Electrification alone (S2) increases this to 140 GW because the boiler ban shifts unreduced heat demand onto heat pumps. Insulation alone (S1) reduces heat-pump capacity to 75 GW, as lower demand and available gas boilers reduce peak requirements. The combined moderate scenario S3 requires

92 GW: below S0 due to retrofit, but above S1 because the boiler ban shifts peak load fully onto heat pumps.

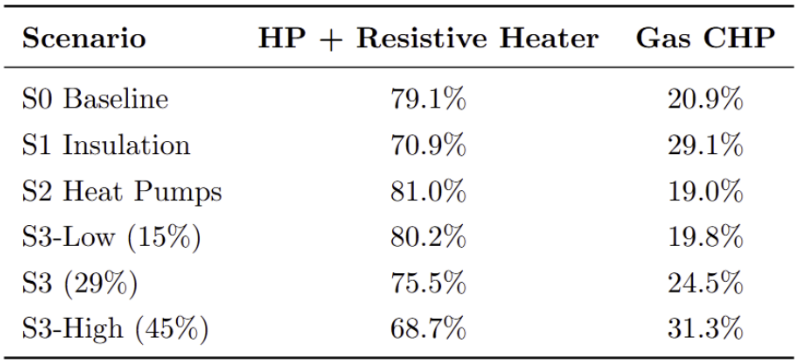
S3-Low remains close to baseline at 115 GW, while S3-High requires only 66 GW — less than S1. This shows that deep retrofit reduces the residual winter peak enough for a smaller heat-pump fleet than even the insulation-only case with boiler back-up. At high ambition, retrofit plus electrification becomes more efficient than insulation alone.

Gas CHP follows the opposite pattern. Capacity rises from 160 GW in S0 to 183 GW in S2, falls to 132 GW in S1, and reaches 149 GW in S3, 166 GW in S3-Low, and 130 GW in S3-High. Although boiler-ban scenarios exclude new fossil boilers, gas CHP remains for cold-period flexibility; under the CO_2 cap, this capacity must operate on hydrogen or biogas to stay within the net-zero envelope.

3.3.1 Endogenous Electrification of Heating

The PyPSA-Eur optimization does not impose a fixed electrification target; the share of heat demand served by electric heating (heat pumps and resistive heaters) versus gas CHP with carbon capture emerges endogenously from the cost-optimal solution under the 2050 net-zero constraint.

Table 7. Electrification Rate



Scenario	HP + Resistive Heater	Gas CHP
S0 Baseline	79.1%	20.9%
S1 Insulation	70.9%	29.1%
S2 Heat Pumps	81.0%	19.0%
S3-Low (15%)	80.2%	19.8%
S3 (29%)	75.5%	24.5%
S3-High (45%)	68.7%	31.3%

The electrification share ranges from 69% to 81% across all six scenarios. Heat pumps emerge as the cost-optimal technology in every scenario; even in S0 and S1 where boilers remain available, the optimizer chose them for only 5-6% of heat supply because heat pumps are cost-optimal under the net-zero CO_2 constraint.. The boiler ban functions as regulatory reinforcement of cost- optimization rather than as the primary electrification mechanism.

Gas CHP with carbon capture provides a structurally constant ~177 TWh/yr of urban district heating across all scenarios where boilers are banned. The electrification share decreases with deeper retrofit (80% at S3-Low to 69% at S3-High). The mechanism is that gas CHP heat output is approximately constant while heat pump heat output scales down with reduced overall demand. The constant CHP contribution therefore becomes a larger fraction of total heat in deeper-retrofit scenarios.

3.4 Storage Installed Capacity

Figure 4 reports new capacity built for the storage (battery energy capacity $E_{n,r}$ and thermal storage $E_{n,r}$).

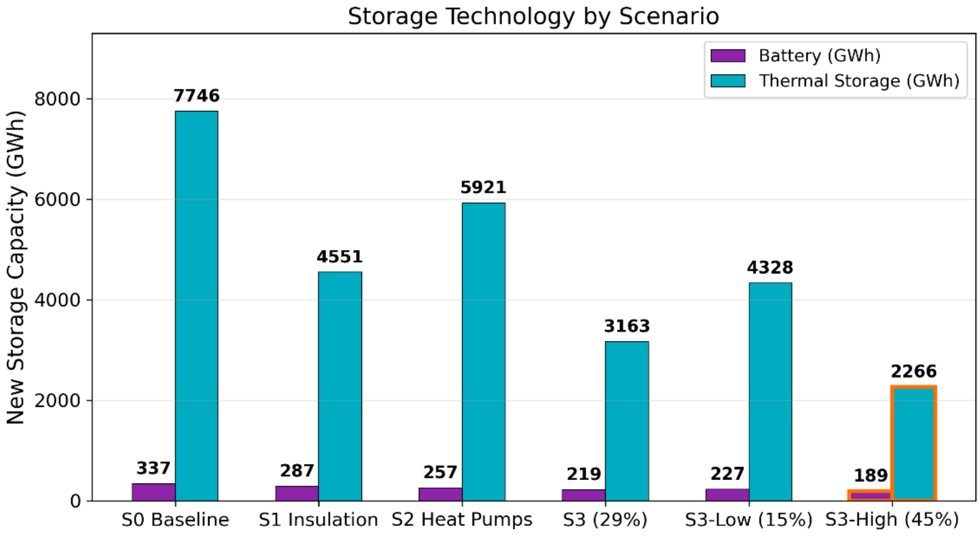


Figure 7. Storage Installed Capacity.

