Quantifying Trade-Offs in Renovation Schemes

A Scenario-Based Material Flow Analysis of Energy Renovation Prioritisation Schemes and Renovation Quotas for Reducing Carbon Emissions, Energy Burdens, and Improving Cost-Effectiveness in Amsterdam's Social Housing Stock

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CONTENT

ABBREVIATIONS

ABS	Acrylonitrile Butadiene Styrene
AFWC	Amsterdam Federation of Social Housing Associations (Amsterdamse Federatie van Woningcorporaties)
a.s.l.	Above Sea Level
ASHP	Air-Source Heat Pump
BAG	Basic Registration Addresses and Buildings (Basisregistratie Adressen en Gebouwen)
BUR	Energy Burden Prioritisation Scheme
CBS	Central Bureau of Statistics (Centraal Bureau voor de Statistiek)
EFF	Economic Efficiency Prioritization Scheme
EFs	Environmental Factors
IMP	Environmental Impact Prioritization Scheme
EPBD	Energy Performance of Buildings Directive
EP-Online	Energy Performance Online Registry
EPS	Expanded Polystyrene
ES	Existing State
ESMs	Energy Saving Measures
GHG	Greenhouse Gas
GIS	Geographic Information System
HIU	Heat Interface Unit
HVAC	Heating, Ventilation, and Air Conditioning
LCA	Life Cycle Assessment
LTRS	Long-Term Renovation Strategies
MDHI	Mean Disposable Household Income
MFA	Material Flow Analysis
nZEB	Nearly Zero-Energy Building
NPA	National Performance Agreement (or National Agreement Program)
OSB	Oriented Strand Board
P00	Renovation Package 00 (Op basis van WoON2018 – huidig)
P01	Renovation Package 01 (ISO, MECH AFVOER)
P02	Renovation Package 02 (ISO, MECH AFVOER, WPe)
P03	Renovation Package 03 (ISO, BALANSVENTILATIE, WPe)
PIR	Rigid Polyisocyanurate
PUR	Polyurethane
RVO	Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland)
Rc-values	Thermal resistance values
SHA	Social Housing Associations
UFA	Usable Floor Area
U-values	Thermal transmittance value
vbo	Verblijfsobject (Residential Unit)
WWII	World War II

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ABSTRACT

This study investigates the trade-offs of energy renovations in Amsterdam's social housing stock from 2025 to 2050, evaluating three renovation prioritisation schemes -BUR (energy-burden focused), IMP (emissions-focused), and EFF (cost-efficient) - across varying deep-renovation quota pathways - LOW (15% deep renovations and 85% limited renovations), MID (50% deep renovations and 50% limited renovations), NPA (85% deep renovations and 15% limited renovations). Using a material-flow and energy-renovation model, the impacts on energy savings, household energy burden, material inflows and outflows, operational and embodied carbon emissions, and renovation costs are quantified.

Results reveal that prioritisation schemes significantly shape renovation outcomes. BUR prioritises foundational envelope improvements, effectively reducing household energy burden and costs, especially for vulnerable tenants. IMP maximises operational CO_2 reductions through renewable heating system upgrades but can increase financial burdens and leave poorly insulated units behind. EFF balances cost and emission performance, gradually shifting focus toward heating system upgrades with higher renovation quotas.

Deep renovations increase material flows and embodied emissions, while envelope components dominate resource use. Higher renovation quotas amplify emission saving and energy costs outcomes, highlighting the importance of burden-sensitive implementation.

Policy implications indicate that achieving Amsterdam's climate and energy goals requires integrating technical, economic, and social objectives. Envelope-first programmes, staged implementation, and financial safeguards are fundamental to prevent inequitable outcomes. From a scientific perspective, future research should adopt full life-cycle assessments, multi-cycle renovation modelling, and behavioural considerations to better capture real-world dynamics.

Overall, this study demonstrates that effective renovation strategies require a careful balance of decarbonisation, cost-efficiency, material use, and equity to ensure a sustainable and just transition of the social housing stock where no household is left behind.

1 INTRODUCTION

Nations worldwide are accelerating efforts to reduce greenhouse gas (GHG) emissions, with energy transition serving as a central strategy. Yet rising energy demand is countering the effectiveness of this shift, making demand-reduction measures increasingly important. In cities, where energy use is concentrated, renovation of existing buildings has emerged as a key solution for reducing both emissions and pressure on the energy grid. This is particularly relevant for Amsterdam, where large-scale energy improvements to residential buildings are becoming essential to achieve municipal and national-level climate goals.

Around 79% of all the world's energy consumption and more than 60% of GHG emissions originate in cities, making urban areas central to climate mitigation [1]. In the Netherlands, the built environment accounts for almost 25% of the nation's final energy demand [2], showing the importance of improving residential energy performance. A large share of this demand comes from the country's unusually substantial social housing sector, which represents almost a third of the national housing stock, much of it older and energy-inefficient [3]. This makes social housing a key lever for national energy-related emission reduction. The city of Amsterdam exemplifies this challenge. With 40-45% of its housing stock owned by social housing associations (SHAs) [4], [5], [6], the city has one of the highest concentrations of SHA residential units in Europe. Much of this stock consists of older buildings with limited insulation and gas-based heating systems: about 20% were built before 1919, 30% built before WWII, and another 20% during immediate post-war reconstruction period [7]. Constructed prior to modern energy-performance regulations, these buildings often lack cavity walls, have poor airtightness, and rely on inefficient heating systems, resulting in high energy demand for liveable indoor comfort [8]. Historically cheap natural gas overcompensated for their inefficiencies, but today these systems are major drivers of both energy costs for households and GHG emissions [9].

Since most of the Amsterdam housing stock is expected to remain in use through 2050 [8], [10], [11], improving their energy performance is central in the Dutch Climate Plan. Despite EU-level and National incentives, renovation rate in the SHA sector has remained low. While policy roadmaps often assume annual renovation rates of 2.5–3% [12], [13]., the Netherlands currently achieves only 1.3–1.4%, a trend also observed in other European countries [38]. At this pace, some studies estimate it could take a century to renovate the majority of the stock [12], showing the urgency of scaling up renovation activities. Amsterdam has introduced several initiatives aimed at accelerating energy-focused renovations. The Transition Heating Plan seeks to phase out natural gas by 2040, while the National Performance Agreement (NPA) requires SHAs to improve envelope insulation and promote heat pump adoption, ultimately eliminating residential units with energy labels E, F, and G. Although these policies provide strong momentum, they raise a fundamental question: *what should SHAs prioritize when renovating?* Reducing energy consumption, lowering carbon emissions, minimizing renovation costs, and easing household energy burdens are all goals to strive for, but they can lead to conflicting renovation strategies.

Stegnar (2025) identifies three common prioritisation schemes often used in renovation policy [8], [14]; (i) construction year–based prioritization, (ii) energy benchmarking, and (iii) energy auditing. Construction year–based approaches assume older buildings perform worse and should therefore be renovated first [15], yet studies show that unregulated, ad-hoc renovations often disrupt the relationship between age and actual energy use [16]. Energy benchmarking, which compares buildings to national energy standards using energy-label registries, offers a more targeted method but is limited by incomplete or outdated datasets [8]. Energy auditing is the most accurate and detailed approach, relying on on-site assessments and residential unit-level simulations, but it is costly, labour-intensive, and impractical to implement across an entire city-wide housing stock [8], [16].

Previous studies have applied these prioritization concepts in various contexts, often focusing on energy savings and investment efficiency. Sankelo et al. (2022) evaluated Finnish detached houses by simulating envelope improvements and heating-system replacements, prioritizing measures aligned with national subsidy schemes and maximizing energy savings per unit of investment [17]. Karmellos et al. (2015) developed a multi-objective tool to prioritize renovations based on primary energy consumption and cost, demonstrating an inverse relationship between these two factors [18]. While such studies provide valuable insights, they have a narrow focus on technical and economic performance of the residential units. A recent study by Stegnar (2025) has managed to bring socio-economic criteria to the stage. Doing so, the study presents an analysis that goes beyond technical efficiency of the previously done work, accounting for both energy poverty and infrastructural need [8].

Although existing studies show how individual prioritization schemes affect energy performance, socio-economic indicators, or renovation costs, most analyses remain focused on a single objective. Very little research compares different prioritization schemes directly or examines how varying renovation quotas influence environmental, economic, and social outcomes. As renovation increasingly replaces new construction, this gap becomes particularly important. Especially for cities like Amsterdam, where renovation needs and policy ambitions are high. In the absence of studies evaluating which prioritization approach performs best, cities are left without clear guidance for structuring their large-scale renovation strategies.

Material Flow Analysis (MFA), a core method in Industrial Ecology, offers a way to quantify material stocks and flows in the built environment [19]. Bottom-up MFA methods combine detailed physical characteristics of buildings (e.g., floor area, volume, or envelope surface) with material intensity data [20], [21], [22]. This granularity allows for component-specific service lives and replacement cycles to be modelled. Though data collection is demanding, advancements in GIS tools and the increasing availability of municipal building data [23], [24], [25], [26], [27], [28], [29], make such analysis feasible. Incorporating a time dimension, such as 4D-GIS method proposed by Tanikawa et al. [30], [31], [32], allows for tracking of material flows over time, supporting dynamic stock modelling. In the context of residential renovation, dynamic bottom-up MFA is often combined with Life Cycle Assessment (LCA) or energy modelling to link material embodied GHG emissions with operational energy use [33]. These approaches have typically focused on heating systems, but less on the broader material consequences of policy-driven prioritization. Most studies assess energy or recycling targets rather than the trade-offs among environmental, social, and economic objectives [22], [34], [31], [35], [36].

This thesis addresses this gap by comparing different renovation-prioritisation schemes for Amsterdam's social housing stock using a scenario-based, bottom-up Material Flow Analysis (MFA) that integrates material flows, embodied and operational carbon emissions, renovation costs, and household energy-burden outcomes. By linking material-based system analysis with policy-relevant prioritisation schemes aligned with the National Performance Agreement (NPA), the study evaluates how alternative renovation schemes perform across environmental, economic, and equity dimensions during the period 2025–2050.

A second, equally underexplored dimension examined in this thesis is the role of renovation quotas, the share of deep versus limited renovations applied each year. While prioritisation schemes determine which residential units are renovated first, renovation quotas determine the depth of interventions across the housing stock. Existing literature typically treats renovation rates or renovation depth targets as fixed parameters, without analysing how different quota configurations interact with prioritisation schemes or influence the magnitude of trade-offs between energy savings, material use, emissions, and household affordability. To incorporate this additional layer of decision-making, the thesis evaluates three renovation-quota pathways, each representing different shares of deep and limited renovation interventions. By assessing renovation schemes under multiple pathways, the study reveals how changing the balance between deep and limited renovations reshapes the performance, trade-offs, and equity outcomes of each prioritisation scheme. This combined approach provides a more comprehensive understanding of the systemic implications of large-scale housing renovation planning.

Overall, the research is guided by a central sustainability dilemma: in pursuing energy-efficient buildings, what compromises are introduced in material intensity, energy affordability, and long-term GHG outcomes?

The analysis is guided by the main research question:

MRQ: To what extent do different renovation-prioritisation schemes and renovation quotas influence the trade-offs among energy savings, material use, household energy burden, and carbon emissions in Amsterdam's social housing stock between 2025 and 2050?

To address this, the study is structured around four sub-questions:

SRQ1: Prioritised Renovation Deepness and Building Typologies: *How are renovation packages distributed across the housing stock renovation prioritisation schemes in different renovation quota pathways? Which dwelling types are prioritized?*

SRQ2: Material Inflows and Outflows of Renovations: *What material quantities are required under each prioritisation scheme, and how do material inflows and outflows differ between renovation depths in terms of quantity at material and component level?*

SRQ3: Changes to Energy Burden of Households: *How do the different renovation schemes and pathways impact energy costs and affordability for vulnerable households?*

SRQ4: Economic and Environmental Trade-offs of the Renovations: *What are the total renovation costs in the different schemes and pathways and how do these renovations impact both embodied carbon emissions from building materials and operational CO_2 reductions from heating and ventilation?*

2 METHODOLOGY

The analysis conducted in this study is organised into four overarching phases, each designed to structure how renovation dynamics occur in the Municipality of Amsterdam. **Phase 1** establishes the baseline by characterising the housing stock and its current renovation condition. **Phase 2** outlines the renovation options considered in the model and specifies how renovation activity is distributed over time. **Phase 3** conceptualises the set of energy-related interventions included in these renovation options and links them to the model's housing stock. Finally, **Phase 4** introduces the prioritisation schemes that determine how renovation efforts are allocated across residential units based on selected criteria.

PHASE 1. Mapping the SHA Stock in Amsterdam and Current Renovation Status

PHASE 2. Renovation Archetypes and Renovation Rates

PHASE 3. Energy Saving Measures and their Material Consumption

PHASE 4. Prioritisation Schemes

2.1 PHASE 1. Mapping the SHA Stock in Amsterdam and Current Energy Performance of the Stock

To map the current state of Amsterdam's SHA-owned residential building stock and understand the level of renovation in individual buildings, a range of national and municipal databases were compiled and processed. Table 1 provides an overview of these data.

Table 1: National- and Municipality-level Databases for Model

Name	Code(s)	Purpose	Year	Scope	Ref
BAG *(Basisregistratie Adressen en Gebouwen)* – Basic Address and Building Registry of Amsterdam	BAG_PAND BAG_VBO	National register of all buildings and addresses in the Netherlands.	2025	AMS	[29]
BAG3D (*Dakvlakken*, derived from *Basisregistratie Adressen en Gebouwen – BAG)* – Amsterdam 3D Roof Dataset	BAG3D_ROOF	Provides roof dimensions and typology, plus height and facade dimensions.	n.a.	AMS	[37]
AFWC *(Amsterdamse Federatie van Woningcorporaties)* – Social Housing Database (2023/24 version)	AFWC_SOCIAL	Spatial identification of SHA owned residential units in Amsterdam region.	2024	AMS	[38]
ESRI (*Woningtypering*)– Residential Typology Layer	ESRI_TYPE	Provides building-type classification (e.g., apartment, semi-detached house, etc.)	2025	NL	[39]
CBS (*Buurtcode, Centraal Bureau voor de Statistiek*) – Neighborhood Code Dataset	CSB_NEIGHBOR	Boundaries for districticts (*wijken*), neighbourhoods (*buurten*), and municipalities (*gemeenten*).	2023	NL	[40]
EP-Online *(Energielabelregister, Rijksdienst voor Ondernemend Nederland – RVO)* – Energy Label Database	EP_LABEL	Registered energy labels and performance indicators of buildings in NL.	2025	NL	[27]
RVO *(Voorbeeldwoningen; Rijksdienst voor Ondernemend Nederland)* – Residential Unit Example Dataset	RVO_ARCHETY	Provides default data of residential unit in different building types and construction period. Representative residential units.	2023	NL	[28]
CBS *(Warmtepompbezit in de sociale huursector, Centraal Bureau voor de Statistiek)* – Heat Pump Ownership in Social Housing	CBS_PUMP	Share of heat pump prevalence in NL SHA-owned rental residential units.	2023	NL	[41]
Gemeente Amsterdam *(Gemiddeld besteedbaar inkomen per stadsdeel)* – Mean Disposable Income by District (MDHI)	AMS_MDHI	For every district in amsterdam there is an average MDHI	2024	AMS	[42]
Gemeente Amsterdam *(Transitievisie Warmte Amsterdam)* – Heat Transition Plan	AMS_HTP	Different heating sources will be installed from now till 2040	2020	AMS	[43]

More detailed information on the filtering and preprocessing of the databases can be found in **Appendix A. Detailed Preliminary Data Processing.**

2.1.1 Building Registrations, Dimensional Attributes, and Building Typologies

The Basisregistratie Adressen en Gebouwen (BAG) is the official national registry of the Netherlands, providing authoritative geospatial and administrative data on all addresses and buildings. It is a key source of information for urban planning, policy development and academic research, offering detailed, standardised data on the physical and geospatial characteristics of buildings across the country [44]. The use of three BAG datasets is employed to map the building stock of Amsterdam: BAG_PAND (building-level data), BAG_VBO (residential unit-level data), and BAG3D_ROOF (three-dimensional building geometries). The BAG_PAND dataset was filtered to retain only buildings currently in use. Spatial matching was then applied to link each residential unit (BAG_VBO) to a single corresponding building (BAG_PAND), ensuring consistent unit(s)-to-building overlays and having no double counting of buildings. The BAG3D_ROOF dataset provides dimensional attributes such as building height, façade area, and roof type. It supports component-level assessments for renovation. The ESRI ArcGIS Woningtypering dataset was incorporated to classify the Amsterdam building stock by typology. Through a spatial join, residential unit-type classifications were linked to the BAG data, resulting in the categorization of buildings into five typologies: apartments, mid-terrace houses, end-terrace houses, semi-detached houses, and detached houses. 6.58% of SHA stock had missing typology classification, which lead to the exclusion of a total of 3,239 SHA buildings from the analysis.

It is important to understand the difference between the terms ‘residential unit’ and 'building'. Throughout this paper, both terms will be used; however, they are not interchangeable. Some data pertains to a single residential unit within a building; this will be referred to as a 'residential unit', while a structure encompassing one or more residential units of the same typology will be called a 'building'. This distinction is important as some data relates to individual units, while other data takes the whole building into account.

2.1.2 Administrative and Socioeconomic Attributes

To incorporate the relevant administrative and socio-economic context into the Amsterdam building stock dataset, three additional data sources were used: CSB_NEIGHBOR (neighbourhood codes), AMS_MDHI (income-related data) and AFWC_SOCIAL (SHA ownership).

Neighbourhood codes and names from the Centraal Bureau voor de Statistiek (CBS) were assigned to each building through a spatial join based on whether the BAG building geometry fell within CBS-defined neighbourhood boundaries, in order to link to broader neighbourhood-based indicators (such as income and heat transition plans). Ownership data from the Amsterdam Federation of Housing Corporations (AFWC) was added by intersecting their geospatial dataset with the BAG building footprints. This identified 45,946 buildings as part of the SHA building stock. Additionally, neighbourhood-level monthly mean disposable household income (MDHI), obtained from the Municipality of Amsterdam, was linked to each residential unit using the CBS neighbourhood codes. While this method assumes uniform income across all residential units within a neighbourhood, it provides a consistent basis for comparing income levels and renovation needs across the city.

2.1.3 Amsterdam Municipality’s Heat Transition Plan 2020-2040

The Netherlands has translated the objectives of the European Renovation Wave into national long-term renovation strategies and operationalized them at the local level through municipal Heat Transition Visions (*Transitievisie Warmte*) [43], [45], [46]. These documents outline the pathway each municipality intends to follow in phasing out natural gas for heating, with the national target set for 2050. The Municipality of Amsterdam has adopted a more ambitious timeline, aiming to achieve a natural gas-free heating system by 2040 [47], [48]. The core strategy for achieving this transition involves a significant expansion of district heating and sustainable gas networks across the city. Delays in the expansion and deployment of district heating infrastructure as well as financial troubles in the Municipality and SHAs with regards to district heating have already been reported [49], [50], [51]. However, for this analysis, the renovation trajectory will be modelled in alignment with the official municipal roadmap of 2020, under the assumption that the strategic objectives will be met as planned.

The heat transition roadmap for Amsterdam includes three key parameters: (i) the type of heating technology, (ii) the locations (i.e. neighbourhoods) in which it will be deployed, and (iii) the time period in which it will be operational (2025–2040). The types that will be distributed in Amsterdam are:

1. **Sustainable Gas Networks –** This "technology" does not necessarily require changes to the existing gas infrastructure, as conventional natural gas networks can also transport green gases. These green gases consist primarily of biofuels, green hydrogen, and green synthetic gas [52]. However, these options are not yet fully operational, and their current or future shares in the gas network remain uncertain, with no reliable prognoses available. For this analysis, the bio-based gas biomethane is used as a representative of the broader category of green gases.
2. **District Heating** - In the city of Amsterdam the district-heating network's central sources are Vattenfall's Diemen power station and *Afval Energie Bedrijf* waste-to-energy Amsterdam plant [53], [54]. Alternative sources such as surface-water heat, residual heat from data centres, geothermal energy and biomass are expected to play a larger role in the future [53]. The Vanttenfall Diemen power station is taken as general representation of the district heating source.
3. **All-electric Heat Pumps –** Where the district heating network and the sustainable gas network do not reach the residential unit, heat pumps will be installed. Air-sourced heat pumps are the most commonly used in the Netherlands [55]. Therefore, when talking about heat pumps, it is referring to a fully electric air-sourced heat pump (ASHP).

In the city's roadmap, sustainable gas use is prioritised in Amsterdam's historic central districts (See Figure 1). This approach reflects the restrictive heritage protection regulation that constrains major structural alterations to listed and culturally significant building [56], [57]. Switching to sustainable gases from the conventional natural gas offers a lower infrastructural impact compared to district heating or fully electric systems, as sustainable gases can utilize the existing gas infrastructure with minimal modifications [58]. Most of the city, however, is transitioning to district heating.

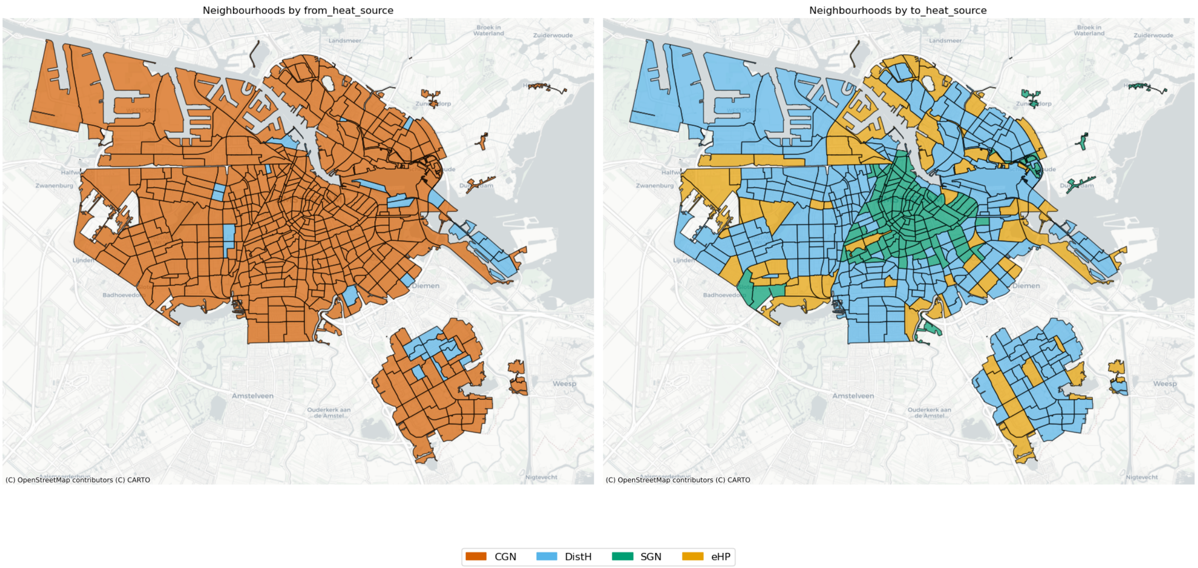

Figure 1: Heat Sources in Amsterdam's Heat Transition Plan pre-2020 to 2040.