Battery energy capacity decreases monotonically with retrofit depth: 337 GWh in S0, 287 GWh in S1, 257 GWh in S2, 219 GWh in S3, 227 GWh in S3-Low, and 189 GWh in S3-High. Reduced electrified-heat peak demand reduces the diurnal balancing requirement that batteries serve.

Thermal storage shows the largest absolute swing of any storage technology. S0 builds 7,746 GWh of thermal storage; S3-High builds 2,266 GWh — a 71 % reduction. Thermal storage is sized principally to ride through cold periods that exceed instantaneous heat-supply capacity; deep retrofit shrinks both the peak and the ride-through requirement, and the system substitutes envelope thermal inertia (effectively delivered by the retrofit itself) for purpose-built thermal storage.

3.5 Retrofit Sensitivity Curve

The S3-Low / S3 / S3-High triplet, supplemented by the S0 baseline, traces a system-cost curve as a function of retrofit ambition under the boiler ban. Figure 4 plots this curve.

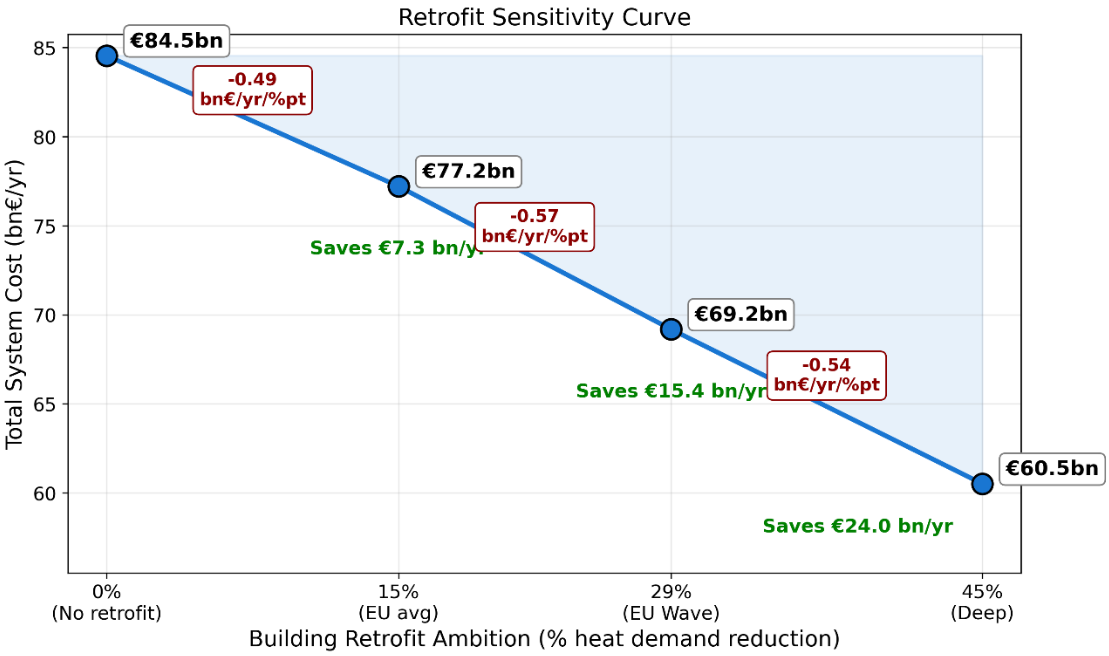


Figure 8. Total system cost as a function of retrofit ambition.

The retrofit sensitivity curve is approximately linear across the 0–45% range. Relative to S0, system savings increase from €7.3 bn/yr at 15% retrofit, to €15.4 bn/yr at 29%, and €24.0 bn/yr at 45%.

The slope is roughly €0.5 bn/yr per percentage point of heat-demand reduction. In other words, each additional percentage point of retrofit delivers an estimated system benefit of about €0.5 billion per year.

This is policy-relevant because the usual assumption is that deeper retrofit becomes less valuable once the “easy wins” are exhausted. The results do not support that assumption within the tested range. Instead, each additional percentage point of demand reduction continues to lower the winter peak and reduce required investment in heat pumps, renewables, storage, and transmission at a similar rate.

The implication is clear: within 0–45% heat-demand reduction, the system-level data do not support stopping at moderate retrofit ambition on the grounds of declining cost-effectiveness. Deeper retrofit remains approximately as valuable per percentage point as shallower retrofit.

3.6 Demand Profile Analysis

Sections 3.1–3.4 quantify the impact of heating on German power-system costs and capacity. This section examines the temporal structure of that impact: when heat demand occurs and how heat-pump dispatch reshapes electricity load. The analysis identifies a substitution mechanism between retrofit ambition and the grid-flexibility value of heat pumps.

Two related but distinct demand quantities are distinguished in the analysis:

- Heat demand is the building heating requirement in thermal MW. It is an exogenous PyPSA-Eur input based on weather, demographics, and the German retrofit factor α_{DE}.
- Heating electricity demand is the electricity drawn by heat pumps and resistive heaters to meet that heat demand. It is an optimisation output, shaped by heat-pump dispatch and thermal storage.