CGN – Conventional natural gas network, DistH - Distric heating, - SGN – Sustainable gas network, eHP – fully electric-heat pumps
On the left, the current 2020 heating system situation of the Municipality of Amsterdam. On the right, the future 2040 heating system of the Municipality of Amsterdam

2.1.4 Energy Performance of the Residential Unit

The Energy Performance Online registry is the official Dutch national database for building energy performance certificates, maintained by RVO. Since 2015, all energy labels issued for buildings are recorded in this open-access dataset [27]. The database is updated daily, with newly registered energy labels appended in real time. Consequently, any downloaded snapshot of the data inherently contains a degree of temporal incompleteness. For the purposes of this study, a static version of the dataset dated 1 May 2025 was used. To harmonize the classification of energy performance within the analysis, high-efficiency labels such as "A+++", "A++++", and "A+++++" were aggregated into a single category labelled "A+". This simplification is mainly done to conform with RVO's energy label ranges that will be used later on in the analysis [59]. The merge of the energy performance data with the BAG data is done via the residential unit identifier. 73.74% of the SHA residential units have an official registered energy label and approximately 26% remain without a recorded label. To address these missing energy labels, an estimation is derived using RVO's example residential units dataset and the energy index approximation from Filippidou et al. (2017) [60], [61]:

(i) RVO's Example Residential Units

RVO's dataset provides a standardized set of Dutch residential units intended to support energy performance assessments and policy development and has previously been used in multiple studies of such nature [62], [63], [64]. The dataset comprises archetypical representations of the residential units based on combinations of key attributes, including:

- **Building Type** (e.g., apartment, mid-terrace, semi-detached),
- **Construction Period** (ranging from pre-1946 to post-2015), and
- **Renovation Status** (ranging from the original, unaltered state to a series of progressive retrofit packages).

Each residential unit archetype is described using a set of technical and physical characteristics, such as usable floor area UFA (m^2), thermal resistance values (Rc-values) for envelope components, thermal transmittance (U-values) for glazing, heating system types, and the theoretical space heating demand expressed in kWh/m^2/year (see Table 2).

Table 2: RVO's Example Residential Unit Dataset Parameters

Code	Parameter	Description of Values
RVO_ARCHETY	Building Type (‘*voorbeeldwoning*’)	The 5 building type categories: • Apartment ('*galerij*') • Mid-terrace house (‘*rijwoning tussen*’) • End-terrace house (‘*rijwoning hoek*’) • Semi-detached house ('*2-onder-1-kap*') • Detached house ('*vrijstaande woning*')
	Construction Period (‘*bouwperiode*)	The 6 construction periods in the RVO database: • Before 1946: “**before_1946**” • 1946 - 1964: “**1946_1964**” • 1965 – 1974: “**1965_1974**” • 1975 – 1991: “**1975_1991**” • 1992 – 2005: “**1992_2005**” • 2006 – 2014: “**2006_2014**” • 2015 – 2018: “**2015_now**”
	Renovation Packages (‘*pakket maatregelen*’)	These are the 4 renovation packages: • Existing State (‘*oorspronkelijk*’): **ES**

		- Package 00 (‘*op basis van WoON2018*[1] *- huidig’*): **P00** - Package 01 (‘*ISO, MECH AFVOER’*): **P01** - Package 02 (‘*ISO, MECH AFVOER, WPe’*): **P02**
	UFA (‘*gebruiksoppervlakte* (m^2)’)	The UFA in m^2 of the example residential unit.
	Component Type	There are multiple components in the RVO database, but the ones used for this analysis are: - Floors (insulation component): Rc-values - Walls (insulation component): Rc-values - Roofs (insulation component): Rc-values - Windows (glazing component): U-values - Heating systems (heating component): CR-ketel, HR107-ketel, and eHP The insulation components all have different Rc-values per renovation package (P00, P01, etc.), for the glazing component the U value changes according to renovation package and lastly the heating system is designated as a different type per renovation package.
	Heating Demand (‘*warmtebehoefte woningen* ($Q_{H,nd}$) *(kWh/m^2)*’)	The heating demand of the example residential unit in kWh per m^2 per year.

As the RVO does not provide official energy label ratings for representative residential units, their estimated theoretical space heating demand serves as a proxy for the Energy Index.

(ii) Energy Index Approximation

The energy index is the metric used to determine the official Dutch energy label (NA8800). However, it is important to note that theoretical space heating demand does not reflect the full energy label calculation, which considers factors such as domestic hot water demand, ventilation heat losses, internal heat gains and patterns of building use. Nevertheless, space heating demand is the dominant driver of energy consumption in residential buildings and can be used to estimate energy performance for comparative modelling [61]. The following equation is used to estimate the energy index of the residential unit:

$$\text{Energy Index}\left[\frac{\text{kWh}}{\text{a}}\right] = \frac{\text{THED}\,[\frac{\text{kWh}}{\text{m}^2\text{a}}]}{\text{UFA}\,[\text{m}^2]} \tag{1}$$

UFA ... Usable Floor Area [m2]

THED...Theoretical Heating Energy Demand $[\frac{\text{kWh}}{\text{m}^2\text{a}}]$

Energy label ranges are used to give a rough estimate on which energy labels correspond with the calculated energy indexes [59] (See Table 3).

Table 3: Energy Label Linkage to Energy Index

Energy Label	Energy Index
A	≤ 1.20
B	1.21 – 1.40
C	1.41 – 1.80

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[1] Based on empirical data from WoON2018—offer statistically representative characteristics of the usual renovation in housing stock.

D	1.81 – 2.10
E	2.11 – 2.40
F	2.41 – 2.70
G	> 2.70

With the use of the energy index and their approximate energy label, the RVO dataset is adjusted to include proxy energy labels to their example residential units. Using the construction year, building typology, and the assumption that units without a registered energy label have not undergone any renovations, the corresponding RVO example residential unit's energy labels are assigned to these units (See Section 2.2).

2.2 PHASE 2. Current Renovation Status of Stock, Renovation Rates and Renovation Types

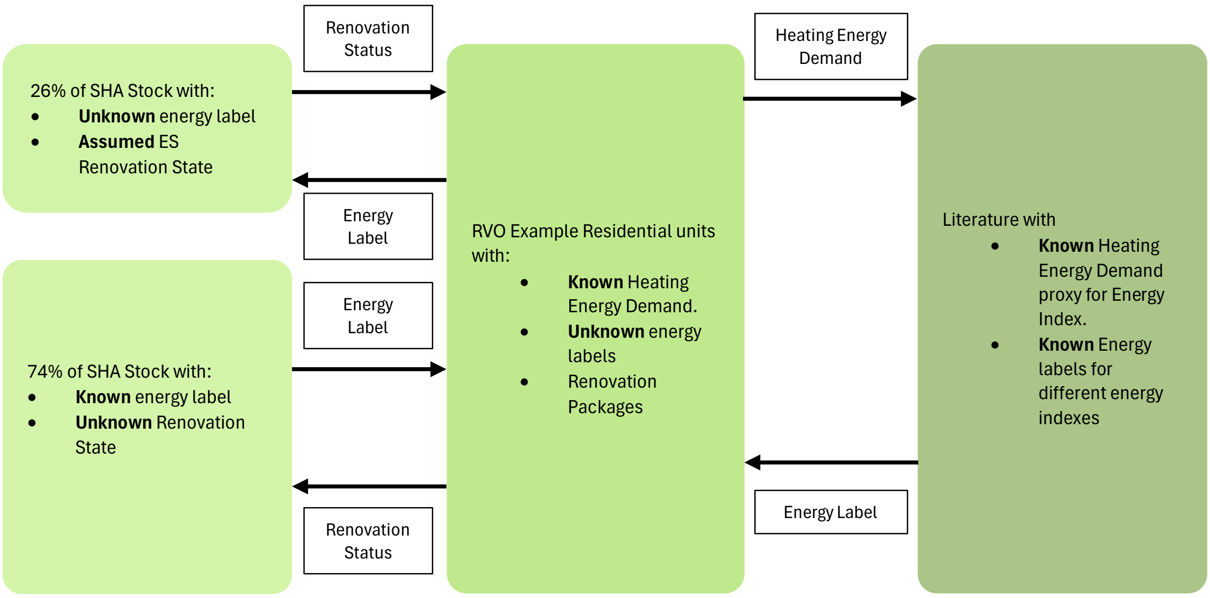
Based on building typologies, construction periods, and energy labels, the current renovation status of the SHA stock can be estimated using the RVO dataset. The dataset defines four renovation statuses (one non-renovated state and three renovation packages), ranging from no renovation at all to extremely thorough renovations. By identifying the appropriate renovation package for each residential, the structural components, heating, ventilation, and window systems of the corresponding RVO renovation packages can be assigned to that unit [60]. This approach provides a systematic framework for estimating insulation levels and energy demand of the residential units.

Additionally, this phase explores the rate of renovations per year as described in the National Performance Agreement (NPA).

2.2.1 Current Renovation Status of SHA Stock

The RVO dataset provides four renovation packages, ranging from the original, unaltered condition (Existing State, ES) to progressively energy-efficient retrofit options (P00–P02). Some modifications were required, particularly regarding changes to the heating technologies, to ensure alignment with Amsterdam's Heat Transition Plan (See Section 2.1.3). For example, in the original RVO P02 package, residential units are assumed to switch from a conventional boiler or HR107 high-efficiency boiler to a fully electric heat pump. However, in Amsterdam, certain designated neighbourhoods are intended to be connected to alternative heating network. Therefore, this package was adjusted so that the assigned heating system reflects the heating technology available in each neighbourhood under the transition plan. To see a detailed table on what the different packages entail for different building typologies and construction years see **Appendix B.1. RVO's Adjusted Renovation Packages.**

As stated in the previous section, units without a registered energy label are assumed to have undergone no renovations (ES renovation status). For the remaining units, their registered energy labels are matched to the corresponding RVO example based on construction year and building typology. This process results in each unit in the SHA stock being assigned an estimated renovation package, which serves as a proxy for understanding its current insulation and heating systems.



2.2.2 Renovation Rate & Renovation Allocation Quota

As set out in the NPA, Dutch SHAs are committed to an ambitious renovation programme from 2025 to 2035 [15]. Those who signed the agreement have set a target of renovating 813,200 social units within this 10-year period. This equates to an annual renovation rate of around 81,320 units. Given that the current national SHA housing stock totals 2,321,421 residential units nationwide, the 81,320 sets out an ambitious goal [66]. It implies that around 35% of the existing stock is expected to be renovated over the next decade. Of the total planned renovations, 691,800 units (approximately 85% of the 813,200) are to undergo deep renovation, while 121,400 units will undergo relatively limited renovation. Translated to an annual rate, this leads to deep renovation quota of 2.93% of the total stock and limited renovations quota on an additional 0.52%, resulting in a combined annual renovation rate of 3.45% of the total SHA housing stock. This target is striking in comparison to the current national average renovation rate of around 1.4% .

Table 4: NPA Agreed Upon Rates of Renovations

Variable	Value	Percentage	Ref.
Total Housing Association Residential units - NL	2,321,421	100,0%	[61], [67]
Total Social housing targeted in NPA 2025-2035 - NL	813,200	35,0%	[65]
Deep renovation share - NL	691,800	29,8%	[65]
Limited renovation Share - NL	121,400	5,2%	[65]

To understand how the proportion of limited versus deep renovations affects the associated trade-offs of the three prioritisation schemes, three distinct renovation allocation quotas have been defined, based on different ratios of deep to limited renovations.:

Table 5: Deep and Limited Renovation Quotas

Name	Description	Deep Renovation Quota	Limited Renovation Quota
LOW	Low uptake of deep renovation	15%	85%
MID	Average uptake of deep renovation	50%	50%
NPA	NPA deep renovation uptake	85%	15%

These three allocation quotas are modelled based on a linear rate over a ten-year period. In practice, however, renovation activity tends to fluctuate due to economic, regulatory and logistical factors.

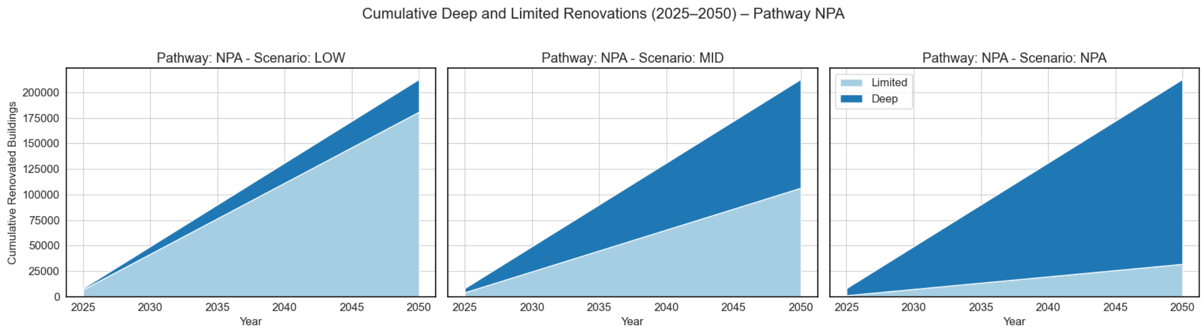
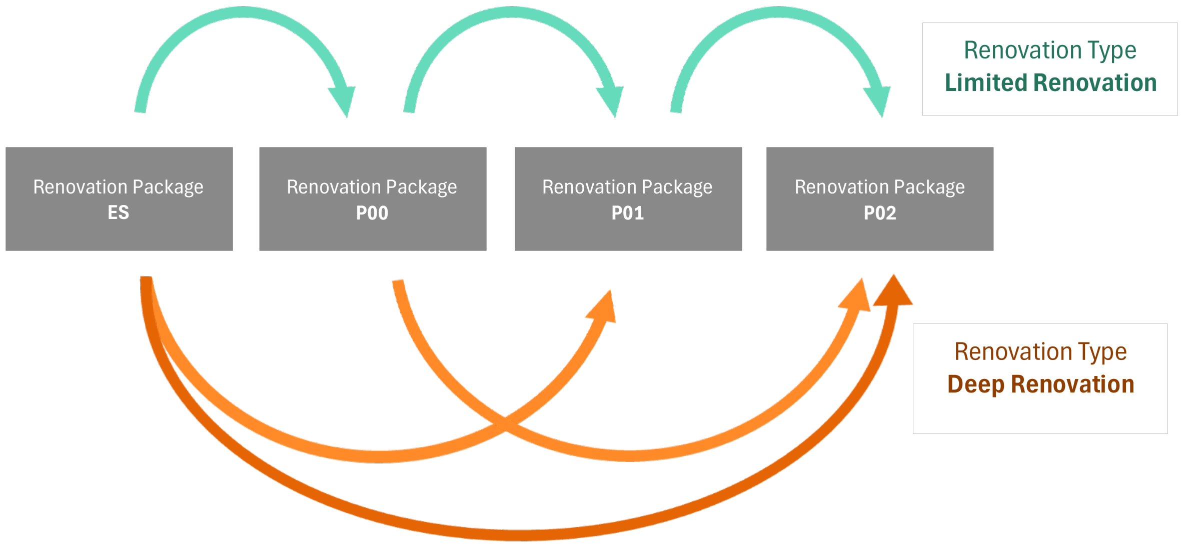


Figure 2: Cumulative Deep and Limited Renovations in Different Pathways with Different Deep/Limited Renovation Shares

2.2.3 Renovation Types and Renovation Packages

One limitation of the NPA is the lack of explicit definitions for 'deep' and 'limited' renovations. For the purposes of this analysis, a working definition has been applied.



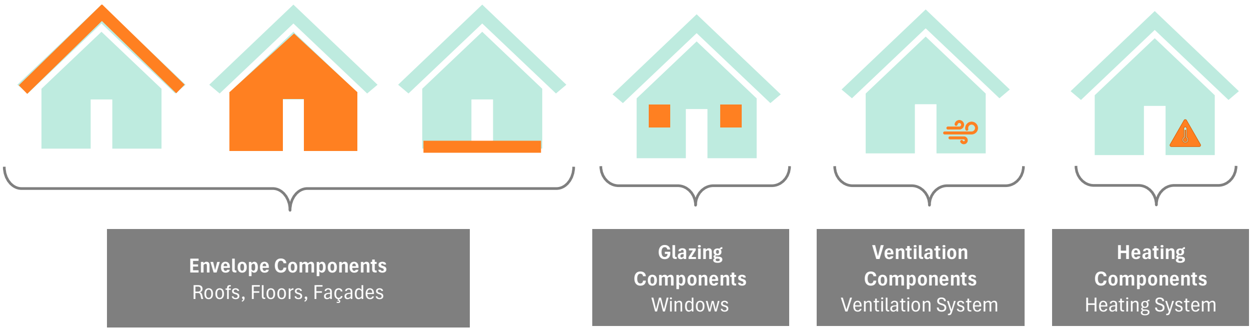
In this study, renovations are described as the process of moving a residential unit from one renovation package to another. Two types of renovations are distinguished:

1. A **deep renovation** upgrades a unit by two or three renovation packages. For example, a unit starting in the ES package may be renovated directly to P01 or P02.
2. A **limited renovation** upgrades a unit by one renovation package. For instance, a unit in the ES package may be improved to P00, or a unit already at P01 may receive additional measures, such as a renewable heating system, to reach P02.

Deep renovations therefore represent larger package jumps, while limited renovations reflect smaller, step-by-step improvements

2.3 PHASE 3 Energy Saving Measures and their Material Consumption

Understanding the material composition of the energy saving measures (ESMs) for each renovation package and the material flows that occur during the renovation when changing from one state to another is essential to evaluating the resource demand, and the economic and environmental impacts of large-scale renovation strategies. To capture the material dynamics, four main component groups are defined:



Each component group is associated with a distinct set of ESMs that vary depending on the building's typology, age cohort, and renovation type. The scale and type of these ESMs are determined by the jump in renovation packages. The material intensity coefficients (MIC) for each ESM are expressed either in kilograms per square meter (kg/m^2) or per unit. These MICs are multiplied by the component's corresponding functional area or number of units per residential unit to estimate total material flows.

2.3.1 Material Intensity Coefficients for Envelop Components

The calculation of MICs for envelope component is based on the renovation type and the required change in thermal resistance (ΔR_c [m^2K/W]) of the component's insulation. R_c values are specified in the renovation packages provided by the RVO for each building typology and construction cohort (See **Appendix B.1. RVO's Adjusted Renovation Packages**). This calculation relies on the relationship between thermal resistance, insulation thickness, and the thermal conductivity of the material (λ [$W/m\cdot K$]). The required insulation thickness is calculated as:

$$d\,[\mathrm{m}] = \Delta Rc \left[\frac{\mathrm{m^2K}}{\mathrm{W}}\right] \cdot \lambda \left[\frac{\mathrm{W}}{\mathrm{mK}}\right] \qquad (2)$$

Where:

- ΔR_c is the required increase in thermal resistance, derived from the renovation package.
- λ is the thermal conductivity of the chosen insulation material.
- d… Thickness of insulating material [m]

Note that insulation can either be fully replaced or added on top of existing layers. In cases of full replacement, the existing insulation thickness is entirely removed and replaced with the new layer. When insulation is added on top, only the additional thickness required to achieve the target thermal resistance ($\Delta Rc = Rc_{to} - Rc_{from}$) is applied. For partial replacements, the retained material continues to contribute to the overall Rc, reducing the required inflow of new material accordingly. Additionally, throughout the analysis it is assumed that the insulation material coming in matches the material that is currently insulating the component.

This insulation thickness is then multiplied with the insulation material's density to calculate the material weight per square metre i.e. the MIC.

$$\mathrm{MIC}\left[\frac{\mathrm{kg}}{\mathrm{m}^2}\right]=\mathrm{d}[\mathrm{m}]\cdot\rho\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right] \tag{3}$$

Where:

- MIC ... Material Intensity Coefficient of insulating material [kg/m2]
- ρ ... Density of insulating material [kg/m3]
- d... Thickness of insulating material [m]

In addition to the insulation layer, fixed surface weights (kg/m^2) are assigned to supplementary materials such as vapour barriers, foam, bonding agents, and interior finishes. These weights are determined based on the ESM and the building component. Since these additional materials do not contribute to the thermal resistance (R_c) of the component, their thickness does not need to be calculated from thermal properties. Instead, they are incorporated into the material flow analysis by multiplying the fixed surface weight by the component area

$$\text{Additional Material Weight [kg]} = \sum (\text{Surface Weight per Material [kg/m}^2]\cdot \text{A [m}^2]) \tag{4}$$

Where:

- A ... Area of envelop component [m]

Consequently, the total material weight added to a building envelope component is the sum of the insulation material and the additional material layer.

2.3.2 Envelope Components Specifics and ESMs

The envelope components represent the physical boundary between the interior and exterior environment of a residential unit and therefore play a main role in determining its overall energy performance. The MICs of these components are defined in kilograms of material per square metre (kg/m^2) of the component's functional area.

$$\mathrm{MI}=\mathrm{MIC}\times\mathrm{FA} \tag{5}$$

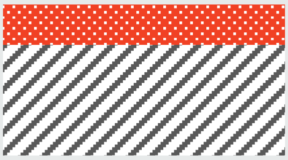
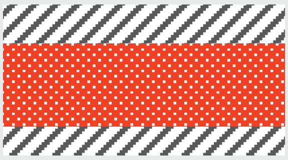
Where:

- MI ... Material intensity of component [kg]
- MIC ... Material intensity coefficient of insulation material used for the component [kg/m^2]
- FA ... Functional area of component [m^2]

Floor Insulation

The functional area of the floor is the usable floor area (UFA) parameter available in the BAG database (See **Appendix A.2. BAG Parameters and Data Cleaning Process**). This assumption implies that insulation is applied over the residential unit's entire UFA.