For both measures, the **peak-to-average ratio** is used as a flatness metric, defined as peak demand divided by annual mean demand. Lower values indicate flatter, more grid-friendly profiles. The smoothing percentage is then calculated as the reduction in peakiness from heat demand to heating electricity demand:

$$\text{Smoothing (\%)} = \left(1 - \frac{\text{Elec P/A}}{\text{Heat P/A}}\right) \times 100 \tag{19}$$

A positive smoothing percentage means heating electricity demand is flatter than heat demand, reflecting flexibility from heat pumps and thermal storage. The analysis uses the model's native 3-hour resolution with 2,920 annual snapshots. Figures 6 and 7 show peak winter-day profiles for both quantities across the six scenarios.

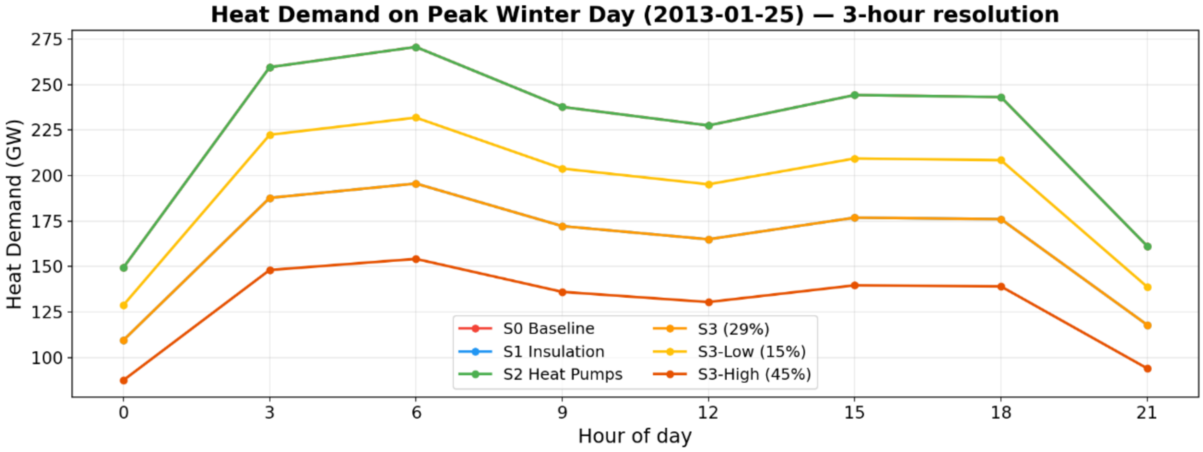


Figure 9. Heat Demand on Peak Winter Day for all scenarios (lines for S0 and S1 are not visible because they are identical to S2 and S3, respectively)

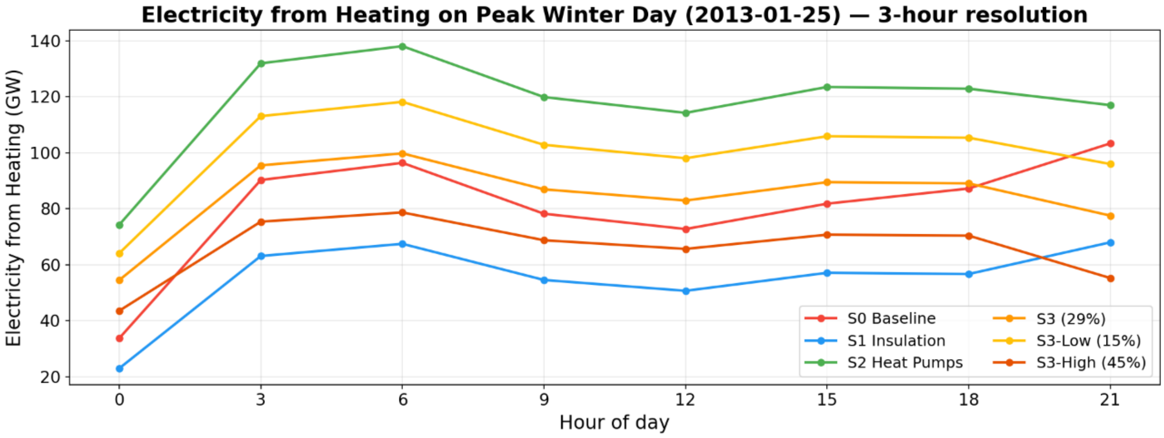
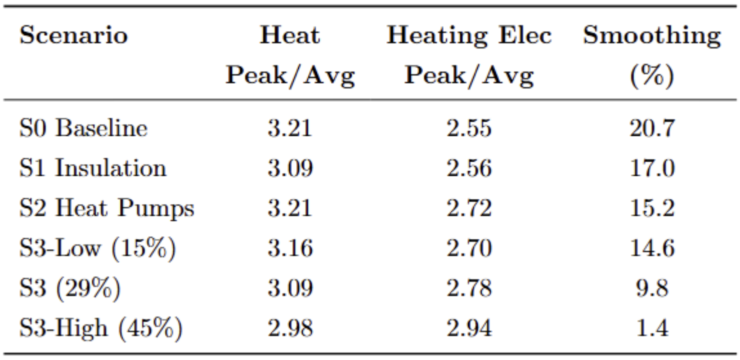


Figure 10. Electricity Consumption for Heating on Peak Winter Day for all scenarios

Table 8 reports the peak-to-average ratios and smoothing values for all six scenarios.