When modelling floor renovations, the presence or absence of a crawl space beneath the floor is a decisive factor for the insulation method and the insulation materials used. Units with crawl spaces can be insulated from below using foams or granulates, whereas those without require insulation to be placed on top of the existing floor structure. Despite a lack of a comprehensive dataset indicating the share of the stock with crawl spaces across Dutch building construction periods, literature on foundation practices suggests that newer homes are built on concrete slabs or sand and generally do not include crawl spaces, whereas older foundations often incorporated them [68]. Therefore, the 30%-70% split is adopted here as a feasible estimate. Additionally, apartments are assumed not to have crawl spaces between residential units.

Insulation Method	Dwelling Archetype Characteristics
Overlay Floor Insulation Crawl space not available. 	Overlay insulation applied directly above the existing floor. **Applicability Criteria**: • **Apartments**: ○ Assumed to lack crawl spaces, regardless of construction period. ○ All apartments receive overlay insulation. • **Non-apartment residential units built from 1992 onwards**: ○ Assumed that 70% do not have crawl spaces. ○ These residential units are selected randomly within the dataset and receive crawl space insulation. ○ These residential units will receive overlay insulation.
Crawl Space Insulation Crawl space available. 	Insulation Method: Insulation installed within the crawl space. **Applicability Criteria:** • **Non-apartment residential units built before 1991:** ○ Assumed to all have crawl spaces. ○ Receive crawl space insulation. • **Non-apartment residential units built from 1992 onwards:** ○ Assumed that 30% have crawl spaces. ○ These residential units are selected randomly within the dataset and receive crawl space insulation. ○ These residential units will receive crawl space insulation.

The material requirements differ significantly between the two insulation types.

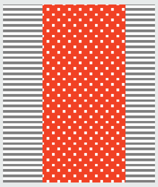
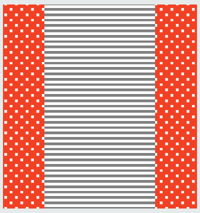
- **Crawl space insulation:** Lightweight materials such as foams, granulates, or expanded pearls are preferred due to their low cost and ease of labour costs, these can be injected directly beneath the floor with minimal labour.
- **Overlay insulation:** prefabricated insulation panels are typically used and placed above the existing floor surface.

Given the wide range of materials available in the insulation market, a comparative assessment of insulation material performance is outside the scope of this study. To standardize the modelling, polyurethane (PUR) foam is assumed as the representative material for crawl space insulation, and white expanded polystyrene (EPS) panels are assumed for overlay insulation. Additional floor finishing layers are also modelled to reflect realistic renovation configurations. For crawl space insulation, a support mesh, vapour barrier, and subfloor layer are included. For overlay insulation, a chipboard layer, damp-proof membrane, and final floor finish (typically laminate) are considered (See Appendix C.1. Envelop Component Material Inventory)

Not all insulation materials are replaced during renovation events. The likelihood of replacement depends on the type of floor renovation and the condition of the existing insulation materials. In this analysis, it is assumed that for overlay floor renovations, new insulation layers are installed directly on top of the existing insulation, without removal of the underlying material. In contrast, for crawl space insulation, the extent of replacement is determined by the physical state of the existing insulation, particularly its exposure to moisture and degradation over time. Therefore, it is assumed that 50% of the existing crawl space insulation is replaced, while the remaining 50% is retained in its original condition.

Façade Insulation

The functional area of the façade is derived from the façade area in the BAG3D dataset for Amsterdam, where all the exterior unshared walls are available in m^2 [37]. Like crawl spaces in floors, the presence or absence of a wall cavity determines the appropriate insulation method and material type. Cavity wall construction became common after the mid-20th century, whereas buildings constructed prior to 1946 are assumed to have solid brick walls without cavities [69], [70]. Based on this criteria, two main façade renovation approaches are modelled:

Insulation Method	Building Characteristics
Cavity Wall Insulation 	Insulation Method: Cavity wall acts like crawl space, where insulation is installed within the cavity in the wall. **Applicability Criteria:** • **Buildings constructed from 1946 onwards:** ○ Assumed to have cavity wall construction. ○ Receive cavity wall insulation.
External and Internal Wall insulation 	Insulation Method: Insulation is attached to the internal or external face of the walls. **Applicability Criteria:** • **All buildings constructed before 1946:** ○ Assumed to have solid brick walls without cavities. ○ Receive external or internal wall insulation.

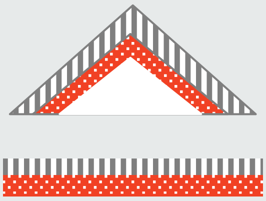
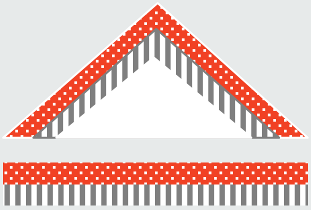
The material requirements differ between the three insulation methods.

- **Cavity wall insulation:** White expanded polystyrene (EPS) is assumed as the standard insulation material, injected into the cavity. An EPS-compatible adhesive (bonding agent) is included as an additional material to secure the insulation.
- **External wall insulation:** Glass wool is used as the insulation core, combined with finishing layers such as silicone render, primer with cerplast, and reinforcing mesh made of glass fibre.
- **Internal wall insulation:** Rock wool is used as the insulation layer, combined with plasterboard, metal studs (steel), and a vapor barrier made of polyethylene.

For external and internal wall insulation, new layers are added directly onto the existing structure (100% inflow, no outflow). For cavity wall insulation, it is assumed that 50% of the existing insulation is replaced due to degradation or moisture exposure, while the remaining 50% is kept. A summary of façade insulation configurations is provided in **Appendix C.1. Envelop Component Material Inventory.**

Roof Insulation

The roof type determines the most appropriate insulation strategy and material composition. In this analysis, roofs are classified as either flat or pitched, with each type assigned one of two possible insulation methods: cold roof insulation or warm roof insulation. In the model, both flat and pitched roofs are assigned either cold or warm insulation with equal probability (50%). The functional area for either roofs is available in the BAG3D data from the Municipality of Amsterdam [37].

Insulation method	Building characteristics
Cold Roof Insulation 	Is applied below the structural deck, typically within the roof cavity or ceiling void. It is commonly used in minor renovations where the existing roof covering is retained
Warm Roof Insulation 	Is applied above or between structural elements, often in deep renovations or full roof replacements, providing better thermal continuity and moisture protection.

The material requirements differ between the two roof types.

- **Pitched roof insulation**: Typically consist of PUR or PIR boards combined with clay tiles, wooden battens, and polyethylene vapour barriers
- **Flat roof insulation:** Commonly use PUR or PIR insulation paired with bitumen or PVC membranes, OSB decking, and plasterboard ceiling finishes.

Additionally, a replacement probability of 50% is applied across all roof types and renovation methods. This means that for any given buildings, there is a 50% chance that the existing insulation is replaced and a 50% chance that it is kept. These percentages are placeholder as there is no concrete data on the preservation of roof insulation materials.

2.3.3 Window Glazing Specifications and ESMs

The dimensions of widows are obtained by combining the ratio between window area and façade area for different dwelling typologies and construction periods from RVO's example residential units with the façade area from the BAG3D.

$$A_W = A_F \times r_{WF} \tag{6}$$

Where:

- A_W ... Area of window [m^2]
- A_F ... Area of façade [m^2]
- r_{WF} ... ratio between window area and façade area [-]

Unlike insulation systems for floors, façades and roofs, window renovations are not dependent on material thickness or density. The main factor that differentiates windows in renovation packages is the number of glazing layers, as this directly influences the window's thermal transmittance, or U-value. As the number of glazing layers increases, the window's thermal performance improves, resulting in a lower U-value. To illustrate this, window types have been categorised according to the typical U-value ranges associated with single, double and triple glazing configurations, as outlined below:

Table 6. U-values for different window types

Window Type	U-Value Range
PVC Single Glazing	4.5 to 5.8 $W/m^2 \cdot K$
PVC Double Glazing	1.3 to 2.8 $W/m^2 \cdot K$
Aluminium Tripple Glazing	0.9 to 1.5 $W/m^2 \cdot K$
PVC Tripple Glazing	0.7 to 1.2. $W/m^2 \cdot K$

This analysis considered two common window frame types: PVC and aluminium. Their MICs can be found in **Appendix C.2. Windows Material Inventory**. Like the envelop components, the material intensity of windows is determined by multiplying the functional window area (A_W) with the MICs.

2.3.4 Heating and Ventilation Systems Specification and ESMs

For a detailed overview of heating and ventilation system characteristics and MICs see **Appendix C.3. Heating and Ventilation Systems Material Inventory.**

Heating Systems

The modification of heating systems in this study follows a relatively straightforward process, primarily involving a change in system type per renovation package. As stated in Section 2.1.3. the RVO heating system types have been adjusted to align with the heat transition plan of Amsterdam. Therefore, four heating technologies are available

- **Conventional gas boiler** represented by a simple CR Boiler
- **Highly efficient gas boiler** represented by a HR107 Boiler. It is assumed that the HR107 gas boilers can utilize sustainable gas.
- **Fully electric heat pump** represented by ASHP, and
- **District Heating.** It is assumed that the costs and environmental impacts borne by the SHA for district heating implementation apply exclusively to the heat interface unit. All upstream infrastructure, specifically the pipework extending up to the building entry, is assumed to be financed by the government and therefore excluded from the SHA's cost and impact assessments.

Ventilation Systems

Unlike with heating systems, there are no modifications to the ventilation types suggested by RVO's renovation packages. Historically, most buildings built before 1992 relied on natural ventilation systems. In these buildings, air exchange was achieved passively through vents, wall grilles, or gaps in the building envelope. There were no mechanical components to actively regulate airflow, and ventilation depended largely on external weather conditions. From the early 1990s onwards, mechanical ventilation systems began to be widely implemented in Dutch housing stock. Type C ventilation systems are the upgrade for natural ventilation. These systems provide mechanical controlled ventilation.

2.3.5 Economic and Environmental Implications of the Material Use

To fully explore all the trade-off linked with renovations, the economic and environmental burdens of the upgrades need to be quantified.

Economic Burdens of Renovations

The financial costs of renovations consist of two main components: (i) Material and labour costs of the ESMs, and (ii) operational costs of the new heating and ventilation systems. The first represents the upfront investment required to upgrade the residential unit to the target renovation package, while the second captures the ongoing costs once the ESMs are in use. These economic burdens are shared between two main stakeholders. The SHA, which bears the cost of purchasing and installing the ESMs. And the tenants, who are responsible for ongoing operational expenses after the renovation.

The material costs for envelope insulation are based on ecoinvent cost factors (expressed in € per kg of material), whereas window costs are calculated in € per m^2 sourced from the industry, and ventilation and heating systems are expressed in € per unit, also sourced from current market available technologies. Labour costs vary depending on the component and the ESM, typically expressed in € per m^2 insulated or € per unit installed. Detailed breakdowns of these costs are presented in the **Appendix D. Economic and Environmental Impacts of ESMs**. Operational costs are made up of the electricity consumption of ventilation systems (type C) and the energy demand of heating systems. The electricity consumption of ventilation systems is derived from the NMD (Nationale Milieu database) category 3 LCA reports, which also provides the material intensity data used [71], [72]. Operational heating costs were calculated based on each residential unit's annual heating energy demand (kWh/year), combined with system-specific technical parameters such as thermal efficiency, calorific value (for combustion systems), and local energy prices for Amsterdam (See **Appendix E.2. Fuel Costs**). The effective energy input of each system was determined by dividing the total heating energy demand by its efficiency. The resulting energy input was then multiplied by the appropriate fuel cost factor to determine the total operational costs. For gas-fuelled systems, the Lower Heating Value (LHV) of natural gas was used to convert energy input (kWh) to gas volume (m^3):

$$\text{Energy Input [kWh]} = \frac{\text{Heating Demand } \left[\frac{\text{kWh}}{\text{m}^2\text{a}}\right] \cdot \text{UFA}[\text{m}^2]}{\text{System Efficiency [-]}}$$

$$\text{Heating Operational Costs [€]} = \text{Energy Input [kWh]} \cdot \text{Calorific Value } \left[\frac{\text{m}^3}{\text{kWh}}\right] \cdot \text{Fuel Cost Factor } \left[\frac{€}{\text{m}^3}\right] \tag{7}$$

Environmental Burdens of Renovations

Environmental burdens reflect the economic ones and consist of two main components: (i) Operational CO_2 emissions, associated with the use of heating systems. And (ii) material-embedded CO_2 emissions, associated with the production of renovation materials and system components. Operational CO_2 emissions are calculated similarly to operational costs, but using emission factors instead of cost factors:

$$\text{Heating Operational Emissions [kg CO}_2\text{eq]} = \text{Energy Input [kWh]} \cdot \text{Emission Factor } \left[\frac{\text{kg CO}_2\text{eq}}{\text{kWh}}\right] \tag{8}$$

Material-embedded CO_2 emissions were determined by aggregating the emissions associated with the production of all materials within each heating unit. Although numerous studies have assessed life-cycle emissions of individual heating systems, cross-comparative LCAs are often inconsistent due to differing system boundaries, cut-off criteria, and regional contexts. To ensure comparability, this study focuses solely on the material composition-related embedded CO_2 emissions, excluding emissions from manufacturing and assembly processes. This exclusion is acknowledged as a limitation, as manufacturing emissions can be quite different across technologies. Material-specific emission factors were sourced from the ecoinvent 3.10 database, ensuring standardized and transparent data across all systems. The total CO_2 embedded in each heating unit was then calculated as the sum of the product of material mass and emission factor for all components.

$$\text{Total } CO_2 \text{ Embedded in Heating Unit Materials} = \sum \text{Material Weight}[kg] \cdot \text{EF}[kg\ CO_2 \text{ per kg}] \qquad (9)$$

Where:

- EF … Emissions factor of material [kg CO_2/kg]

2.4 PHASE 4 Prioritisation Schemes

To guide the implementation of large-scale renovations, the direction of the renovation quotas must be defined. This depends on the goals and focus of SHAs' long-term strategies. In the Netherlands, SHAs generally pursue three main goals:

Goal 1: Reduce the energy burden for tenants. For instance, in their 'Sustainable Together' project, Eigen Haard explicitly state that they plan their renovations around the aim of making their homes more energy-efficient to lower their tenants' energy costs [73]

Goal 2: Reduce the environmental impact of their building portfolio. As semi-public construction clients, Dutch SHAs have been assigned an important role in helping to achieve the national goal of a CO_2-neutral housing stock by 2050. Aedes introduced the Housing Agenda 2017–2021, stating that each association should have a plan in place by the end of 2018 to achieve a CO_2-neutral housing stock by 2050 [74].

Goal 3: Keeping renovation costs manageable. This goal is not set for the tenants or in line with national climate targets. It aims to ensure that renovations remain within the manageable cost limits of the SHAs' non-profit budgets. Since renovations are expensive, a balance must be struck between improvements and affordability. Cost-effectiveness metrics such as €/kWh saved or €/tonne of CO_2 avoided are considered when planning renovation measures. Within the Dutch Climate Agreement, the Starter Engine Framework ('*Startmotorkader*'), SHAs are expected to choose renovation schemes according to CO_2 reduction at an acceptable cost per unit of emissions avoided [75], [76].

These three distinct goals often lead to trade-offs with each other. The main objective of this study is to understand how these different focuses can result in different trade-offs in environmental, economic and social factors. For that the following three prioritisation schemes are investigated:

Table 7. Prioritisation schemes

Name	Code	Brief Description	Stakeholder of Interest	Goal
Energy Burden Priority	BUR	Reducing energy consumption and energy costs in low household income households.	Tenants	1
Environmental Impact Priority	IMP	Minimizing environmental impact.	SHA and Tenants	2
Economic Efficiency Priority	EFF	Maximizing energy consumption reduction and return on investment	SHA	3

2.4.1 Energy Burden Prioritisation Scheme (BUR)

The BUR scheme is designed to address the issue of energy burden by targeting households that experience disproportionately high energy burdens. '*Energy burden'* is commonly defined as the share of the gross household income that is spent on energy costs (often for heating the house) [77]. This means that a high energy burden indicates a struggle by the household to pay the annual energy service bills. It is calculated like this:

$$\mathrm{EB}\,[-] = \frac{\mathrm{HEC_a}\left[\frac{€}{\mathrm{a}}\right]}{\mathrm{MDHI_m}\left[\frac{€}{\mathrm{month}}\right] * 12} \tag{10}$$

Where:

- EB ... Energy Burden
- HEC_a ... Annual Heating Energy Costs [€/a.]
- $MDHI_m$ ... Monthly Mean Disposable Household Income [€/month]

The annual heating energy costs calculation is available in the Section 2.3.5 Economic and Environmental Implications of the Material Use. The BUR prioritisation scheme will prioritise the residential units with the highest energy burden first and will renovate the ones with the lower energy burden last.

2.4.2 Environmental Impact Priority (IMP) Scheme

The IMP scheme focuses on minimising GHG emissions, particularly CO_2 equivalent emissions during the production of materials and heating systems, and emissions saved through the operation of new more efficient heating systems. Renovations are therefore evaluated based on their net emissions, which is defined as the difference between the kilograms of CO_2 equivalent embedded in the production of materials and heating systems and the emissions saved through the improved performance of the newly installed systems.

$$\text{Net emissions}\ [CO_2eq] = \text{Production Embedded Emissions}\ [CO_2eq] + \text{Operational Emissions}\ [CO_2eq] \tag{11}$$

Operational CO_2 reductions are realized through the replacement of conventional gas boilers with high-efficiency units or the adoption of electric heat pumps, a transition that aligns with the Netherlands' broader decarbonization objectives (i.e.. Heat Transition Plans). Cities like Amsterdam aim for a fully gas-free housing stock by 2040, making the IMP prioritization scheme particularly relevant in urban areas. This dual consideration of embodied emissions (from material production) and operational savings (from energy system changes) allows for a thorough environmental assessment of renovation schemes. The renovation net emissions are then normalised with the UFA of the residential unit, to reduce bias against larger units.

2.4.3 Economic Efficiency Priority (EFF) Scheme

The EFF prioritization scheme aims to maximize the heating energy demand reduction per unit of investment. More specifically, renovations are evaluated based on their euros spent per kilowatt-hour of heating energy saved annually. This is then normalized by the UFA of each residential unit to account for big variations in footprint and size, which ensures a fair comparison across the housing stock. Cost calculations are made up of the material and system costs of renovation measures installed:

$$\begin{gathered}\text{Cost of Renovation Jump}\ [€]= \\ \sum \text{Envelope Costs} \left[\frac{€}{m^2}\right] \cdot \text{Area of Envelop Component}\ [m^2]+ \\ +\sum \text{Heating System Costs} \left[\frac{€}{\text{Unit}}\right] \cdot \text{Number of Heating Units[Unit]} \\ +\sum \text{Ventilation System Costs} \left[\frac{€}{\text{Unit}}\right] \cdot \text{Number of Ventilation Units[Unit]}\end{gathered} \tag{12}$$

For envelope upgrades (e.g., insulation and glazing), standardized costs per square meter were utilized, while for heating system upgrades (e.g., gas boilers, heat pumps), unit costs were applied. These cost estimates offer a rule-of-thumb assessment of financial requirements per renovation package. Alongside, the energy consumption of the residential units is calculated as the product of the energy demand (obtained from the RVO representative buildings for each BAG registered unit) and its UFA (from BAG).

$$\text{Heat Energy Consumption} \left[\frac{\text{kWh}}{a}\right] = \text{Theoretical Energy Demand}_{\text{RVO}}\ [\frac{\text{kWh}}{m^2 a}] \times \text{UFA}[m^2] \tag{13}$$

Section 2.3.5 Economic and Environmental Implications of the Material Use describes the economic costs of the materials and heating and ventilation systems in detail. Labour costs were included.

2.4.4 Renovation Type Allocation

Now that the prioritisation schemes (BUR, IMP and EFF) and their indicators (energy burden, net emissions and cost of renovation jump) have been firmly established, the next step in the methodology is to delegate and assign the deep and limited renovation quotas to the different schemes. In other words, if one of the prioritisation schemes is chosen, which units will be selected for renovation first, according to the prioritisation indicator, to ensure that the deep and limited renovation quota pathways (LOW, MID, NPA) are fulfilled in accordance with the national SHA objectives mentioned in the NPA?

Initially, for each residential unit in the housing stock, all feasible renovation combinations are mapped out. These combinations reflect the range of possible renovations available for a unit. For instance, consider a unit built between 1965–1974 currently in renovation status P00. Two upgrade options may be considered: A limited renovation moving the dwelling from P00 to P01, and a deep renovation upgrading it directly from P00 to P02.

Residential Units	**Initial Renovation Status (i.e. Package)**
RU01	P01
RU02	ES
RU03	P00

Residential Units	**Target Renovation Status (ie.Package)**	**Renovation Type (ie. Jump)**
RU01	P02	Limited
RU02	P00	Limited
RU02	P01	Deep
RU02	P02	Deep
RU03	P01	Limited
RU03	P02	Deep

Each possible renovation combination is then classified as either deep or limited based on the magnitude of the renovation status jump, in line with the definitions established in Section 2.2.3. All these potential combinations for each residential unit are evaluated against the priority scheme indicators. This results in a dataset where each dwelling has at least one or more renovation options, each of which is scored according to the currently analysed prioritization indicator and simultaneously labelled as either deep or limited. The performance of the different renovation combinations are then globally ranked into a single prioritized list, sorted according to the chosen indicator.

Residential Units	**Target Renovation Status (ie.Package)**	**Renovation Type (ie. Jump)**	**Change in Energy Burden**	**Rank**	**Change in Net Emissions**	**Rank**	**Cost of Renovation Jump**	**Rank**
RU01	P02	Limited	-0.030	5	-10.50	4	3.500	3
RU02	P00	Limited	-0.065	2	-3.00	6	5.000	4
RU02	P01	Deep	-0.070	1	-7.00	5	7.000	5
RU02	P02	Deep	-0.060	3	-45.00	2	8.500	6
RU03	P01	Limited	-0.010	6	-11.00	3	2.100	1
RU03	P02	Deep	-0.035	4	-78.00	1	3.000	2

This ensures that the highest-impact renovations are considered first in the allocation process. Renovation assignments are then made on a yearly basis, adhering to the quota structure set out in each pathway (80,000 total renovations per year, with proportions based on LOW, MID, or NPA deep-limited splits).

The allocation proceeds as follows: For each year, the highest-ranking renovation options designated as deep are selected first, until the annual quota for deep renovations is met. Once the deep quota is filled, the highest-ranking limited renovations are selected to fulfil the remaining yearly quota. It is important to note that once a residential unit is selected for renovation, whether deep or limited, it is removed from the pool of eligible candidates for renovations in following years, up to and including 2050. This rule assumes that a renovated unit will not require further upgrades till the end of analysed timeframe.

Residential Units	Target Renovation Status (ie.Package)	Renovation Type (ie. Jump)	Change in Energy Burden	Rank	Selection
RU01	P02	Limited	-0.030	5	3
RU02	P00	Limited	-0.065	2	-
RU02	P01	Deep	-0.070	1	1
RU02	P02	Deep	-0.060	3	-
RU03	P01	Limited	-0.010	6	-
RU03	P02	Deep	-0.035	4	2

Residential Units	Target Renovation Status (ie.Package)	Renovation Type (ie. Jump)	Change in Net Emissions	Rank	Selection
RU01	P02	Limited	-10.50	4	3
RU02	P00	Limited	-3.00	6	-
RU02	P01	Deep	-7.00	5	-
RU02	P02	Deep	-45.00	2	2
RU03	P01	Limited	-11.00	3	-
RU03	P02	Deep	-78.00	1	1

Residential Units	Target Renovation Status (ie.Package)	Renovation Type (ie. Jump)	Cost of Renovation Jump	Rank	Selection
RU01	P02	Limited	3.500	3	3
RU02	P00	Limited	5.000	4	-
RU02	P01	Deep	7.000	5	2
RU02	P02	Deep	8.500	6	-
RU03	P01	Limited	2.100	1	-
RU03	P02	Deep	3.000	2	1

This methodology has one major limitation. In certain cases, a residential unit may have a deep renovation option that is ranked higher than its limited alternative. However, if the annual deep renovation quota has already been filled, the system could potentially assign the limited renovation option instead, thereby excluding the unit from any future renovation opportunities, including its optimal deep upgrade. This could lead to outcomes where the renovation option with the greatest impact is not implemented. Nevertheless, it is assumed that, across the entire housing stock and over the full modelling time period, such mismatches will be negligible with regards to the overall material flows and subsequent environmental and economic flows.

3 RESULTS

For the next sections it should be noted that the values are the aggregation of the outcomes within the period 2025-2050. For instance, when talking about the material amounts, environmental impacts, and economic costs of the renovations, it is the summed-up values from 2025 to 2050. However, for the values of energy burden this is not the case, as it is a ratio and therefore the average of the energy burden improvement from the units in 2050 is taken.

3.1 Renovation Package Allocation and Building Type Dominance

The allocation of renovation packages (P00, P01, P02) varies across the three prioritisation schemes (BUR, IMP, EFF) and renovation quota pathways (LOW, MID, NPA). Table 8 summarises the distribution of said packages, and the following sections describe the observed patterns.

Table 8. Shares of the Renovation Packages in the Prioritisation Schemes under the different Renovation Quota Pathways

P00	BUR	IMP	EFF
NPA	1,4%	0,0%	5,9%
MID	27,4%	12,4%	25,7%
LOW	58,8%	47,4%	59,5%
P01	BUR	IMP	EFF
NPA	75,0%	8,7%	25,7%
MID	53,1%	15,4%	26,6%
LOW	27,0%	15,4%	19,4%
P02	BUR	IMP	EFF
NPA	23,6%	91,3%	68,4%
MID	19,4%	72,2%	43,3%
LOW	14,2%	37,2%	21,0%

3.1.1 LOW Pathway Renovation Package and Building Type Analysis

Under the LOW pathway, the BUR and EFF schemes prioritise more basic renovation packages, which focus on building up strong enveloip insulation whilst keeping heating system changes to simply more

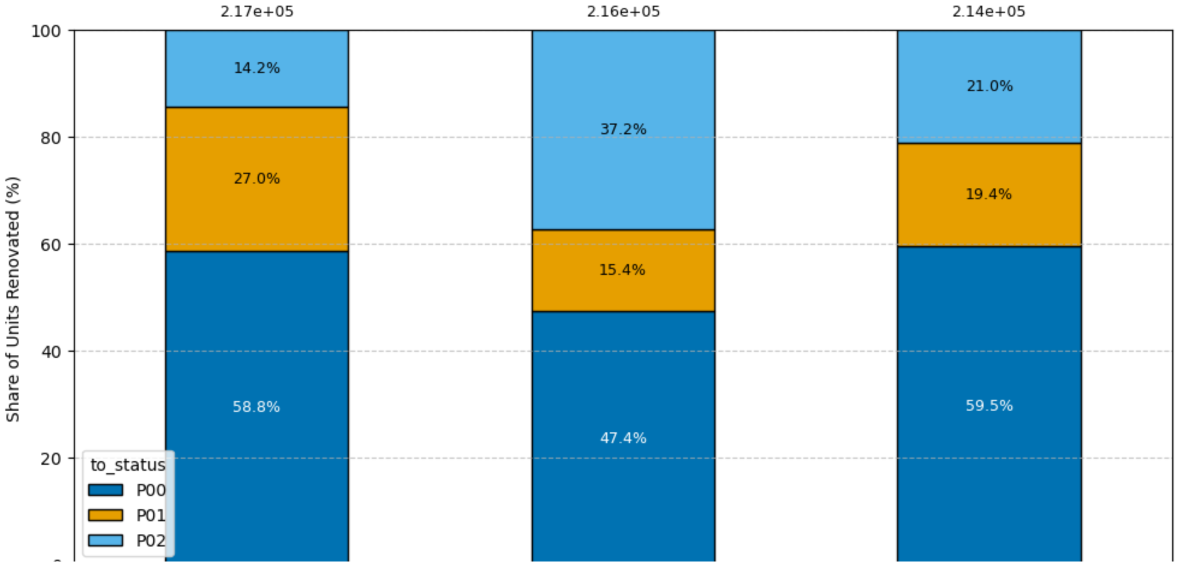


Figure 3. LOW Pathway Renovation Package Allocation

efficient gas boilers and not particularly changing to renewable sourced systems. In the BUR scheme, 58.8% of renovations correspond to P00, 27.0% to P01, and 14.2% to P02, indicating a strong preference for build up measures and putting the energy transition ESM such as ASHPs and district heating to the side. Similarly, the EFF scheme allocates 59.5% of renovations to P00, 19.4% to P01, and 21.0% to P02. In contrast, the IMP scheme places a stronger emphasis on energy transition ESMs, with P02 accounting for 37.2%, P00 at 47.4%, and P01 at 15.4%. Overall, while BUR and EFF focus on basic foundation ESM renovations, IMP shifts the distribution toward renewable heating systerm related interventions.

As for the type of buildings that are renovated, the dominant type is the apartment blocks. In all the schemes the apartments are the main focus with all of them having a share of apartment residential units of more that 90%.

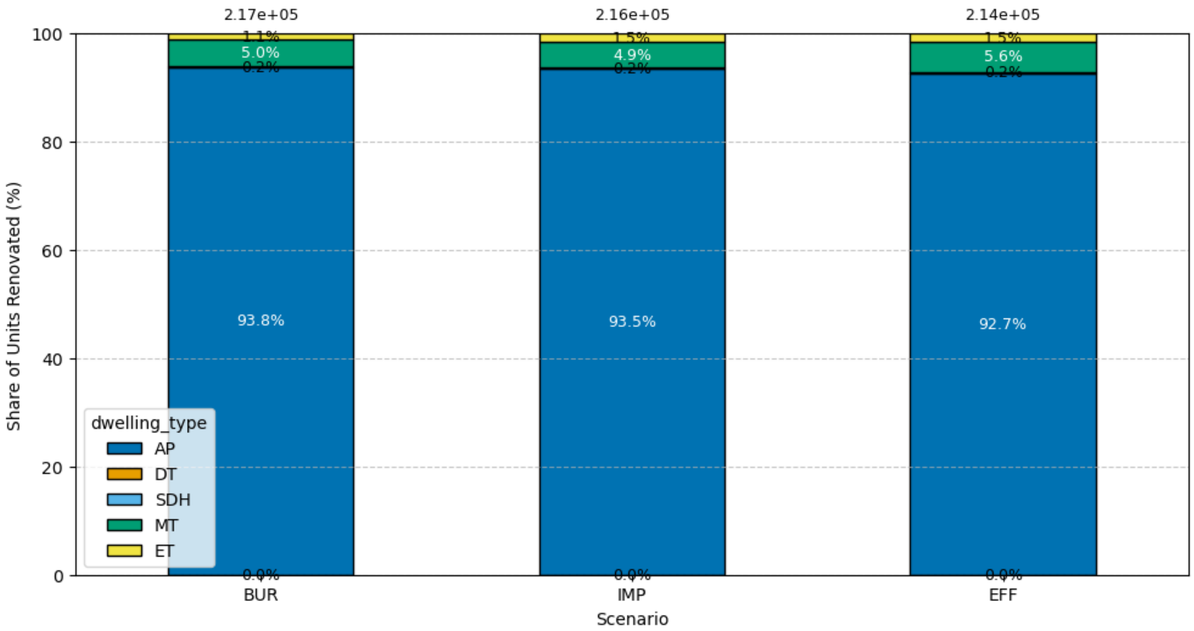


Figure 4. LOW Pathway Building Type Shares

3.1.2 MID Pathway Renovation Package and Building Type Analysis

In the MID pathway, the general rule is that the distribution shifts towards renovations with more diverse ESMs other than just envelop insulation across all schemes, albeit to different extents. BUR shows a moderate shift, with P01 becoming dominant (53.1%), P00 decreasing to 27.4%, and P02 rising to 19.4%.

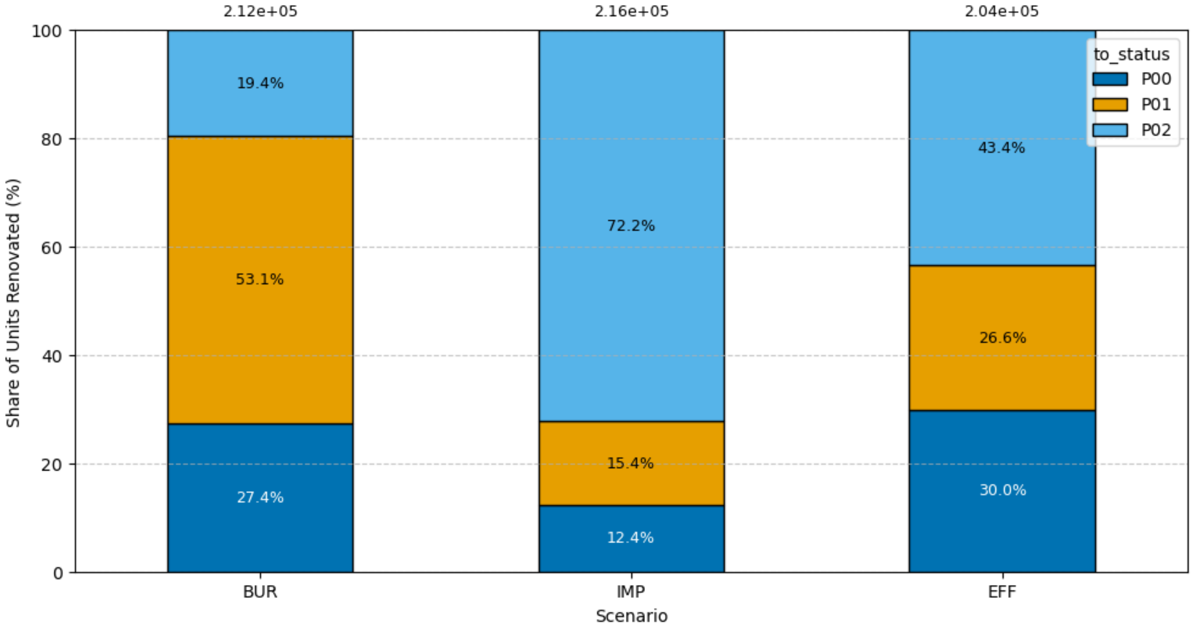


Figure 6. MID Pathway Renovation Package Allocation

EFF presents a more balanced distribution, with P02 becoming the largest category at 43.3%, P01 at 26.6%, and P00 at 25.7%. So while the quota of deep renoations has increased from 15% to 50% the BUR scheme continues to focus on basic packages such as P00 and P01, where energy systems are not radically changed, but maintain gas as their primary source. They focus more on insulating the envelop of all residential units that have yet to have a renovation. The IMP scheme, however, strongly prioritises deep renovations, with P02 representing 72.2% of the total, P01 at 15.4%, and P00 declining sharply to 12.4%. This clearly shows that the IMP is not focusing resources into envelop insulation of bad energy performing

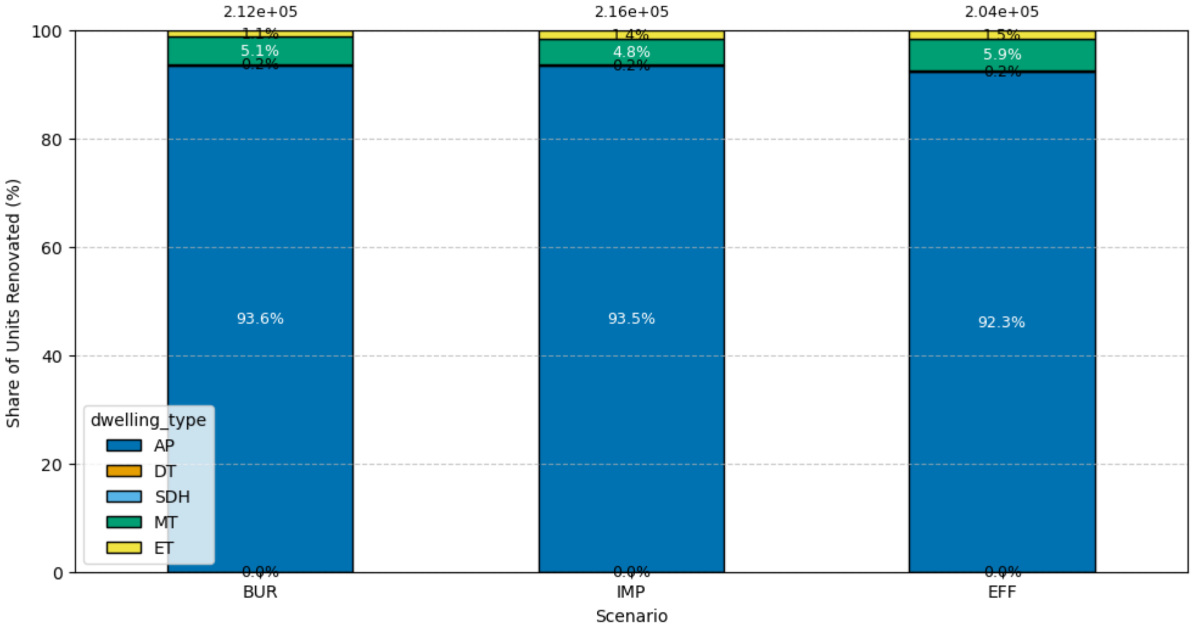


Figure 5. MID Pathway Building Type Shares

residential units, but on the energy transition to renewable heating sources. The MID pathway thus highlights the divergence between schemes: BUR favours moderate interventions, EFF balances basic and deep measures, and IMP strongly emphasises deep renovations.

3.1.3 NPA Pathway Renovation Package and Building Type Analysis

The NPA pathway exhibits the most pronounced differences in package allocation. In BUR, P01 dominates at 75.0%, P02 increases to 23.6%, and P00 is nearly absent (1.4%), indicating that most renovations are of moderate depth. In contrast, the IMP scheme overwhelmingly allocates renovations to the energy transition package, P02 (91.3%), with only a minor share to the envelop insulation package of P01 (8.7%) and no basic P00 interventions. EFF similarly prioritises energy system related renovations, with P02 at 68.4%, with some envelop insulation improvements in P01 at 25.7%, and P00 reduced to 5.9%. These results demonstrate that, under a NPA pathway, BUR maintains a focus on moderate measures, whereas IMP and EFF predominantly implement energy transition renovations, with IMP representing the most aggressive approach.

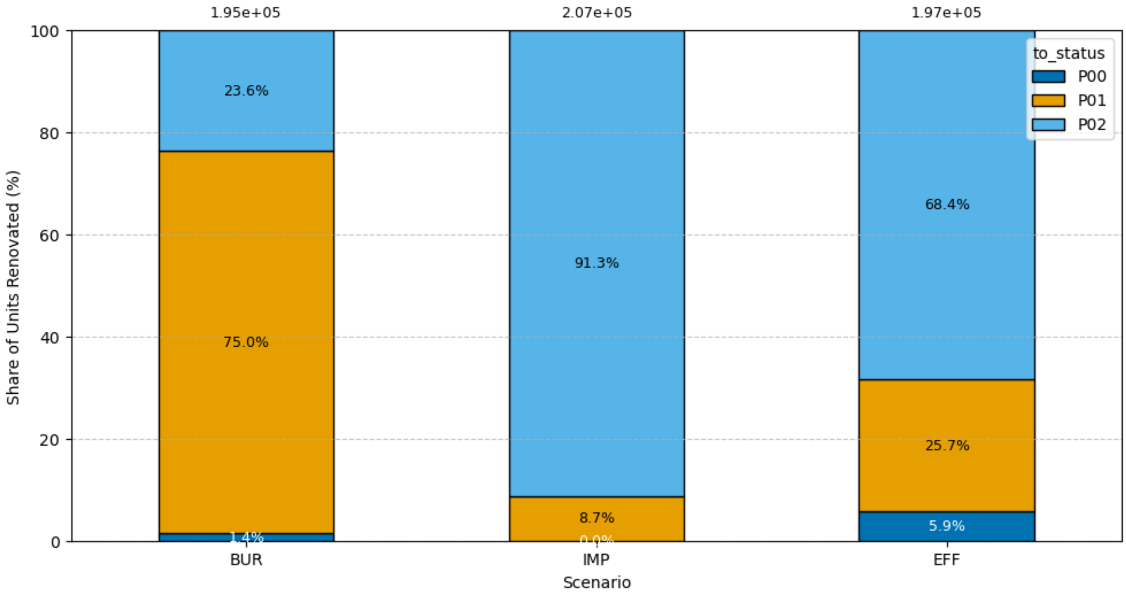


Figure 7. NPA Pathway Renovation Package Allocation

Much like the last two pathways, the distribution of building typology remains dominated by apartments.

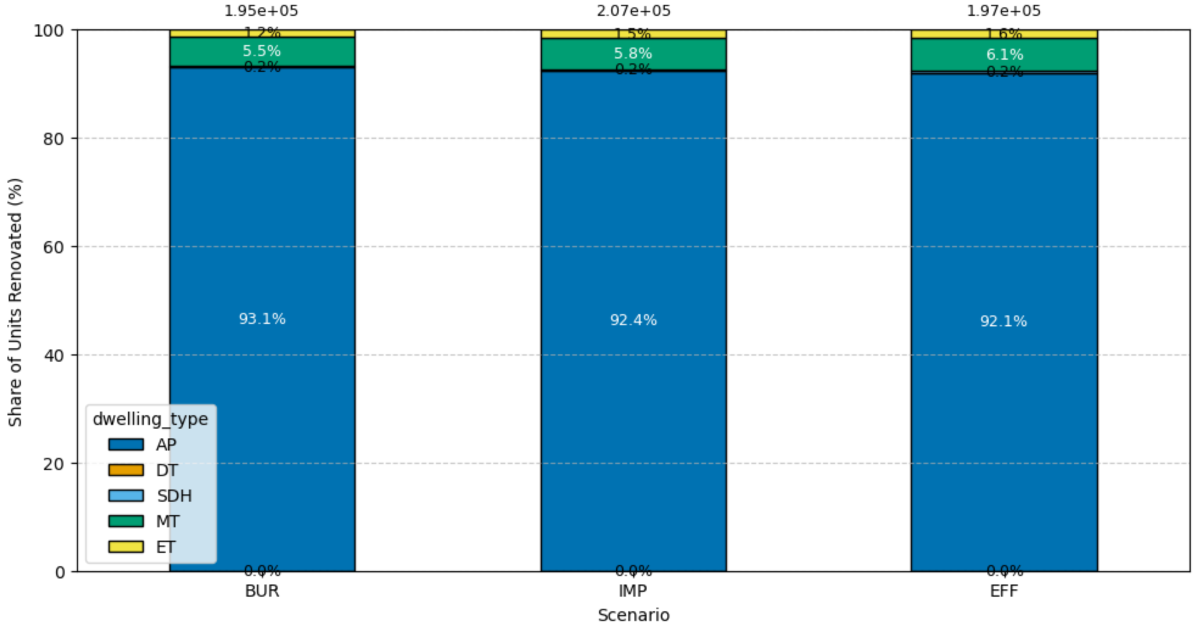


Figure 8. NPA Pathway Building Type Shares

Across pathways, a clear pattern emerges. BUR consistently emphasises basic envelop insulation renovation packages (P00 and P01), with P02 only becoming relevant in higher deep renovation quota pathways. EFF shows a progressive shift toward energy transition renovations (P02) as the pathway deep renovation quota increases, maintaining a balance between P01 and P02. IMP exhibits the strongest prioritisation of deep renovations, with P02 dominating particularly in the MID and NPA pathways. These results indicate that the choice of prioritisation scheme significantly affects the intensity of renovation intervention.

3.2 Material Inflows and Outflows of Renovations

The analysis of material flows under the BUR, IMP, and EFF prioritisation schemes reveals differences in inflow, outflow, and net accumulation across the LOW, MID, and NPA pathways. Table 9 summarises inflow, outflow, and net accumulation for each scheme and pathway.

Table 9. Inflows, Outflows and Net Accumulation of Material in different Prioritisation Schemes and Renovation Quotas

Inflows	BUR	IMP	EFF
NPA	5,52E+08	5,79E+08	5,48E+08
MID	5,69E+08	5,85E+08	5,51E+08
LOW	5,59E+08	5,50E+08	5,56E+08
Outflows	BUR	IMP	EFF
NPA	4,62E+08	4,78E+08	4,66E+08
MID	4,24E+08	4,24E+08	4,11E+08
LOW	3,26E+08	3,13E+08	3,22E+08
Net Accumulation	BUR	IMP	EFF
NPA	9,00E+07	1,01E+08	8,20E+07
MID	1,45E+08	1,61E+08	1,40E+08
LOW	2,33E+08	2,37E+08	2,34E+08

3.2.1 LOW Pathway Material Analysis

In the LOW pathway, net accumulation is highest across all schemes. BUR records an inflow of 5.59×10^8 kg and an outflow of 3.26×10^8 kg, resulting in a net accumulation of 2.33×10^8 kg. Similarly, IMP shows an inflow of 5.50×10^8 kg and an outflow of 3.13×10^8 kg, yielding a slightly higher net accumulation of 2.37×10^8 kg. EFF falls between these values, with an inflow of 5.56×10^8 kg, an outflow of 3.22×10^8 kg, and a net accumulation of 2.34×10^8 kg. Overall, the LOW pathway exhibits significant material accumulation, with differences between schemes largely driven by variations in outflow.