Table 8. Demand Profile Metrics



Scenario	Heat Peak/Avg	Heating Elec Peak/Avg	Smoothing (%)
S0 Baseline	3.21	2.55	20.7
S1 Insulation	3.09	2.56	17.0
S2 Heat Pumps	3.21	2.72	15.2
S3-Low (15%)	3.16	2.70	14.6
S3 (29%)	3.09	2.78	9.8
S3-High (45%)	2.98	2.94	1.4

Three observations follow. First, heat demand is largely technology-independent. S0 and S2 have the same peak-to-average ratio of 3.21, because heat demand is an exogenous PyPSA-Eur input based on weather and building characteristics. Technology choice cannot reshape the underlying heat requirement; only retrofit can.

Second, retrofit modestly flattens heat demand. The peak-to-average ratio falls from 3.21 in S0 to 2.98 in S3-High, a 7% reduction in peakiness. This occurs because retrofit reduces temperature-sensitive space heating more than relatively constant hot-water demand.

Third, the smoothing value of heat-pump dispatch declines with retrofit depth. In S0, heating electricity demand is 20.7% smoother than heat demand, reflecting load shifting through heat pumps and thermal storage. This falls to 17.0% in S1, 14.6% in S3-Low, 9.8% in S3, and only 1.4% in S3-High. At deep retrofit, heat and heating-electricity profiles become almost identical.

The mechanism is that deep retrofit reduces peak heat demand enough that thermal storage becomes less valuable. Thermal storage falls by 71%, from 7,746 GWh in S0 to 2,266 GWh in S3-High, limiting the optimiser’s ability to shift heat-pump operation away from peaks. As a result, the grid-flexibility value of heat pumps declines as retrofit deepens.

This identifies a flexibility–retrofit substitution: in low-retrofit pathways, heat pumps with thermal storage provide major peak-smoothing value; in high-retrofit pathways, demand reduction itself captures most of that benefit. Policy models should therefore not treat heat pumps as a fixed source of grid flexibility. Their flexibility value depends on the renovation pathway, so thermal storage and dispatch-control investments should be planned jointly with renovation-rate assumptions.

3.7 Smart Control Sensitivity Scenarios

Section 4.6 showed that the grid-smoothing value of heat-pump dispatch declines as retrofit depth increases and thermal storage deployment falls. However, PyPSA-Eur does not explicitly model sub-dispatch smart-control strategies such as peak shaving, weather-based pre-heating, or dynamic-pricing response. To estimate the system value of this unmodelled flexibility, two additional S3-based scenarios smooth the heat demand profile in pre-processing, which a presented in the following table.

Table 9. Cost-Optimal System Under Different Smart Control Assumptions

Metric	S3 Original (peaky)	S3 Smoothed-12h (thermal mass)	S3 Smoothed-24h (TM + buffer)
Peak heat demand	196 GW	180 GW	163 GW
Peak reduction	–	-8.2%	-16.7%
System cost	€69.2 bn	€52.2 bn	€51.4 bn
Savings vs S3	–	€17.0 bn (-25%)	€17.8 bn (-26%)
Heat pumps	92.5 GW	57.8 GW	57.7 GW
Wind+Solar	354 GW	202 GW	186 GW
Thermal storage	3,171 GWh	1,647 GWh	1,380 GWh

The first scenario uses 12-hour smoothing, representing building thermal mass exploited through smart control software. The second uses 24-hour smoothing, representing thermal mass plus external buffer storage. Annual heat demand remains fixed at 555 TWh; only the timing of demand changes.

The results are substantial. Peak heat demand falls from 196 GW in S3 to 180 GW with 12-hour smoothing and 163 GW with 24-hour smoothing. System cost falls from €69.2 bn/yr to €52.2 bn/yr and €51.4 bn/yr, respectively. Thus, 12-hour smoothing saves €17.0 bn/yr, or 25%, while 24-hour smoothing adds only €0.8 bn/yr of further savings.

Capacity reductions are also large. With 12-hour smoothing, heat pumps fall from 92.5 to 57.8 GW, wind from 119.3 to 84.5 GW, solar from 234.9 to 118.0 GW, and thermal storage from 3,171 to 1,647 GWh. The main benefit therefore comes from reducing peak heat demand and the infrastructure required to serve winter peaks

The key finding is strong diminishing returns. Building thermal mass alone captures most of the smart-control benefit, while additional buffer storage provides only a small extra gain. The policy implication is that Germany should prioritise software-based smart heat-pump control standards — including dynamic-tariff compatibility, grid-aware dispatch, and interoperable control protocols — rather than mandating expensive buffer storage hardware.

3.8 Summary of Findings

The technical and economic research questions from Chapter 1 can now be answered directly. Renovation rates strongly shape cost-optimal capacity across the coupled electricity-heat system. In the deep retrofit and full electrification scenario (S3-High), new onshore wind falls from 65 to 20 GW, solar from 65 to 10 GW, transmission from 11 GW to zero, heat pumps from 116 to 66 GW, gas CHP from 160 to 130 GW, battery storage from 337 to 189 GWh, and thermal storage from 7,746 to 2,266 GWh. This shows that retrofit affects the whole energy system, not only the building sector.

The demand-profile analysis identifies a flexibility–retrofit substitution mechanism. As retrofit deepens, the grid-smoothing value of heat-pump dispatch falls from 20.7% in the baseline to 1.4% under deep retrofit, mainly because thermal storage capacity falls by 71%. The smart-control sensitivity supports the same logic: an 8% smoothing of heat demand through building thermal mass reduces system cost by 25% (€17 bn/yr), but further smoothing delivers much smaller additional gains. Together, these results show that demand reduction and demand-side flexibility partly substitute for each other.

Economically, the system value of retrofit is approximately linear across the 0–45% range. The slope is roughly €0.5 bn/yr per percentage point of heat-demand reduction, meaning that each additional percentage point of retrofit delivers around €0.5 billion per year in system benefit. At 45% retrofit, cumulative system savings reach €24.0 bn/yr.

There is no evidence of diminishing returns within the tested range, making this linear relationship one of the central findings of the thesis.

The lowest LP system cost occurs in S3-High, at €60.5 bn/yr. However, this does not include retrofit investment costs or wider value streams such as CO_2 pricing, energy security, health, and comfort benefits. The next chapter therefore applies the cost-benefit framework from Section 2.6 to estimate net annual benefits and benefit-cost ratios for each retrofit depth, and then translates the results into concrete recommendations for German renovation policy.

4 Discussion and Policy Implications

Chapter 3 established the technical results: deep retrofit substantially reduces the cost-optimal infrastructure build across every technology category, and the marginal system value of retrofit is approximately constant at €0.5 bn/yr per percentage point of heat-demand reduction across the 0–45% range. These are answers to RQ1 and RQ2. They are not yet, on their own, an answer to RQ3, because RQ3 asks what combination of renovation depth, electrification, and grid-flexibility investment minimises total economic cost — and what that implies for German policy. This chapter completes the analysis. Section 4.1 explains the four mechanisms that account for the observed results. Section 4.2 sets the findings against the existing literature. Section 4.3 applies the cost-benefit framework to translate the system-cost results into net annual benefit. Section 4.4 translates these results into concrete policy recommendations. Section 4.5 acknowledges the limitations honestly. Section 4.6 summarises.

4.1 Four Mechanisms

Across the eight scenarios, four mechanisms explain the main results. First, retrofit creates a demand-reduction cascade: lower heat demand reduces heat-pump capacity, peak electricity demand, renewable capacity, storage, and transmission needs. This is why each percentage point of retrofit delivers roughly constant system value.

Second, electrification without retrofit creates an absent-retrofit penalty. The boiler-ban scenario without insulation, S2, is the most expensive case at €86.0 bn/yr, because unreduced winter heat demand must be served through a larger heat-pump fleet and additional power-system capacity. However, the main driver is demand level rather than the boiler ban itself: even when boilers remain available, the optimisation selects heat pumps for most heat supply under the net-zero constraint.

Third, retrofit and electrification interact differently depending on ambition. At 29% retrofit, the boiler ban is slightly cost-increasing relative to insulation alone, but at 45% retrofit, it becomes cost-decreasing: S3-High costs €7.5 bn/yr less than S1. This shows that the two levers are partly antagonistic at moderate ambition but complementary at deep retrofit.

Fourth, the analysis identifies a flexibility–retrofit substitution. In low-retrofit pathways, heat pumps with thermal storage smooth grid-side electricity demand by 20.7%. Under deep retrofit, this falls to 1.4%, because thermal storage drops by 71% and heat pumps lose much of their flexibility role. Smart-control sensitivity confirms the same pattern: 12-hour smoothing through building thermal mass saves €17 bn/yr, while 24-hour smoothing adds only €0.8 bn/yr more. This implies that renovation-rate assumptions and heat-pump flexibility investments must be planned together, not separately.

4.2 Literature Comparison

The findings of this thesis can be located against the published literature on system-coupled retrofit analysis, which is shown in the Table 10.

Table 10. Findings of this thesis set against the existing literature.

Finding	This Thesis	Existing Literature
Retrofit reduces total system cost	28% reduction (S0 → S3-High)	Zeyen et al. [10]: up to 17-20% at European aggregate
Cost-optimal demand reduction	45% is the cheapest scenario in the LP	Zeyen et al. [10]: 44-51% range - consistent
Retrofit reduces grid-infrastructure need	New transmission: 11 GW (S0) → 0 GW (S3-High)	Wüllhorst et al. [33]: retrofit reduces grid stress
Retrofit–electrification synergy at deep ambition	S3-High beats S1 by €7.5 bn/yr	Novel contribution of this thesis
Linear marginal value of retrofit	€0.49-0.57 bn/%pt across 0-45%	Not previously quantified
Flexibility–retrofit substitution	Heat-pump grid smoothing falls from 21%	Novel contribution of this thesis

	to 1.4% across S0 → S3-High	
Campaign-period economic optimum	1-2%/yr renovation rate	Not directly quantified at national scale for Germany

The directional findings are confirmed at higher resolution. Zeyen et al. [10] established at European aggregate that retrofit reduces total system cost by 17–20%. This thesis, focused on Germany at 5-node resolution, finds a 28% reduction (S0 to S3-High). The German-specific reduction being larger than the European average is consistent with Germany's structural conditions: high heating-degree-days, heavy dependence on fossil gas for residential heating, and significant internal transmission constraints — all of which retrofit alleviates. The cost-optimal demand- reduction range identified at European aggregate (44–51%) is consistent with this thesis identifying 45% as the cheapest of the tested LP depths.