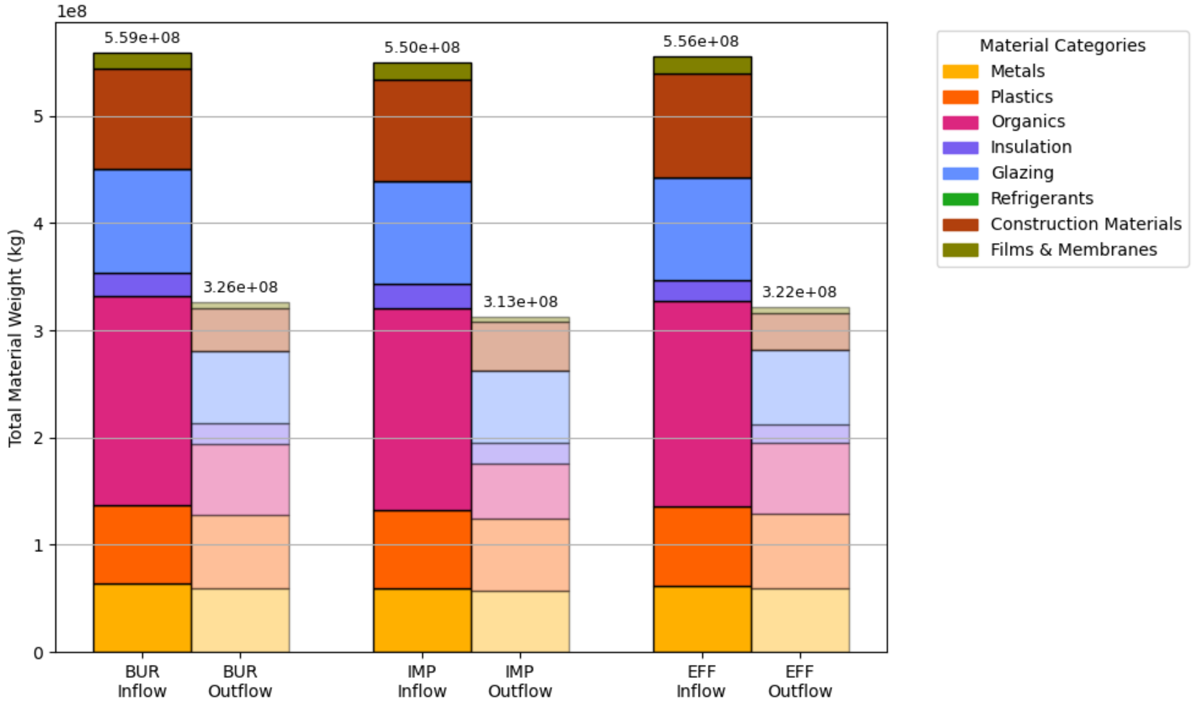


Figure 9. LOW Pathway Material-level Inflows and Outflows

Table 10. LOW Pathway Material-level Inflows and Outflows

LOW	BUR - IN	BUR - OUT	IMP - IN	IMP - OUT	EFF - IN	EFF - OUT
Metals	5,27E+07	5,43E+07	5,59E+07	5,65E+07	6,13E+07	5,94E+07
Plastics	7,33E+07	6,51E+07	7,59E+07	6,79E+07	7,50E+07	6,90E+07
Organics	1,76E+08	1,61E+08	1,82E+08	1,25E+08	1,92E+08	6,68E+07
Insulation	4,26E+07	3,67E+07	3,18E+07	2,72E+07	1,91E+07	1,71E+07
Glazing	9,97E+07	5,95E+07	9,71E+07	6,36E+07	9,54E+07	6,90E+07
Refrigerants	8,13E+02	0,00E+00	9,41E+03	0,00E+00	2,35E+04	0,00E+00
Construction Materials	8,89E+07	7,63E+07	9,31E+07	5,98E+07	9,73E+07	3,46E+07
Films & Membranse	1,44E+07	1,31E+07	1,50E+07	1,05E+07	1,58E+07	6,07E+06
Total	**5,48E+08**	**4,66E+08**	**5,51E+08**	**4,11E+08**	**5,56E+08**	**3,22E+08**

Across all schemes, organics constitute the largest share of both inflows and outflows, with inflows ranging from $1.76{\times}10^8$ to $1.92{\times}10^8$ kg. This makes organics the dominant contributor to material flows within the LOW quota. Glazing and construction materials also represent major flows, each contributing on the order of $9{\times}10^7$ kg to inflow, followed by plastics and metals, which circulate in comparatively smaller but still significant quantities (approximately $5{\times}10^7$–$7{\times}10^7$ kg). In contrast, refrigerants account for only a negligible fraction of the overall flows, contributing less than 10^4 kg. Outflow patterns follow a similar hierarchy, reaffirming the prominence of organics, glazing, and construction materials in determining the overall magnitude of material movement within the LOW pathway.

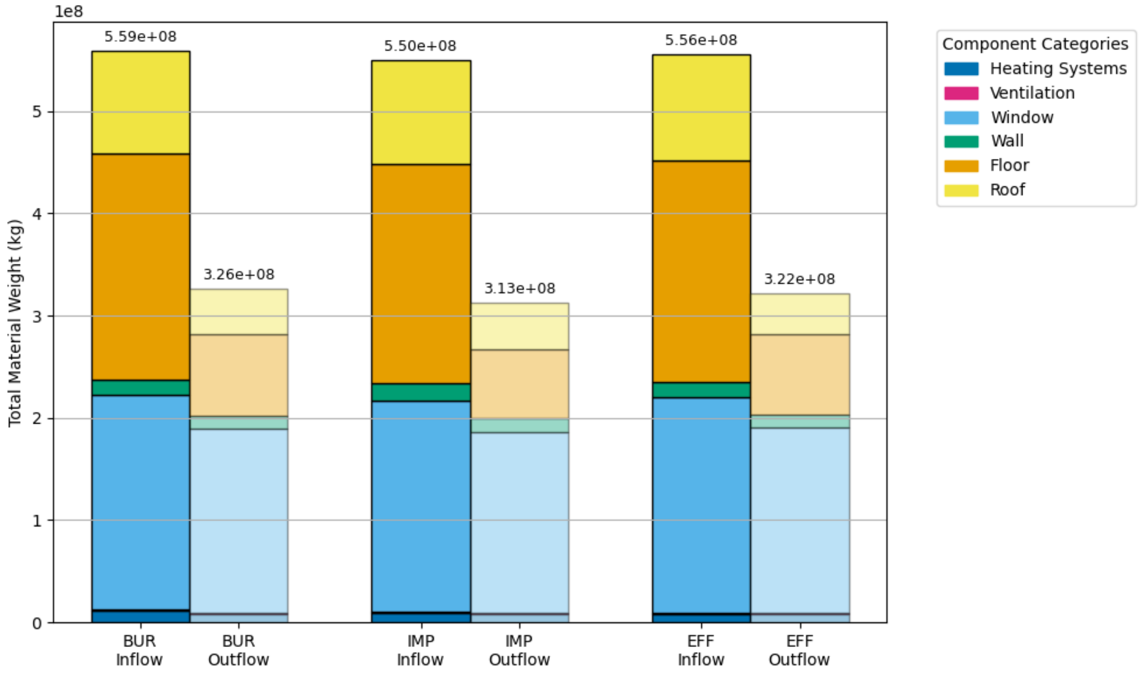


Figure 10. LOW Pathway Component-level Inflows and Outflows

Table 11. LOW Pathway Component-level Inflows and Outflows

LOW	BUR - IN	BUR - OUT	IMP - IN	IMP - OUT	EFF - IN	EFF - OUT
Heating Systems	1,39E+07	8,18E+06	1,17E+07	8,35E+06	6,67E+06	7,90E+06
Ventilation Systems	1,08E+06	1,64E+05	1,64E+06	5,57E+05	1,09E+06	4,22E+05
Window	2,15E+08	1,74E+08	2,19E+08	1,77E+08	2,10E+08	1,71E+08
Wall	1,78E+07	1,46E+07	2,11E+07	1,65E+07	1,66E+07	1,37E+07
Floor	2,22E+08	1,59E+08	2,27E+08	1,49E+08	2,16E+08	1,52E+08
Roof	9,98E+07	6,82E+07	1,05E+08	7,23E+07	1,01E+08	6,57E+07

For the components, flows in the LOW pathway are dominated by windows and floors, which together account for the bulk of both inflows and outflows across all schemes. Window inflows range from 2.10×10^{8} to 2.19×10^{8} kg, while floor inflows are similarly high at 2.16×10^{8} to 2.27×10^{8} kg. These two components therefore represent the largest contributors to total component flows. Roofs also form a significant share, with inflows near 1.0×10^{8} kg across schemes. In contrast, walls and heating systems constitute mid-range flows (approximately 1.2×10^{7}–2.1×10^{7} kg), while ventilation systems represent by far the smallest component flows, contributing less than 2×10^{6} kg to inflows. Outflow patterns mirror these trends, with windows and floors again making up the dominant share of material leaving the system. Overall, the component-level flows in the LOW pathway are primarily shaped by envelope elements, windows, floors, and roofs, while mechanical systems play a relatively minor role in total mass flow.

3.2.2 MID Pathway Material Analysis

In the MID pathway, net accumulation decreases in all schemes due to increased outflows relative to inflows. BUR has an inflow of 5.69×10^{8} kg and an outflow of 4.24×10^{8} kg, producing a net accumulation of 1.45×10^{8} kg. IMP exhibits a higher inflow of 5.85×10^{8} kg and an outflow of 4.24×10^{8} kg, resulting in a net accumulation of 1.61×10^{8} kg. EFF shows the lowest values among the three schemes, with an inflow of 5.51×10^{8} kg, an outflow of 4.11×10^{8} kg, and net accumulation of 1.40×10^{8} kg. These results indicate that material accumulation diminishes in the MID pathway, with IMP maintaining slightly higher accumulation than BUR and EFF.

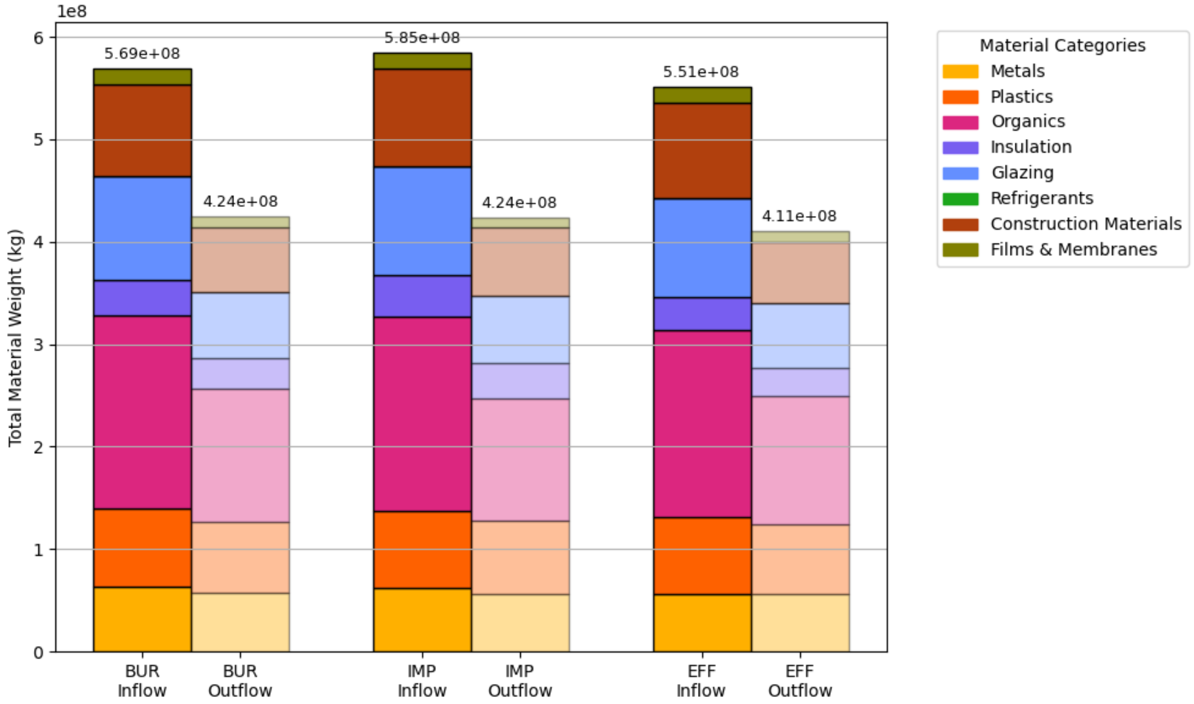


Figure 11. MID Pathway Material-level Inflows and Outflows

Table 12. MID Pathway Material-level Inflows and Outflows

MID	BUR - IN	BUR - OUT	IMP - IN	IMP - OUT	EFF - IN	EFF - OUT
Metals	6,00E+07	5,65E+07	6,24E+07	5,63E+07	5,99E+07	5,68E+07
Plastics	7,80E+07	6,82E+07	7,48E+07	7,17E+07	7,28E+07	6,79E+07
Organics	1,88E+08	1,62E+08	1,90E+08	1,19E+08	1,87E+08	5,05E+07
Insulation	4,39E+07	3,73E+07	4,02E+07	3,44E+07	2,36E+07	2,03E+07
Glazing	1,04E+08	6,38E+07	1,06E+08	6,59E+07	9,55E+07	6,73E+07
Refrigerants	1,83E+05	0,00E+00	1,49E+05	0,00E+00	5,17E+04	0,00E+00
Construction Materials	9,04E+07	7,68E+07	9,54E+07	6,64E+07	9,48E+07	4,47E+07
Films & Membranse	1,52E+07	1,31E+07	1,57E+07	1,02E+07	1,55E+07	5,53E+06
Total	**5,80E+08**	**4,78E+08**	**5,85E+08**	**4,24E+08**	**5,49E+08**	**3,13E+08**

Across all schemes in the MID pathway, organics remain the largest contributor to both inflows and outflows, with inflows ranging from 1.87×10^{8} to 1.90×10^{8} kg. Although outflows vary a lot, particularly to 5.05×10^{7} kg in the EFF scheme, organics continue to dominate the material balance. Glazing and construction materials follow as major flow categories, each contributing between roughly 9×10^{7} and 1.06×10^{8} kg to inflows. Plastics and metals constitute mid-level flows, each on the order of 6×10^{7}–8×10^{7} kg, while insulation materials form a smaller but still notable share of total flows. As in the LOW pathway, refrigerants represent only a negligible portion of total material movement, contributing less than 2×10^{5} kg to inflows and no measurable outflow. Overall, the MID pathway shows a similar hierarchy of materials to the LOW pathway, with organics, glazing, and construction materials driving the majority of flows, but with higher outflows reducing net accumulation across all schemes.

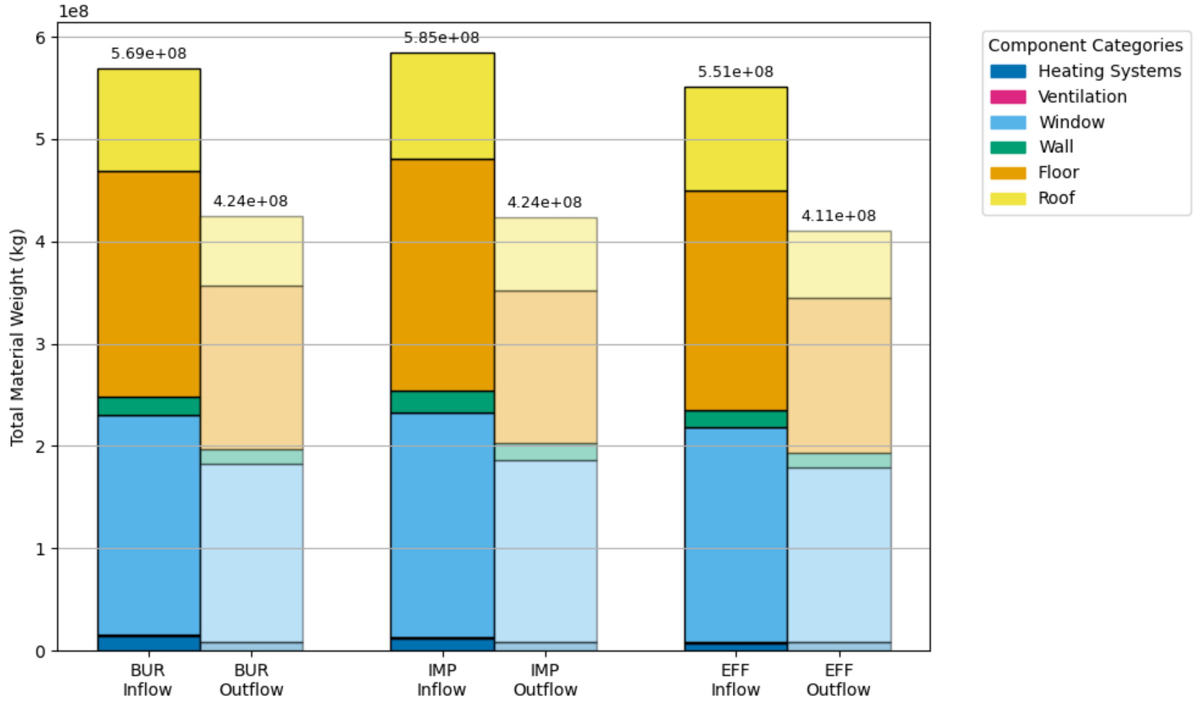


Figure 12. MID Pathway Component-level Inflows and Outflows

Table 13. MID Pathway Component-level Inflows and Outflows

MID	BUR - IN	BUR - OUT	IMP - IN	IMP - OUT	EFF - IN	EFF - OUT
Heating Systems	1,55E+07	7,55E+06	1,22E+07	8,01E+06	5,54E+06	7,61E+06
Ventilation Systems	1,20E+06	1,33E+06	1,33E+06	2,42E+05	1,30E+06	2,35E+05
Window	2,06E+08	1,59E+08	2,19E+08	1,71E+08	2,09E+08	1,62E+08
Wall	1,89E+07	1,65E+07	1,95E+07	1,70E+07	1,93E+07	1,69E+07
Floor	2,15E+08	1,96E+08	2,28E+08	1,98E+08	2,15E+08	1,96E+08
Roof	9,51E+07	8,11E+07	1,00E+08	8,42E+07	9,82E+07	8,34E+07
Total	**5,52E+08**	**4,61E+08**	**5,80E+08**	**4,78E+08**	**5,48E+08**	**4,66E+08**

For the components in the MID pathway, the largest inflows and outflows once again stem from windows and floors, which dominate total component mass across all schemes. Window inflows range from 2.06×10^{8} to 2.19×10^{8} kg, while floor inflows reach similar levels between 2.15×10^{8} and 2.28×10^{8} kg. These two components therefore remain the primary drivers of overall component flows, mirroring patterns observed in the LOW pathway. Roofs also contribute significantly, with inflows close to 1.0×10^{8} kg and correspondingly high outflow values. Walls represent a medium-scale flow category, with inflows near 1.9×10^{7} kg and outflows around 1.65×10^{7}–1.70×10^{7} kg. Heating systems contribute modestly—on the order of 5.5×10^{6} to 1.55×10^{7} kg—while ventilation systems constitute the smallest component flow, with values below 1.4×10^{6} kg. Overall, the MID pathway shows a consistent pattern: building envelope elements (windows, floors, and roofs) dominate material movement, while mechanical systems represent only a small fraction of total mass flows.

3.2.3 NPA Pathway Material Analysis

The NPA pathway exhibits the lowest net accumulation across all schemes, reflecting the smaller difference between inflow and outflow. BUR records an inflow of 5.52×10^8 kg, an outflow of 4.62×10^8 kg, and net accumulation of 9.00×10^7 kg. IMP shows higher flows, with an inflow of 5.79×10^8 kg and an outflow of 4.78×10^8 kg, yielding a net accumulation of 1.01×10^8 kg. EFF records the lowest accumulation overall, with inflow of 5.48×10^8 kg, outflow of 4.66×10^8 kg, and net accumulation of 8.20×10^7 kg. In this pathway, IMP retains the highest net accumulation, while BUR and EFF are similar but lower

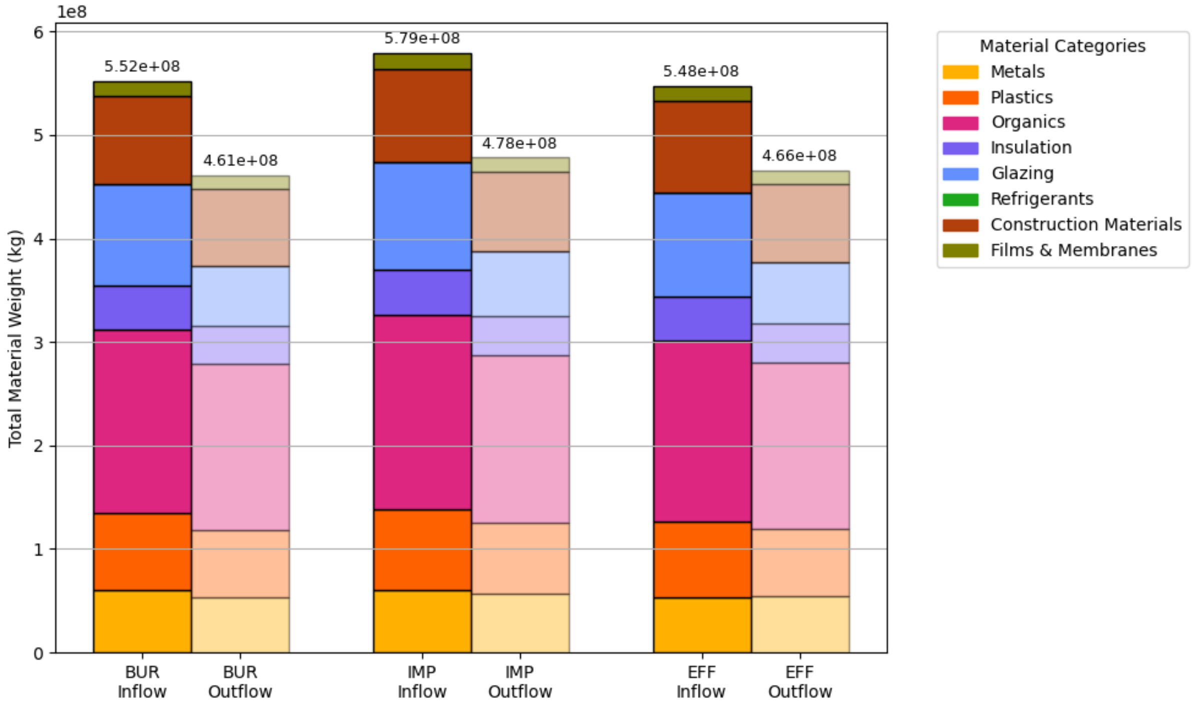


Figure 13. NPA Pathway Material-level Inflows and Outflows

Table 14. NPA Pathway Material-level Inflows and Outflows

NPA	BUR - IN	BUR - OUT	IMP - IN	IMP - OUT	EFF - IN	EFF - OUT
Metals	6,04E+07	5,36E+07	6,35E+07	5,76E+07	6,38E+07	5,90E+07
Plastics	7,40E+07	6,46E+07	7,57E+07	6,86E+07	7,36E+07	6,89E+07
Organics	1,78E+08	1,61E+08	1,88E+08	1,30E+08	1,95E+08	6,62E+07
Insulation	4,24E+07	3,58E+07	3,50E+07	2,96E+07	2,22E+07	1,93E+07
Glazing	9,77E+07	5,82E+07	1,01E+08	6,52E+07	9,63E+07	6,77E+07
Refrigerants	2,21E+05	0,00E+00	1,64E+05	0,00E+00	9,07E+04	0,00E+00
Construction Materials	8,50E+07	7,43E+07	9,02E+07	6,23E+07	9,31E+07	3,90E+07
Films & Membranse	1,43E+07	1,30E+07	1,53E+07	1,08E+07	1,57E+07	6,21E+06
Total	**5,52E+08**	**4,61E+08**	**5,69E+08**	**4,24E+08**	**5,60E+08**	**3,26E+08**

Materials such as metals and plastics exhibit moderate but stable contributions, each ranging between 6×10^7 and 7.6×10^7 kg in inflows, with slightly lower outflows. Insulation, though important, contributes a smaller fraction compared with organics and glazing. The least dominant categories are refrigerants and films & membranes, both representing comparatively negligible flows. Refrigerants, in particular, show minimal inflow and no outflow under all schemes. Overall, the material distribution is heavily influenced by high-mass organic and glazing components, while smaller categories contribute only marginally to total flows.