Three findings are distinctive contributions of this thesis. The flexibility-retrofit substitution mechanism has not been reported in the previously published literature; it emerges from the sensitivity- decomposition approach combined with the hourly-resolution demand- profile analysis. The smart-control sensitivity quantification provides an estimate of the value of demand-side flexibility that PyPSA-Eur does not endogenously model. And the empirical observation that the optimization endogenously selects 69-81% heating electrification regardless of explicit policy mandates refines how the boiler-ban policy should be interpreted.

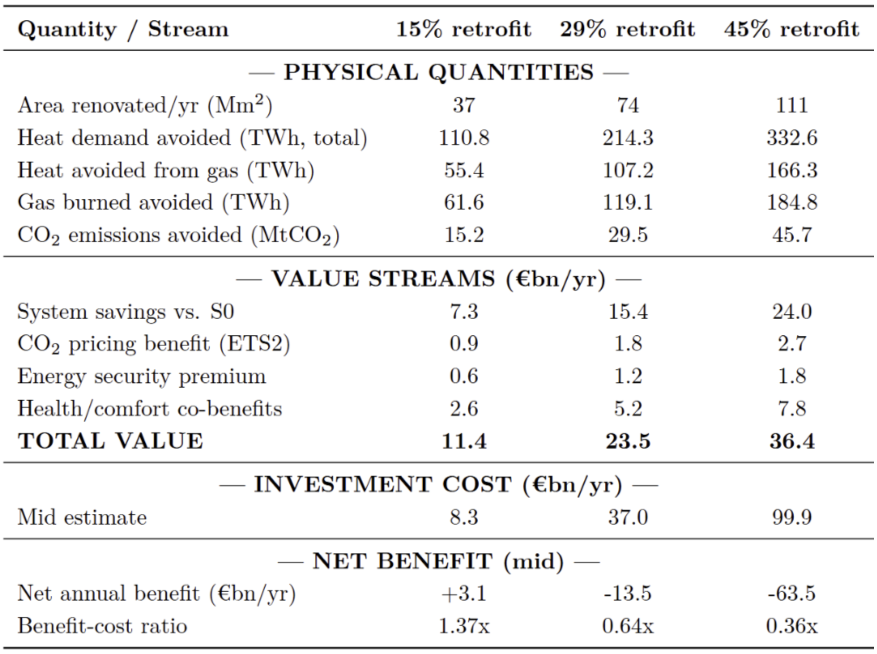
The transmission finding — that new expansion falls to zero in S3-High — is more aggressive than the existing literature has reported. It is conditional on the Germany-in-isolation modelling assumption: with cross-border imports, the marginal value of internal transmission might differ. However, the directional finding (that deep retrofit substantially reduces the need for new domestic transmission) is robust to this assumption and is complementary to the low-voltage grid findings of Wüllhorst et al. [33] at neighbourhood scale, which operate at a different spatial resolution.

4.3 System-Level Cost-Benefit Analysis

The system-cost savings reported in Chapter 4 are the avoided power-system investment that retrofit delivers — the rigorously computed system-side benefit. Converting this into a policy-actionable assessment requires three additional inputs: the cost of doing the retrofit itself, the additional value streams that retrofit creates outside the power-system optimization, and a net-benefit comparison.

The table below stacks system savings, ETS2 benefit, energy security premium, and health/comfort co-benefits, and overlays the mid-estimate annual investment cost across the three retrofit ambitions.

Table 11. Value Decomposition



Quantity / Stream	15% retrofit	29% retrofit	45% retrofit
— PHYSICAL QUANTITIES —			
Area renovated/yr (Mm^2)	37	74	111
Heat demand avoided (TWh, total)	110.8	214.3	332.6
Heat avoided from gas (TWh)	55.4	107.2	166.3
Gas burned avoided (TWh)	61.6	119.1	184.8
CO_2 emissions avoided ($MtCO_2$)	15.2	29.5	45.7
— VALUE STREAMS (€bn/yr) —			
System savings vs. S0	7.3	15.4	24.0
CO_2 pricing benefit (ETS2)	0.9	1.8	2.7
Energy security premium	0.6	1.2	1.8
Health/comfort co-benefits	2.6	5.2	7.8
TOTAL VALUE	**11.4**	**23.5**	**36.4**
— INVESTMENT COST (€bn/yr) —			
Mid estimate	8.3	37.0	99.9
— NET BENEFIT (mid) —			
Net annual benefit (€bn/yr)	+3.1	-13.5	-63.5
Benefit-cost ratio	1.37x	0.64x	0.36x

The total annual value rises approximately linearly with depth, because each value stream is mechanically proportional to the heat- demand reduction. The investment cost, by contrast, rises non-linearly with depth: deeper retrofit requires more invasive measures, with construction costs roughly tripling from shallow to deep retrofit under central IWU 2024 assumptions.

Computing total annual value minus annual investment cost at each retrofit depth gives the net annual benefit during the 2025-2050 campaign period:

- 15% retrofit (1%/yr renovation): +€3.1 bn/yr, BCR 1.37x. The only scenario that is robustly net-positive under conservative accounting and the highest BCR of any tested ambition.
- 29% retrofit (2%/yr renovation): -€13.4 bn/yr, BCR 0.64x. Net-negative during the campaign period. Becomes net-positive only with extended- lifetime NPV accounting that captures benefits accruing beyond 2050.
- 45% retrofit (3%/yr renovation): -€63.5 bn/yr, BCR 0.36x. Clearly net-negative during the campaign period. Becomes defensible only under low-cost retrofit variants or full-lifetime NPV.