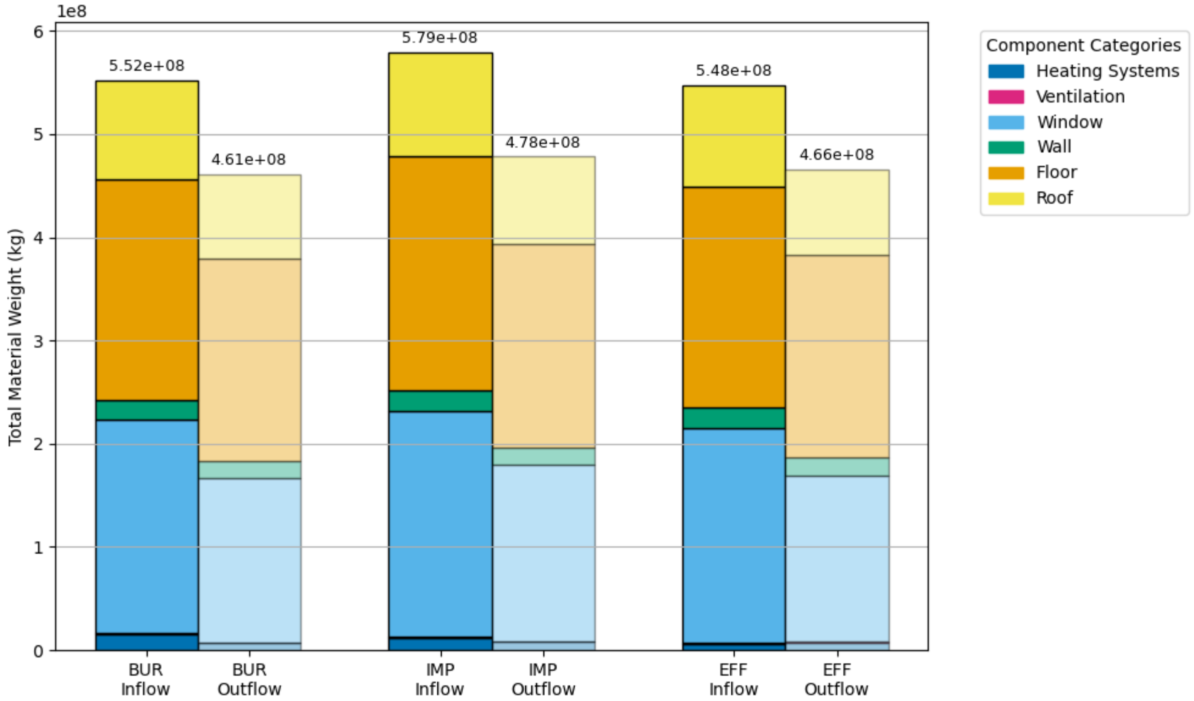


Figure 14. NPA Pathway Component-level Inflows and Outflows

Table 15. NPA Pathway Component-level Inflows and Outflows

NPA	BUR - IN	BUR - OUT	IMP - IN	IMP - OUT	EFF - IN	EFF - OUT
Heating Systems	1,14E+07	8,37E+06	9,09E+06	8,33E+06	8,49E+06	8,28E+06
Ventilation Systems	1,02E+06	4,30E+05	1,21E+06	5,52E+05	1,10E+06	5,21E+05
Window	2,10E+08	1,80E+08	2,07E+08	1,77E+08	2,11E+08	1,82E+08
Wall	1,51E+07	1,25E+07	1,68E+07	1,33E+07	1,46E+07	1,20E+07
Floor	2,21E+08	8,07E+07	2,14E+08	6,75E+07	2,17E+08	7,88E+07
Roof	1,01E+08	4,41E+07	1,01E+08	4,62E+07	1,03E+08	4,03E+07
Total	**5,60E+08**	**3,26E+08**	**5,49E+08**	**3,13E+08**	**5,55E+08**	**3,22E+08**

When flows are assessed at the component level, windows, floors, and roofs dominate the NPA pathway across all schemes. Window assemblies generate the highest flows overall, with inflows exceeding 2.07×10^8 to 2.11×10^8 kg, closely matched by substantial outflows. Floor systems similarly display major contributions, with inflows around 2.14×10^8 to 2.21×10^8 kg, though outflows vary more widely across schemes. Roofs represent another influential component category, maintaining high inflow values across BUR, IMP, and EFF. Wall systems contribute moderately, with inflows below 2×10^7 kg, showing a smaller but still relevant role.By contrast, heating systems and ventilation systems represent the least substantial flows. Their inflows remain below 1.2×10^7 kg, with outflows even smaller, highlighting their minor contribution to the overall mass balance.

Across all pathways, the IMP scheme consistently shows the highest inflows and outflows for both materials and components, which results in the highest net accumulation, particularly visible in the MID and NPA pathways. This reflects its renovation prioritisation strategy, which retains more material in the system. BUR and EFF produce similar total flows but differ in their distribution: BUR shows slightly higher outflows in several categories, reflecting more material turnover. EFF generally exhibits lower outflows, especially in organics under the MID pathway, reducing net accumulation but also lowering material removal. The differences between schemes are subtle in the LOW pathway, moderate in the MID pathway, and most pronounced in the NPA pathway, where renovation quotas create stronger divergence in material flows.

3.3 Energy Burden

The impact of the BUR, IMP, and EFF prioritisation schemes on energy burden, annual energy costs, and energy consumption was analysed across the LOW, MID, and NPA pathways. Table 16 summarises the energy burden of all different prioritisation schemes in each quota pathway. Additionally, the directly related indicators that make up part of the energy burden: energy costs and energy consumption are also summarised for the schemes in Table 17 and Table 18 respectively.

Table 16. Energy Burden in different Prioritisation Schemes and Renovation Quota Pathways

From (Current State)	BUR	IMP	EFF
NPA	4,18E-02	4,02E-02	4,04E-02
MID	3,96E-02	3,74E-02	3,87E-02
LOW	3,91E-02	3,74E-02	3,77E-02
To (State in 2050)	BUR	IMP	EFF
NPA	1,74E-02	4,88E-02	5,12E-02
MID	2,04E-02	4,38E-02	4,07E-02
LOW	2,55E-02	4,02E-02	3,29E-02
Difference	BUR	IMP	EFF
NPA	-2,44E-02	8,60E-03	1,08E-02
MID	-1,92E-02	6,40E-03	2,00E-03
LOW	-1,36E-02	2,80E-03	-4,80E-03

Table 17. Energy Cost in different Prioritisation Schemes and Renovation Quota Pathways

From (Current State)	BUR	IMP	EFF
NPA	2,65E+08	2,71E+08	2,66E+08
MID	2,74E+08	2,71E+08	2,72E+08
LOW	2,79E+08	2,68E+08	2,79E+08
To (State in 2050)	BUR	IMP	EFF
NPA	1,01E+08	3,47E+08	3,21E+08
MID	1,35E+08	3,10E+08	2,96E+08
LOW	1,81E+08	2,74E+08	2,57E+08
Difference	BUR	IMP	EFF
NPA	-1,64E+08	7,60E+07	5,50E+07
MID	-1,39E+08	3,90E+07	2,40E+07
LOW	-9,80E+07	6,00E+06	-2,20E+07

Table 18. Energy Consumption in different Prioritisation Schemes and Renovation Quota Pathways

From (Current State)	BUR	IMP	EFF
NPA	1,62E+09	1,66E+09	1,62E+09
MID	1,67E+09	1,63E+09	1,66E+09
LOW	1,70E+09	1,61E+09	1,70E+09
To (State in 2050)	BUR	IMP	EFF
NPA	6,92E+08	7,28E+08	6,87E+08
MID	8,90E+08	7,91E+08	9,54E+08
LOW	1,18E+09	1,09E+09	1,24E+09
Difference	BUR	IMP	EFF
NPA	-9,28E+08	-9,32E+08	-9,33E+08
MID	-7,80E+08	-8,39E+08	-7,06E+08
LOW	-5,20E+08	-5,20E+08	-4,60E+08

3.3.1 LOW Pathway Energy Burden Analysis

Under the LOW pathway, the BUR scheme produces the largest reductions in energy burden and costs. The energy burden decreases from 3.91×10^{-2} to 2.55×10^{-2} ($\Delta = -1.36\times10^{-2}$), annual energy costs decline from 2.79×10^{8} € to 1.81×10^{8} € ($\Delta = -9.80\times10^{7}$ €), and energy consumption falls from 1.70×10^{9} kWh/year to 1.18×10^{9} kWh/year ($\Delta = -5.20\times10^{8}$ kWh/year). In contrast, the IMP scheme shows a slight increase in energy burden from 3.74×10^{-2} to 4.02×10^{-2} ($\Delta = +2.80\times10^{-3}$) and a minor increase in annual costs ($+6.00\times10^{6}$ €), while energy consumption decreases by 5.20×10^{8} kWh/year. The EFF scheme achieves moderate reductions in energy burden ($\Delta = -4.80\times10^{-3}$) and costs ($\Delta = -2.20\times10^{7}$ €), with a consumption decrease of 4.60×10^{8} kWh/year.

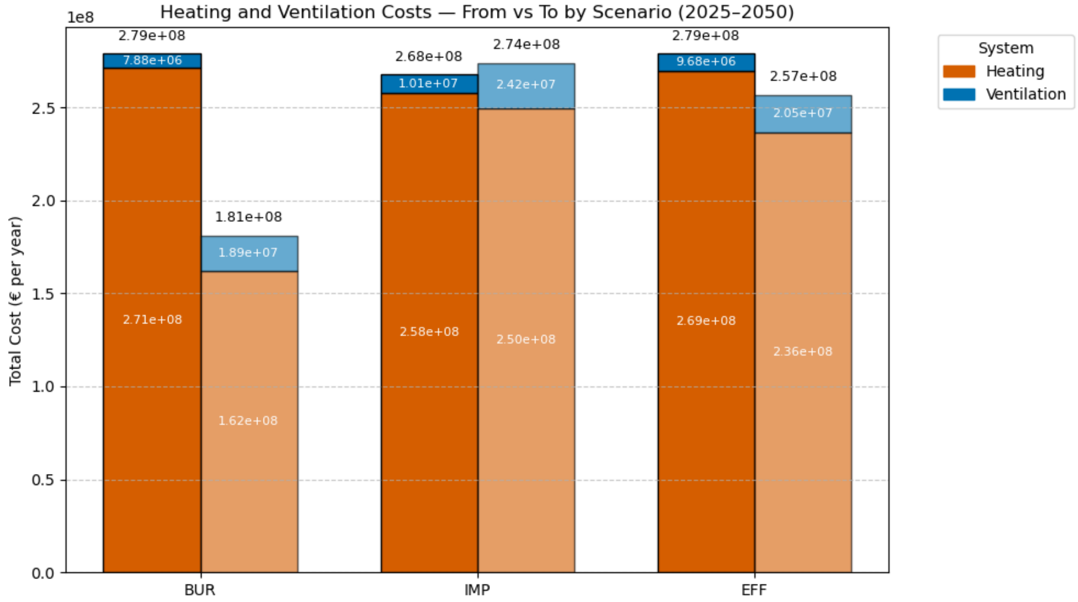


Figure 15. LOW Pathway Heating and Ventilation Costs

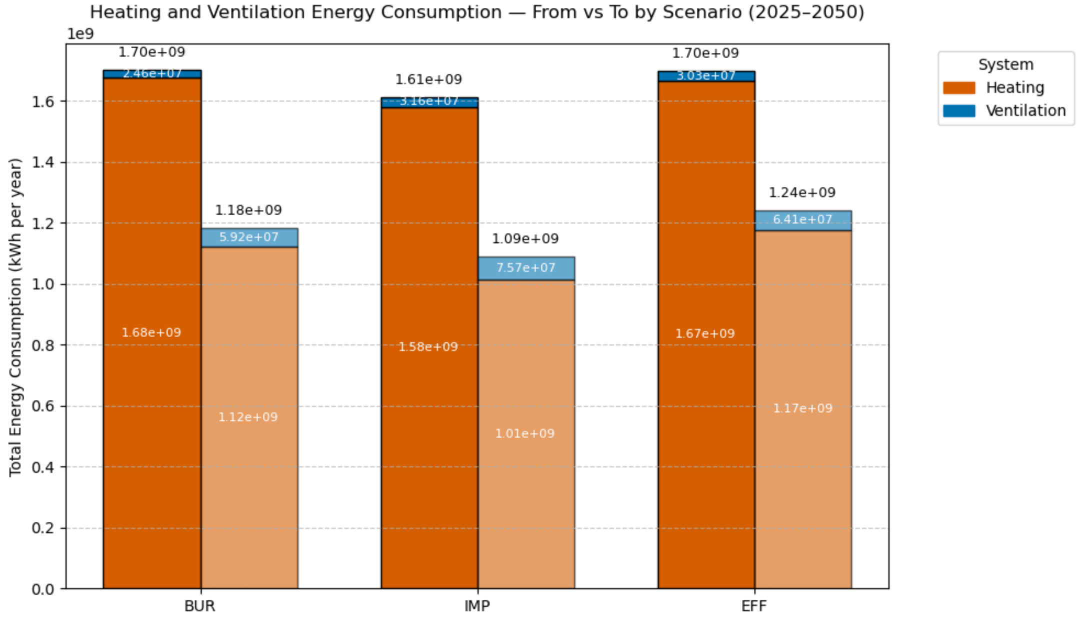


Figure 16. LOW Pathway Heating and Ventilation Energy Consumption

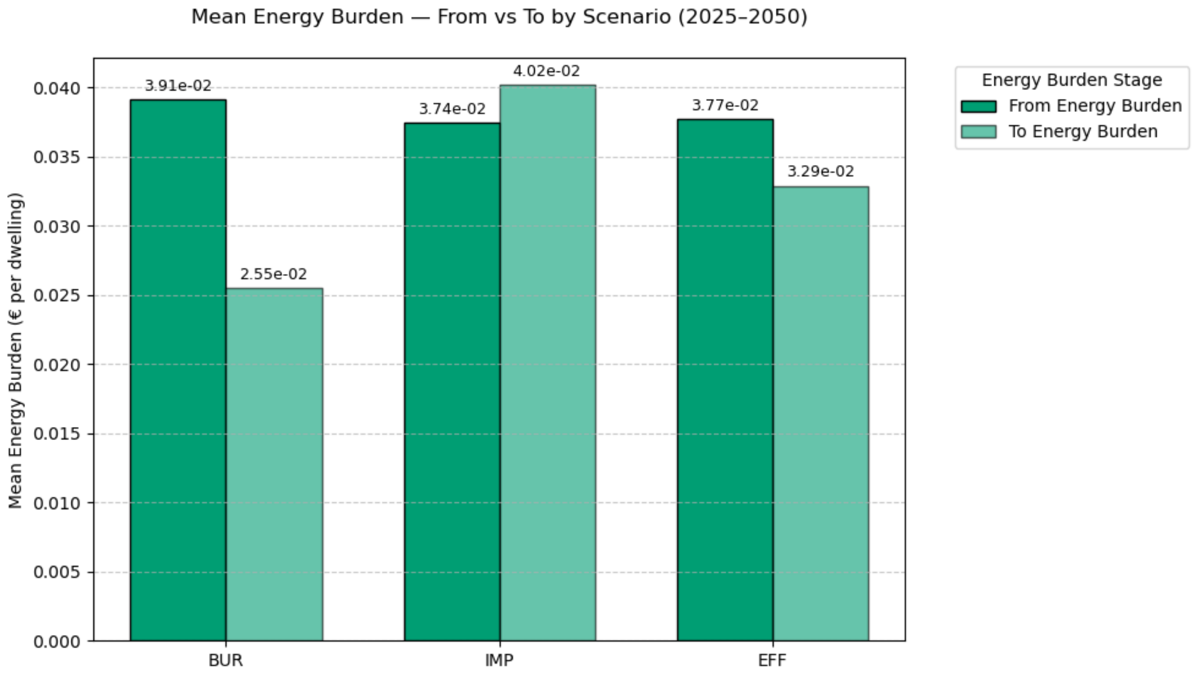


Figure 17. LOW Pathway Energy Burden

BUR provides the most significant reductions in energy burden, costs, and consumption in the LOW pathway, whereas IMP increases burden and costs slightly despite reducing consumption. EFF yields moderate improvements

3.3.2 MID Pathway Energy Burden Analysis

In the MID pathway, BUR continues to reduce energy burden substantially ($3.96\times10^{-2} \rightarrow 2.04\times10^{-2}$, $\Delta = -1.92\times10^{-2}$), with annual costs decreasing by 1.39×10^{8} € and consumption falling by 7.80×10^{8} kWh/year.

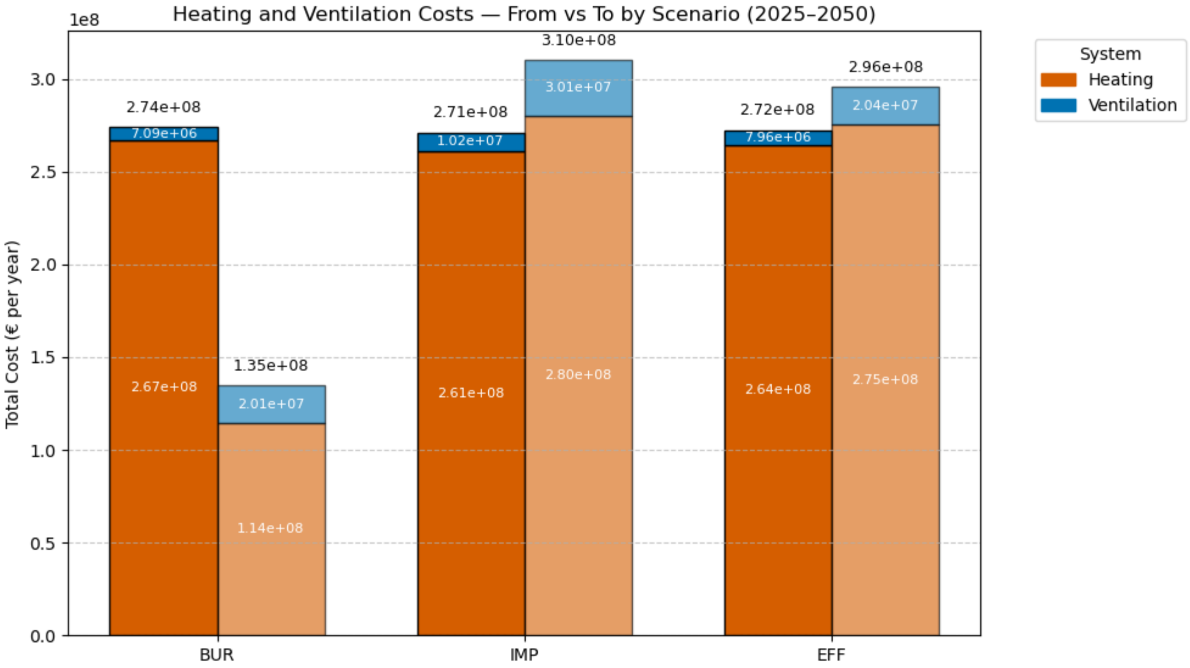


Figure 18. MID Pathway Heating and Ventilation Costs

The IMP scheme, however, shows an increase in energy burden ($3.74\times10^{-2} \rightarrow 4.38\times10^{-2}$, $\Delta = +6.40\times10^{-3}$) and costs ($+3.90\times10^{7}$ €), while achieving a consumption reduction of 8.39×10^{8} kWh/year. EFF shows a slight increase in energy burden ($\Delta = +2.00\times10^{-3}$) and annual costs ($+2.40\times10^{7}$ €), with consumption decreasing by 7.06×10^{8} kWh/year.