The qualitative finding is robust: 1%/yr is the highest BCR option, and the system value of retrofit follows an approximately linear pattern even though the net-benefit balance becomes increasingly negative at deeper retrofit due to the disproportionate rise in retrofit investment cost. A time-asymmetry caveat applies throughout: retrofit costs are concentrated in the 2025-2050 campaign window, while retrofit benefits persist for 30-50+ years of building lifetime. The campaign-period framing is methodologically conservative and likely under-states the case for deeper ambition.

4.4 Policy Recommendations

Three concrete recommendations follow from the analysis.

Recommendation 1 — For the Federal Ministry for Economic Affairs and Climate Protection (BMWK). Target the EU Renovation Wave rate of 2%/yr, paired with industrial cost-reduction policies.

The 2%/yr target corresponds to the 29% cumulative heat-demand reduction analysed in S3. Under conservative campaign-period accounting, the 2%/yr target is net-negative at -€13.4 bn/yr — this represents the campaign-period cost of binding climate compliance under the Federal Climate Change Act 2045 net-zero target. The gap should be addressed through industrial cost-reduction policies: prefabricated insulation systems at scale, serial deep-retrofit programs, simplified permitting, and supply-chain consolidation. These interventions can plausibly reduce mid-range retrofit costs by 30-50%, which would bring the 2%/yr pathway toward net-positive within the campaign window. Without such cost reductions, the 2%/yr trajectory requires approximately €13 bn/yr of policy support during the 2025-2045 period — comparable in magnitude to existing BEG subsidy programs. The 1%/yr status-quo trajectory delivers higher capital efficiency (BCR 1.37) and €3.1 bn/yr net-positive economics, but the absolute climate impact (15.2 $MtCO_2$/yr avoided) is inadequate for the binding 2045 target. The 3%/yr stretch ambition is clearly net-negative under campaign accounting (BCR 0.36) and is defensible only with full-lifetime NPV.

Recommendation 2 — For the German Federal Network Agency. Require renovation-rate and smart-control sensitivities in the Network Development Plan (NDP).

The current NDP for the German power system uses fixed heat-demand projections that do not vary with retrofit ambition. This thesis demonstrates that retrofit ambition is one of the most consequential drivers of grid-expansion need: new transmission falls from 11 GW (S0) to zero (S3-High). Sound system planning requires that the NDP be conducted under multiple renovation-rate pathways — at minimum, low (1%/yr), medium (2%/yr), and high (3%/yr) — with the resulting grid plans compared on robustness across the pathway uncertainty. The flexibility-retrofit substitution finding (Mechanism 4) and the smart-control sensitivity reinforce this point: heat-pump flexibility infrastructure investment should be planned jointly with renovation-rate assumptions, not as a separate decision. Smart heat-pump control standards — software-based dispatch and control logic exploiting building thermal mass — should be evaluated alongside hardware investments because they capture the majority of the smart- control benefit at substantially lower cost than buffer storage infrastructure.

Recommendation 3 — For the German Building Energy Act (GEG) and Energy Performance of Buildings Directive (EPBD) national transposition. Sequence the boiler-ban requirement behind the insulation requirement.

A boiler ban without prior demand reduction is the worst-performing scenario in this study (S2 at €86.0 bn/yr). However, a methodological refinement is important: even when boilers are allowed in S1, the optimization chooses them only 5-6% of the time because heat pumps are cost-optimal under the 2050 net-zero constraint. The €18 bn/yr penalty between S2 and S1 therefore reflects the impact of unreduced heat demand combined with electrification, not the boiler ban per se. The implication is that demand reduction (renovation rate) is the dominant policy lever, with the boiler ban functioning as regulatory reinforcement of cost-optimal technology choices. Implementation should therefore: mandate envelope retrofit before or alongside the 2028 fossil-boiler phase-out for new installations; tie heat-pump subsidies (BEG, KfW) to a minimum envelope-performance threshold (e.g., EPC-D or better) so that subsidised heat pumps operate efficiently in adequately insulated buildings; and treat the boiler ban as the culmination of the renovation policy rather than as a separate parallel instrument. This sequencing maintains consumer signal and policy clarity while avoiding the system cost of forcing electrification onto a still-unrenovated building stock.

4.5 Limitations

Five limitations bound the interpretation of the results, which are presented in Table 12.

Table 12. Limitations of this study and corresponding directions for future research.

Scope boundary of this thesis	Direction for future work
Germany modelled in isolation, without coupling to neighbours	Include the European interconnected system; the present results are an upper bound on domestic infrastructure investment

Single weather year (2013)	Multi-year weather analysis to capture inter-annual variability and consecutive dark-lull events
Single-shot ("overnight") optimisation for 2050 only	Myopic pathway optimisation across 2030 → 2040 → 2050 to capture transition dynamics
Retrofit factor α_{DE} set exogenously	Endogenous co-optimisation with α_{DE} as a continuous decision variable
Transport and industry sectors disabled	Full sector coupling to capture cross-sector flexibility
Aggregated building stock at three segment levels	TABULA building-archetype resolution to capture stock heterogeneity
Single-year ("campaign-period") cost-benefit framing	Full 50-year lifetime NPV accounting
Heat-pump electrification share was decided by the program	Parameterised electrification scenarios at 30 %, 50 %, 70 % heat-pump shares

Two specific limitations deserve additional comment. The Germany-in- isolation choice is conservative: cross-border imports would reduce required German build-out, so the absolute capacity numbers reported here are upper bounds. The single-shot 2050 optimization is well suited to identifying end-state cost-optimal configurations but does not answer questions about the rate at which the transition can be implemented; the policy recommendation that 2%/yr is the appropriate ambition does not, by itself, settle the question of whether 2%/yr is institutionally achievable in the German construction sector. The campaign-period framing of the cost-benefit analysis is methodologically conservative and likely understates the case for deeper ambition; full- lifetime NPV is identified as a priority for future research.