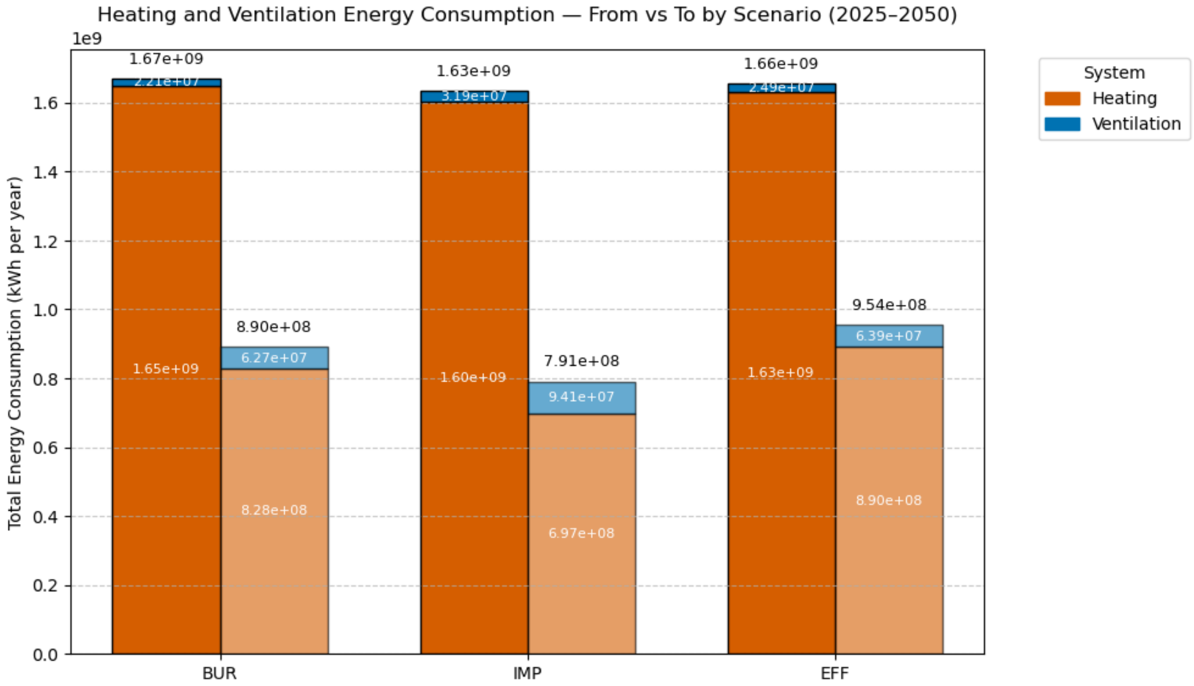


Figure 20. MID Pathway Heating and Ventilation Energy Consumption

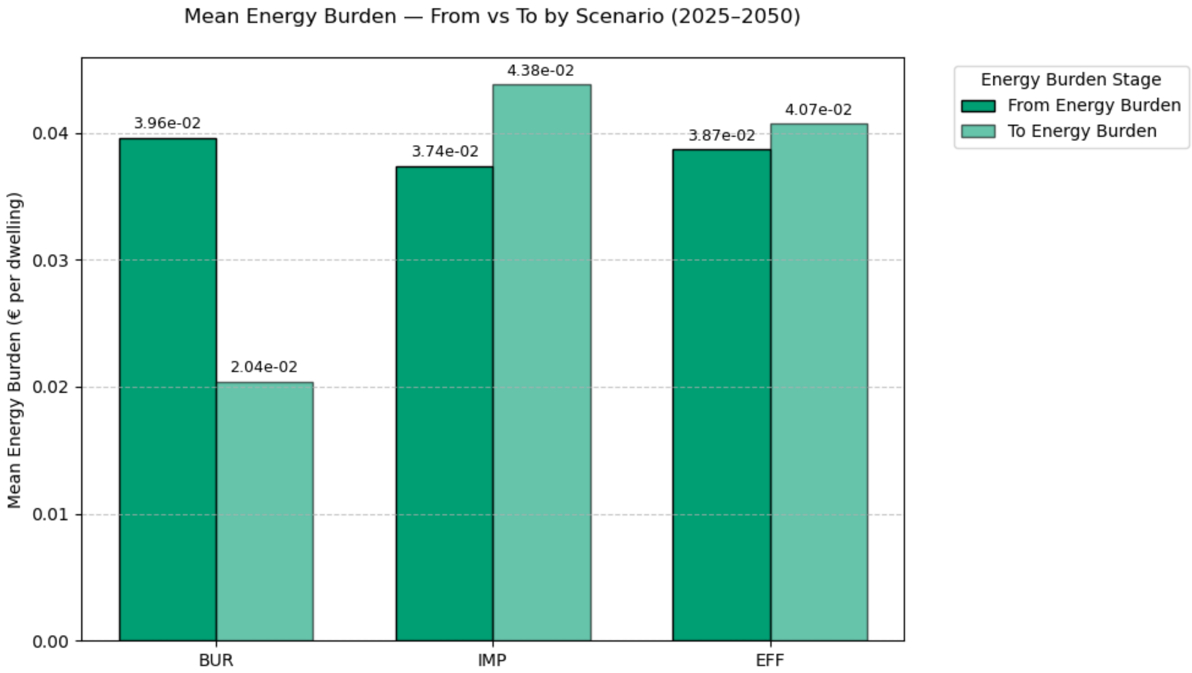


Figure 19. MID Pathway Energy Burden

BUR achieves the largest reductions in both energy burden and costs. IMP and EFF reduce energy consumption effectively, but at the expense of higher burdens and/or costs.

3.3.3 NPA Pathway Energy Burden Analysis

Under the NPA pathway, BUR continues to provide substantial improvements, with energy burden decreasing from 4.18×10^{-2} to 1.74×10^{-2} ($\Delta = -2.44\times10^{-2}$), annual costs declining by 1.64×10^{8} €, and consumption falling by 9.28×10^{8} kWh/year. IMP shows increased energy burden ($4.02\times10^{-2} \rightarrow 4.88\times10^{-2}$, $\Delta = +8.60\times10^{-3}$) and higher costs ($+7.60\times10^{7}$ €), while consumption decreases by 9.32×10^{8} kWh/year. EFF similarly exhibits an increase in energy burden ($4.04\times10^{-2} \rightarrow 5.12\times10^{-2}$, $\Delta = +1.08\times10^{-2}$) and costs ($+5.50\times10^{7}$ €), with a consumption reduction of 9.33×10^{8} kWh/year.

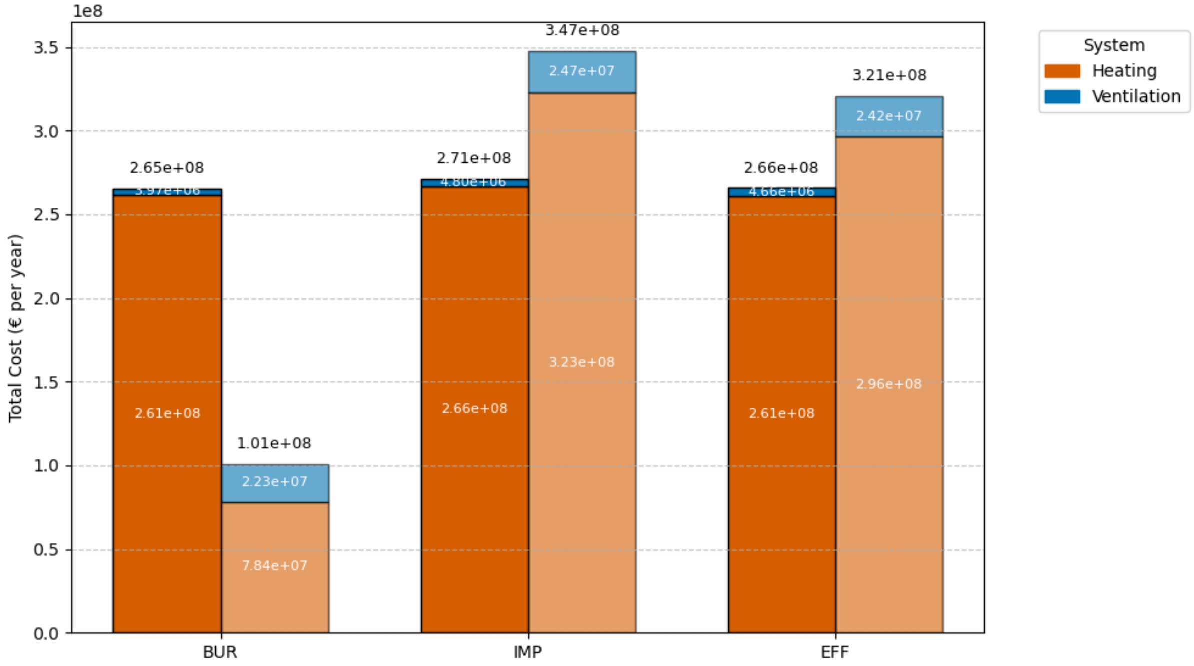


Figure 22. NPA Pathway Heating and Ventilation Costs

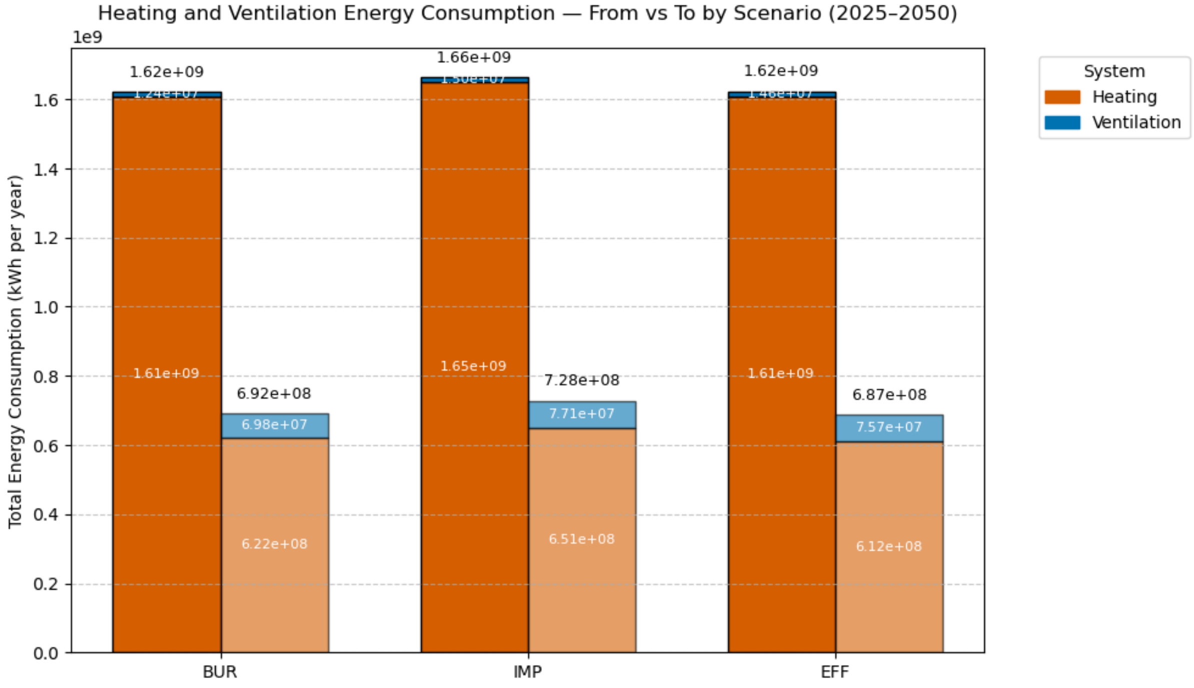


Figure 21. NPA Pathway Heating and Ventilation Energy Consumption

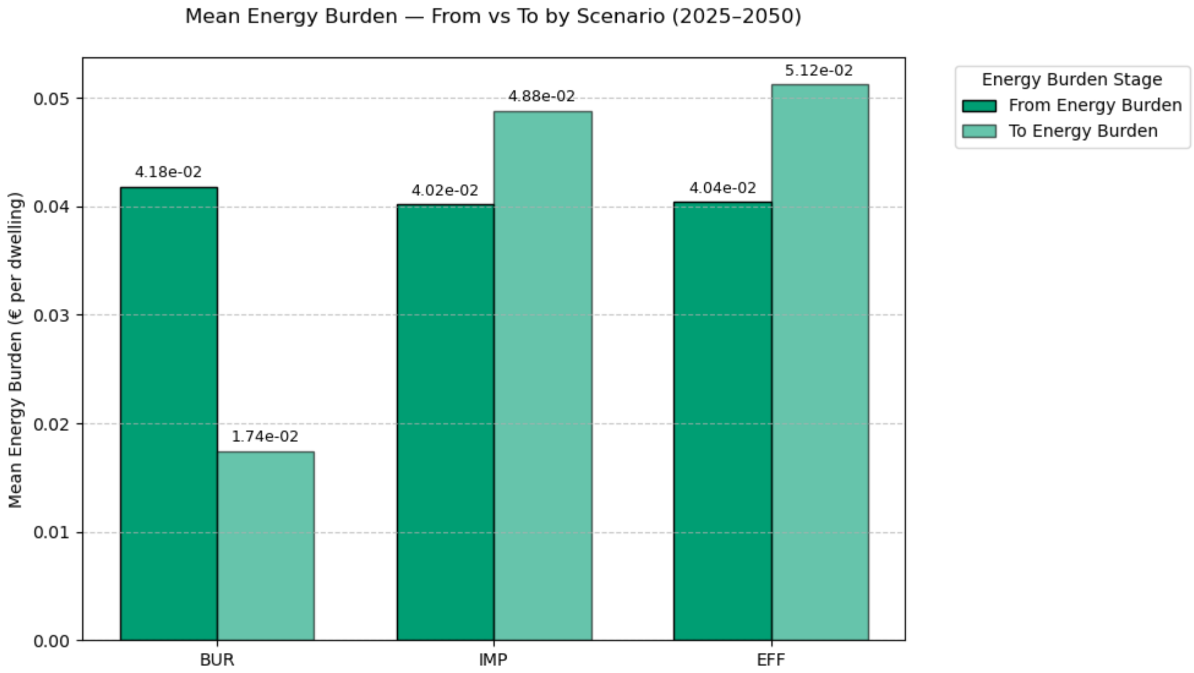


Figure 23. NPA Pathway Energy Burden

In the NPA pathway, BUR remains the most effective scheme in reducing energy burden and costs. IMP and EFF achieve comparable reductions in energy consumption but at the cost of increased burden and expenditures.

Across all pathways, BUR consistently achieves the largest reductions in energy burden and costs while also lowering energy consumption. IMP and EFF reduce energy consumption effectively but may increase energy burden and/or costs, particularly in the MID and NPA pathways. The results highlight the trade-offs between consumption reduction and energy burden management across prioritisation schemes.

3.4 Economic and Environmental Trade-offs

The impact of renovation prioritisation schemes on operational and material-embedded CO_2 emissions, as well as associated renovation costs, was analysed across the LOW, MID, and NPA renovation quota pathways. Table 19 summarises the reductions in operational emissions and material-embedded emissions for each scheme in each pathway. Table 20 summarises the material and the labour costs of the ESMs for each prioritisation scheme and pathway.

Table 19. Operational and Material-embedded CO_2 Emissions in different Prioritisation Schemes and Pathways

Operational CO_2 Emission	BUR	IMP	EFF
NPA	-3,18E+13	-4,11E+13	-3,45E+13
MID	-2,57E+13	-3,45E+13	-2,53E+13
LOW	-1,74E+13	-2,17E+13	-1,59E+13
Material Embedded	BUR	IMP	EFF
NPA	6,56E+08	8,21E+08	7,68E+08
MID	6,86E+08	8,09E+08	7,31E+08
LOW	6,74E+08	7,18E+08	6,93E+08
Net Emissions	BUR	IMP	EFF
NPA	-3,18E+13	-4,11E+13	-3,45E+13
MID	-2,57E+13	-3,45E+13	-2,53E+13
LOW	-1,74E+13	-2,17E+13	-1,59E+13

Table 20. Material-and labour costs cost in different prioritisation schemes and pathways

Material	BUR	IMP	EFF
NPA	7,93E+10	8,65E+10	7,53E+10
MID	7,94E+10	8,82E+10	7,41E+10
LOW	7,6E+10	7,73E+10	7,45E+10
Installation	BUR	IMP	EFF
NPA	3,22E+10	3,25E+10	2,93E+10
MID	3,27E+10	3,49E+10	2,98E+10
LOW	3,2E+10	3,22E+10	3,14E+10
Total	BUR	IMP	EFF
NPA	1,115E+11	1,19E+11	1,046E+11
MID	1,121E+11	1,231E+11	1,039E+11
LOW	1,08E+11	1,095E+11	1,059E+11

3.4.1 LOW Pathway Economic and Environmental Analysis

In the LOW renovation pathway, BUR achieves operational CO_2 reductions of 1.74×10^{13} kg, accompanied by material-embedded emissions of 6.74×10^{8} kg CO_2. When combined, the net emissions remain strongly negative (-1.74×10^{13} kg), indicating that operational savings overwhelmingly offset material-related emissions. IMP delivers the largest operational reductions in the LOW pathway at 2.17×10^{13} kg CO_2, surpassing both BUR and EFF. Although its material-embedded emissions (7.18×10^{8} kg) are slightly higher than BUR's, the resulting net emissions still reflect the highest overall climate benefit among the three schemes (-2.17×10^{13} kg CO_2). This positions IMP as the most effective in reducing total emissions. EFF, in contrast, produces the smallest operational reduction at 1.59×10^{13} kg CO_2 and material-embedded emissions of 6.93×10^{8} kg CO_2. With a resulting net emission reduction of -1.59×10^{13} kg, EFF trails behind BUR and IMP in environmental performance but still delivers substantial

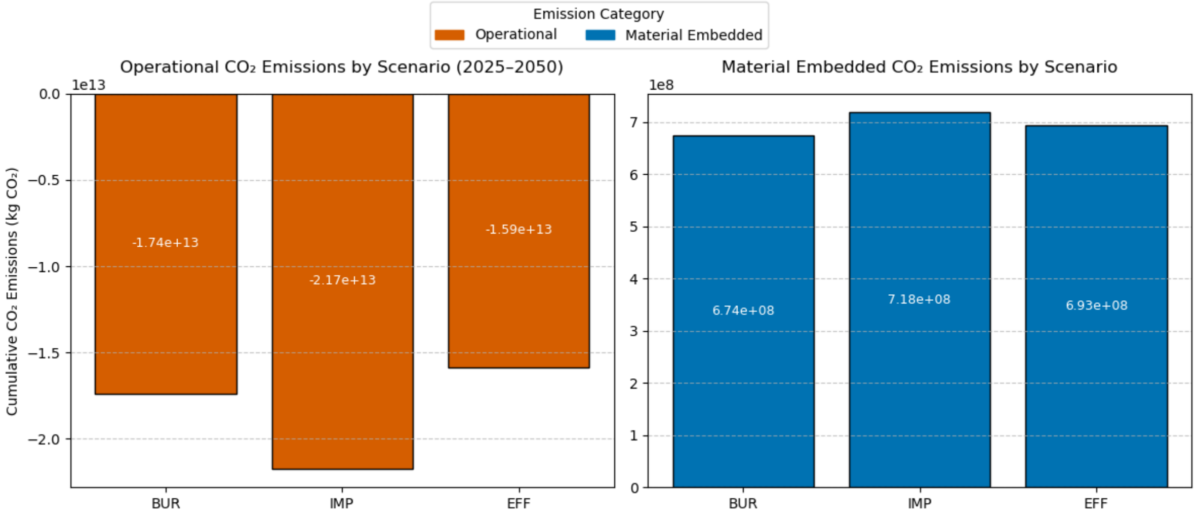


Figure 24.LOW Pathway Operational and Material-embedded CO₂ Emissions

overall CO_2 savings. On the economic-side of things, BUR incurs material and labour costs of €7.60×10^{10} and €3.20×10^{10}, respectively, totalling €1.08×10^{11}. IMP requires slightly higher expenditures, reaching a total of €1.095×10^{11}, reflecting its broader and more impactful renovation scope. EFF again shows its cost-efficiency strength, achieving the lowest total costs at €1.059×10^{11}, consistent with its lower renovation intensity.

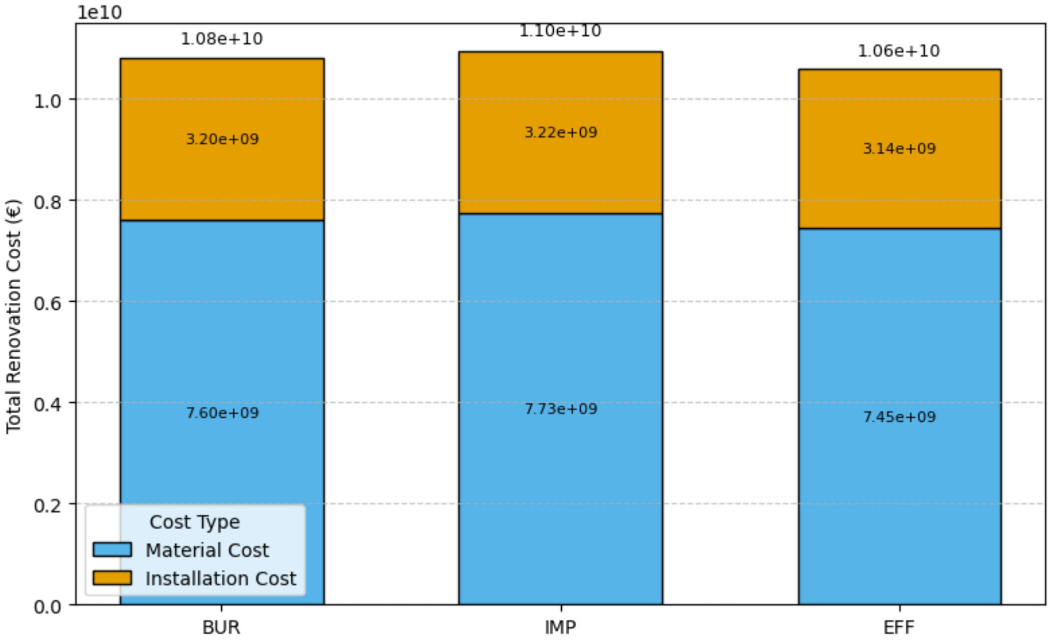


Figure 25. LOW Pathway Material and Labour costs

In the LOW pathway, IMP clearly delivers the largest net CO_2 reductions, albeit at a marginally higher cost than the other schemes. BUR offers moderate net environmental benefits at slightly lower cost, while EFF prioritises cost minimisation, achieving the lowest expenditures but also the lowest net emissions reduction.