4.6 Summary

The three research questions stated in Chapter 1 can now be answered in compact form:

- **RQ1 (technical):** Renovation rates strongly affect cost-optimal installed capacities. Deep retrofit at 45% combined with full heating electrification reduces new wind by 69%, solar by 84%, transmission by 100%, heat pumps by 43%, and thermal storage by 71% relative to baseline.
- **RQ2 (economic):** The marginal system value of retrofit is approximately constant at €0.5 bn/yr per percentage point of heat-demand reduction across 0–45% — no diminishing returns. Cumulative savings reach €24.0 bn/yr at 45%.
- **RQ3 (policy):** The campaign-period economic optimum is 1%/yr renovation (15% reduction) at BCR 1.37x and net benefit +€3.1 bn/yr. The recommended ambition is nevertheless 2%/yr (29% reduction), corresponding to the EU Renovation Wave target, which is net-negative at -€13.4 bn/yr in the campaign period but becomes net-positive with extended-lifetime accounting and represents the binding-climate compliance pathway. The 3%/yr stretch target is clearly net-negative in the campaign period. The boiler ban should be sequenced behind, not parallel to, the insulation requirement, with renovation rate treated as the primary policy lever.

Three additional findings emerge as novel contributions. The flexibility-retrofit substitution mechanism shows that the grid-side flexibility value of heat pumps depends critically on retrofit context, dropping from 20.7% smoothing in the baseline to 1.4% at deep retrofit. The smart-control sensitivity demonstrates that demand-side flexibility software captures 25% of system cost in the cost-optimization. And the endogenous electrification finding shows that heat pumps emerge as cost-optimal at 69-81% share regardless of explicit policy mandates. Flexibility infrastructure planning, renovation-rate policy, and the boiler-ban policy should be conducted jointly, not separately.

5 Conclusion and Future Work

This thesis quantified the techno-economic impact of building-envelope retrofit and heat-pump electrification on the German energy system using PyPSA-Eur. The results show that retrofit reduces infrastructure requirements across the coupled electricity-heat system: under 45% deep retrofit with full electrification, new onshore wind falls by 69%, solar by 84%, heat pumps by 43%, thermal storage by 71%, and new transmission expansion is eliminated. A flexibility-retrofit substitution effect is also identified, with the grid-side smoothing value of heat-pump dispatch declining from 20.7% in the baseline to 1.4% under deep retrofit.

Economically, each percentage point of heat-demand reduction lowers system cost by approximately €0.5 bn/yr, with no evidence of diminishing gross system returns across the 0–45% range. Smart heat-pump control reduces system cost by around 25% (€17 bn/yr), while additional buffer storage provides only marginal savings. Heat pumps reach a cost-optimal share of 69–81% across scenarios regardless of explicit mandates, indicating that boiler bans reinforce rather than drive the main system-cost outcome.

Under conservative campaign-period accounting, 1%/yr renovation is the economic optimum, yielding €3.1 bn/yr net benefit and a BCR of 1.37. The 2%/yr EU Renovation Wave target is net-negative during the campaign period but becomes net-positive under extended-lifetime accounting, while the 3%/yr stretch target remains clearly net-negative. The thesis therefore recommends a 2%/yr renovation target combined with industrial retrofit cost-reduction policies, fabric-first sequencing, renovation-rate integration into grid planning, and mandatory smart heat-pump control standards.

Future work should focus on 2025–2050 pathway optimisation, full European cross-border coupling, bottom-up building-stock disaggregation, and detailed thermal-model integration. Overall, the findings show that Germany’s building-sector decarbonisation requires coordinated planning of retrofit, heat pumps, grid flexibility, and smart-control standards as one integrated transition strategy.

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Appendices

Appendix 1. Statement on the AI Use

AI tools were used during the development of this thesis for two specific purposes:

(i) Code debugging and analysis: assistance in interpreting PyPSA-Eur output structures, debugging Python scripts for post-processing analysis, and developing visualization code for results figures. The author wrote all original code and verified all results.

(ii) Writing refinement: editing assistance for thesis text including sentence-level clarity improvements and consistency checks. The author wrote all original content; AI was used to refine phrasing.

The author retains full responsibility for all analytical decisions, all scientific claims, all numerical results, and the integrity of the methodology. AI tools were used as supportive instruments for debugging and refinement — not for generating original research content, performing simulations, or producing the substantive analytical conclusions of this thesis. All simulation results were produced by PyPSA-Eur and verified by the author directly.

Appendix 2. Another appendix title

For reproducibility, a GitHub repository (link) is included, which provides clean code, scenario outputs, thesis plots, and replication results.