3.4.2 MID Pathway Economic and Environmental Analysis

BUR achieves operational CO_2 reductions of 2.57×10^{13} kg, paired with material-embedded emissions of 6.86×10^{8} kg CO_2. The resulting net emissions (-2.57×10^{13} kg) show that operational savings dominate despite moderate material-related emissions. IMP provides the highest operational CO_2 reductions in the MID pathway, reaching 3.45×10^{13} kg, which is substantially higher than both BUR and EFF. Its material-embedded emissions (8.09×10^{8} kg) are also the highest among the schemes, yet these are negligible compared with the operational benefits. Consequently, IMP delivers the largest net emissions reduction in the MID scenario (-3.45×10^{13} kg CO_2). EFF achieves operational reductions of 2.53×10^{13} kg CO_2, similar to BUR but lower than IMP. Material-embedded emissions are the lowest among the three schemes (7.31×10^{8} kg CO_2). With net emissions of -2.53×10^{13} kg, EFF performs comparably to BUR but clearly below the IMP scheme in overall climate impact.

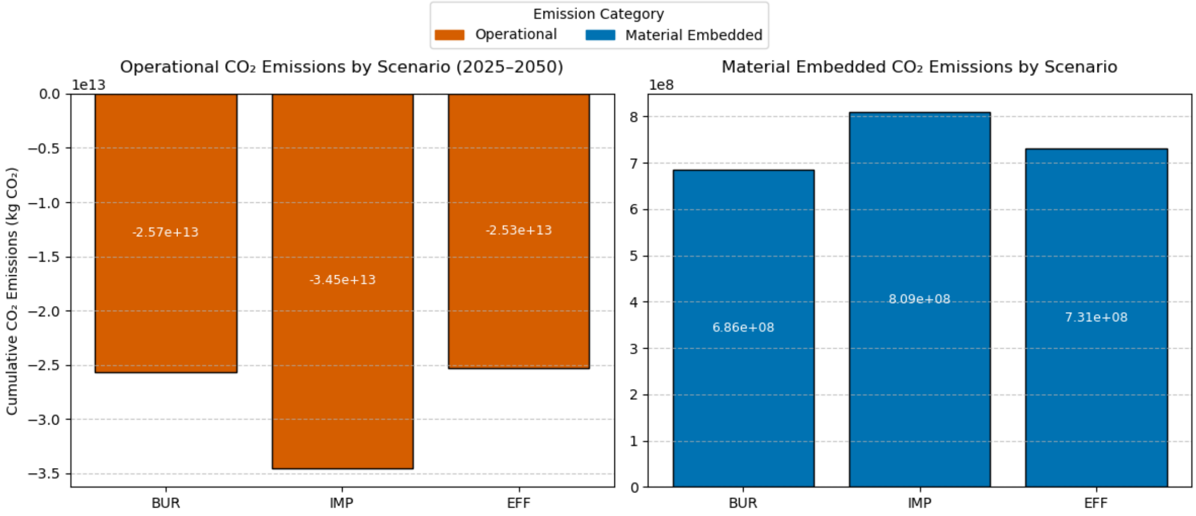


Figure 26. MID Pathway Operational and Material-embedded CO_2 Emissions

In the economic sitiation, material and labour costs follow a similar structure to the environmental trends. BUR incurs total renovation costs of €1.121×10^{11}, placing it in the mid-range among the schemes. IMP, reflecting its higher intervention intensity, has the highest total costs at €1.231×10^{11}. EFF, consistent with its efficiency-focused prioritisation, achieves the lowest total cost at €1.039×10^{11}.

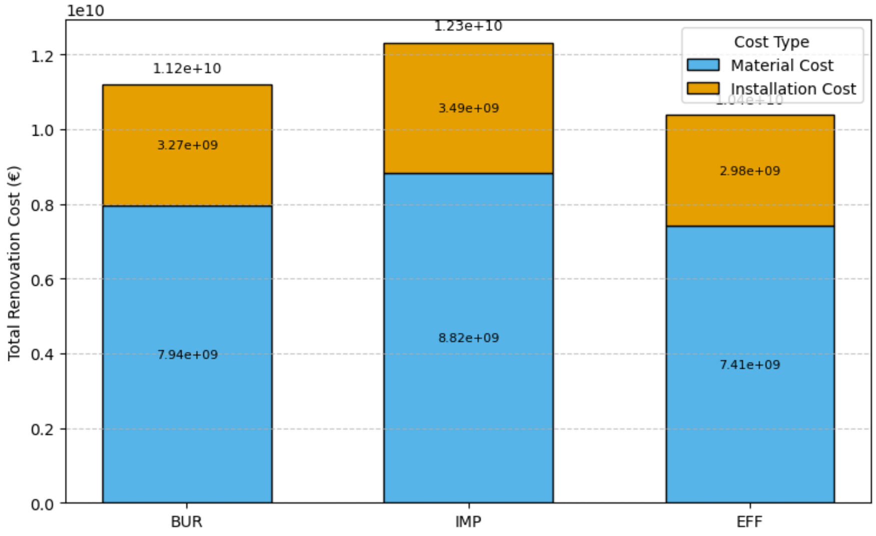


Figure 27. MID Pathway Material and Labour costs

In the MID pathway, IMP delivers the greatest net CO_2 reductions, though at the highest cost. BUR and EFF provide similar net climate benefits, with EFF offering slightly lower reductions but the lowest cost. The trade-off is therefore clear: IMP maximises emissions savings, while EFF minimises expenditures, and BUR sits between these two extremes.

3.4.3 NPA Pathway Economic and Environmental Analysis

Under the NPA renovation quota, BUR achieves operational reductions of 3.18×10^{13} kg CO_2, accompanied by material-embedded emissions of 6.56×10^{8} kg CO_2. These material emissions are small relative to the operational savings, resulting in a strong net emissions reduction of -3.18×10^{13} kg CO_2. IMP again stands out as the highest-performing scheme environmentally, with the largest operational reductions of 4.11×10^{13} kg CO_2—the greatest across all pathways and schemes. Material-embedded emissions (8.21×10^{8} kg) are the highest in the NPA pathway, but still negligible compared to operational gains. The net emissions reduction of -4.11×10^{13} kg CO_2 confirms IMP as the most impactful option. EFF yields operational reductions of 3.45×10^{13} kg CO_2, somewhat lower than IMP but higher than BUR. Material-embedded emissions reach 7.68×10^{8} kg CO_2, placing EFF in an intermediate position. The resulting net emissions (-3.45×10^{13} kg) highlight that EFF again delivers strong climate benefits, though not surpassing IMP.

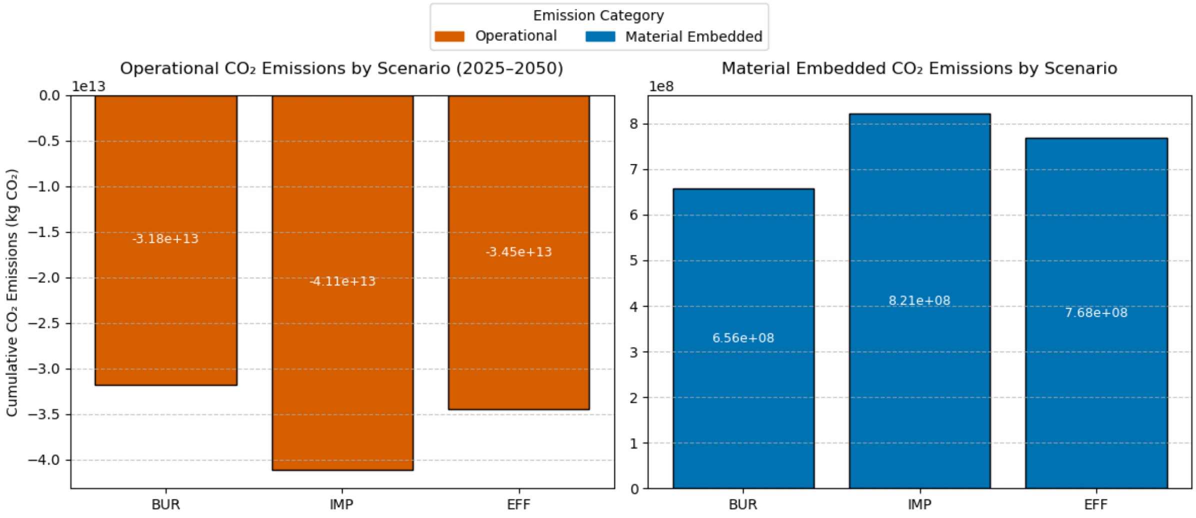


Figure 28. NPA Pathway Operational and Material-embedded CO_2 Emissions

Economic trends mirror the environmental pattern. BUR incurs total renovation costs of €1.115×10^{11}, placing it below IMP but above EFF. IMP, with the largest renovation intensity, records the highest total costs at €1.19×10^{11}. EFF maintains its characteristic cost-efficiency, producing the lowest total costs at €1.046×10^{11} despite substantial emission reductions.

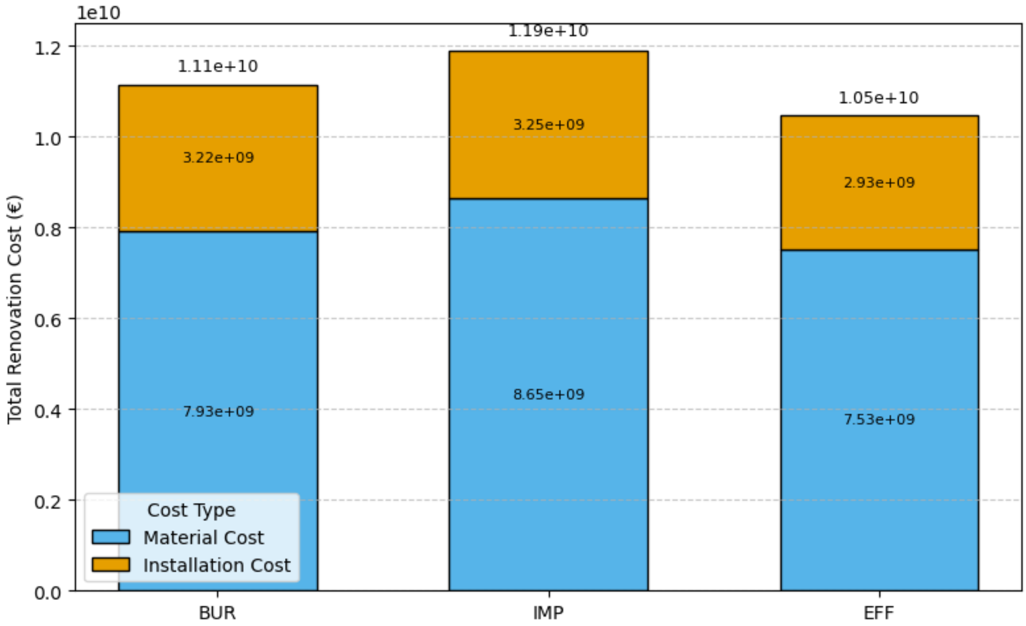


Figure 29. NPA Pathway Material and Labour costs

Within the NPA pathway, IMP provides the largest net emissions reduction, though at the highest cost. BUR and EFF both deliver substantial net savings, with EFF being the most cost-efficient option. Overall, the NPA pathway amplifies the differences between prioritisation schemes: IMP maximises environmental benefit, BUR offers a balanced performance, and EFF continues to prioritise cost savings while still achieving significant net emissions reductions.

4 DISCUSSION

This MFA aims to explore the quantification of different energy improvement renovation trade-offs when different prioritisation schemes are deployed in the Municipality of Amsterdam to the social housing stock at different renovation quota pathways. The focus was on three prioritisation schemes, the BUR where social houses with high energy burdens would be renovated first, the IMP where the renovations with the highest reduction of emissions of kg CO2eq per m^2 renovated would be prioritised, and the EFF where the renovations with the lowest cost per kWh saved would be prioritised. A total 80,000 renovations per year are conducted. These renovations are prioritised based on the scheme but allocated and applied in accordance with a range of deep renovation quotas (ie. Pathways), a range of three pathways on the renovation quotas of the total stock were investigated. Starting with the LOW pathway where 85% of the renovations are deep renovations and the 15% left over limited, followed by the MID pathway where deep and limited renovations are allocated equally at 50:50, and the NPA ambitious AEDES goal of 15% limited and 85% deep renovations. The outcome of the analysis gives an estimated quantification of the different trade-offs these prioritisation schemes and pathways have on the SHA and on the renters, building a foundation to find hotspots within each scheme and renovation quota pathway.

The analysis is split into 4 SRQs focused on the four parameters the trade-offs are based off to answer the MRQ: *To what extent do different renovation-prioritisation schemes and renovation quotas influence the trade-offs among energy savings, material use, household energy burden, and carbon emissions in Amsterdam's social housing stock between 2025 and 2050?*

4.1 Prioritised Renovation Deepness and Dwelling Typologies

4.1.1 Interpretation of Results

The results demonstrate that the type of renovation packages applied in Amsterdam's SHA between 2025 and 2050 is significantly shaped by both the prioritisation scheme and the renovation quota pathway. A clear and consistent pattern emerges across all pathways: the three prioritisation schemes allocate basic foundational envelope insulation-focused renovation packages (P00 and P01) and renewable-sourced heating system renovation packages (P02) differently.

The BUR scheme (energy burden-orientated) systematically favours foundational envelope improvements with the P00 and P01 renovation packages dominating the share, especially in the LOW and MID pathways. Even when the quota of deep renovations increases, such as in the NPA pathway with 85% deep renovation requirements, BUR still directs a significant share toward basic packages. This indicates that BUR prioritises raising the minimum energy performance across the stock rather than maximising carbon savings per residential unit and seeking to transition to renewables as fast as possible. In practice, this means many poorly insulated units receive their first significant envelope upgrade before any shift to renewable heating systems occurs.

By contrast, the IMP scheme (which is environmentally focused) shows a strong bias towards energy transition-oriented renovations (P02). In both the MID and NPA pathways, P02 dominates, accounting for 72.2% and 91.3% of renovations, respectively. This illustrates that the IMP scheme prioritises emissions reductions achieved through rapid electrification and the deployment of renewable energy systems over foundational improvements to the entire stock. This also creates an important trade-off: buildings without prior envelope insulation improvements, which often represent the 'worst energy performers', are deprioritised because their renovation potential per kg of CO_2 emission saved is initially low compared to residential units that already have the necessary foundations to support renewable heating systems. Existing literature supports this, concluding that the effectiveness of renovations depends on the state of the building prior to renovation [78], meaning that houses that have already undergone some renovation work have more effective outcomes. In extreme cases, as seen in the NPA pathway, basic envelope improvement packages (P00) are eliminated entirely. This risks leaving the worst-performing homes behind, deepening the renovation divide within the housing stock and creating a worse state of energy injustice within the system.

The EFF scheme (economic efficiency-oriented) sits between the other two. Under lower deep renovation quotas, its distribution resembles that of the BUR scheme, focusing on foundational measures (P00 and P01). However, as the deep-renovation quota increases, the EFF scheme progressively shifts towards P02, slowly acting like the IMP scheme. In the NPA pathway, P02 becomes dominant (68.4%), which is not as high as the IMP, but still maintains a significant proportion of envelope improvements (P01). This indicates that the EFF scheme balances system upgrades with the need to improve the quality of the building envelope of properties that have never been renovated. Compared to the IMP scheme, EFF is less extreme, yet still more responsive to overall quota pressures than the BUR scheme.

Overall, the results show that higher deep-renovation quota pathways (ie. NPA) amplify the differences between schemes. BUR remains envelope-oriented regardless of quota; IMP becomes increasingly selective and heavily electrification-driven; and EFF transitions gradually toward renewable energy system-related interventions but maintains some basic envelope-orientated renovations. This highlights the importance of selecting a combination of prioritisation scheme and renovation quota pathway that aligns with policy goals: envelope equity, rapid decarbonisation, or incremental efficiency improvement.

The results regarding building types are highly consistent: apartment buildings dominate the selection for renovation across all schemes and pathways, representing over 90% of renovated units. This reflects the composition of the SHA stock but also indicates that multi-unit buildings offer greater cost efficiency and emissions reduction potential per renovation. Terrace houses follow as the second most common type, but their share remains marginal in comparison. Importantly, no scheme exhibited strong typology-specific biases; the dominance of apartments appears to be primarily driven by the composition of the stock rather than by prioritisation rules.

4.1.2 Implications for Policy-making in Amsterdam

This section discusses the implications of the modelling results for ongoing decarbonisation and renovation policies in Amsterdam. The findings show that renovation outcomes are not solely determined by technical potential or renovation quotas, but are critically shaped by the policy embedded within prioritisation schemes. In practice, municipal and sectoral policies strongly influence which buildings are renovated first, which renovation packages are applied, and how equitably renovation benefits are distributed across the housing stock. This subsections shows how current policies align with the behaviour of the IMP and EFF schemes, and what this means for the feasibility and fairness of the city's long-term heat transition.

Implications for Amsterdam's Gas Phase-Out Strategy

Amsterdam has committed to phasing out natural gas by 2040, an ambition operationalised through the Transitievisie Warmte, neighbourhood heat plans, and subsidies for gas-free conversion (e.g. heat pumps and district heating) [48], [79]. These instruments prioritise interventions that lead to direct and immediate decarbonisation, such as electrification or district-heating connection. This strategy closely resembles the model's IMP scheme, which prioritises packages (e.g. P02) that produce immediate CO_2 reductions. However, the model highlights a significant drawback of this approach: prioritising heating-system transitions leads to a systematic deprioritisation of poorly insulated buildings, particularly those requiring multi-step improvements. Because poorly insulated homes cannot transition efficiently to heat pumps or district heating without first receiving envelope upgrades, these residential units are pushed to the back of the renovation queue. Given that such buildings often house lower-income or otherwise vulnerable households, this dynamic risks exacerbating energy inequality. Vulnerable households may remain longer on natural gas due to insufficient insulation, while better-performing homes transition sooner simply because they require fewer sequential steps (P00 → P02, and not ES →P01 + P01 → P02).

In practice, renovation rates in the Netherlands remain low, and delays in district-heating expansion have already led to uncertainty in neighbourhood heat planning [49], [50], [61], [80]. The model suggests that even high deep-renovation quotas do not compensate for slow infrastructure roll-out or insufficient renovation capacity, which has already been flag before by other studies [61]. As a result, the 2040 gas-free target is unlikely to be achieved under current renovation rates, regardless of which prioritisation scheme is applied at the highest deep renovaiton quota.

In order to avoid an uneven and socially regressive transition, Amsterdam's gas phase-out strategy should be supplemented with targeted envelope-first programmes, minimum insulation thresholds and protected renovation slots for properties with the worst energy performance. Without such measures, a policy framework similar to the IMP risks delivering rapid decarbonisation for some households while systematically delaying improvements for those already facing the highest energy burdens.

Implications for the SHA/Aedes Push for High Deep-Renovation Quotas

SHA/Aedes has expressed strong ambitions to increase the share of deep renovations across the social housing sector. This ambition is represented in the model through the NPA pathway, in which roughly 85% of renovations between 2025–2050 are deep renovations. Intuitively, high deep-renovation quotas should accelerate decarbonisation and improve long-term building performance. The model results, however, reveal that when these quotas interact with a cost-optimised prioritisation scheme (EFF), there is a substantial risk of unintended outcomes. Under low or mid renovation quotas, EFF maintains a balanced distribution of renovation packages. But under high deep-renovation quotas, EFF shifts increasingly toward P02, exhibiting behaviour similar to IMP. This occurs because deep renovations are more cost-effective in buildings that already possess reasonable envelope standards, and significantly more expensive in buildings that require major insulation upgrades before a deep renovation can be meaningfully applied [78].

As a result, high deep-renovation quotas under cost-optimised and environmental schemes do not prioritise the worst-performing buildings. Instead, they favour buildings that are already on an upward trajectory. Over time, this creates a bifurcated building stock: one group transitions rapidly to high efficiency standards, while older or poorly maintained units lag behind because upgrading them is less effective. This pattern runs counter to sectoral objectives to eliminate low energy labels and prioritise upgrades for the most inefficient homes [65]. It demonstrates that quotas alone are insufficient to ensure equitable renovation outcomes.

To avoid this misalignment, deep-renovation ambitions must be accompanied by prioritisation mechanisms that explicitly weight energy-performance gaps for worst-performing units, independent of cost-minimisation considerations.

The renovation landscape in Amsterdam is shaped not only by long-term strategies but also by the interaction of multiple policy instruments, including: Subsidies for gas-free conversion (supporting heat pumps and district heating), The SAH scheme for rental-sector decarbonisation, Neighbourhood-based heat planning and associated infrastructure timelines. These instruments collectively bias decision-making toward system-level transitions and away from sequential envelope-first schemes. When combined with limited renovation capacity and infrastructure delays, such policies effectively push the system toward IMP-like behaviour, regardless of official sectoral intentions or equity goals. This insight highlights the importance of recognising that policy implementation acts as a prioritisation mechanism.

4.1.3 Implications for the Scientific Community

Interaction Effects Between Prioritisation Schemes and Renovation Quotas

Although the prioritisation schemes in this study are constrained by the model's structure of the RVO renovation categories and their specific combinations of ESMs, the results demonstrate that the interaction between prioritisation schemes and renovation quota pathways generates emergent behaviours not visible when either element is analysed in isolation. This layered approach reveals that renovation quotas are not neutral parameters: they actively shape the expression of prioritisation schemes, amplifying their inherent biases. For example, high deep-renovation quotas push both the IMP and EFF schemes toward increasingly strong system-upgrade orientations, while the BUR scheme remains structurally resistant to such shifts. For the scientific community, this shows the necessity of studying renovation rate policies and prioritisation goals not merely as additive components, but as co-evolving mechanisms whose interactions can produce non-linear or unexpected allocation patterns.

Sequential vs. Single-Cycle Renovation Modelling

A key methodological insight from this study is that the current model operates on a single-cycle renovation logic, where each dwelling receives only one renovation package within the analysed period. This design choice reflects a simplification commonly used in renovation optimisation models, but it also explains a central outcome: worst-performing buildings are systematically left out when schemes prioritise deep or system-focused renovations. Because these buildings require significant sequential improvements (first major envelope insulation, then system upgrades) they cannot reach their full renovation potential within a single renovation cycle. As a result, algorithms that rank residential units on impact or cost-effectiveness naturally deprioritise them in favour of "renovation-ready" units that can realise deep savings in one step. This behaviour is not merely a feature of the prioritisation schemes; it is a structural consequence of the one-hop renovation framework.

In reality, many residential units, especially those with poor insulation, require multi-step, path-dependent renovation trajectories. Modelling such trajectories would allow worst-performing units to gradually move toward higher performance classes and eventually become eligible for system-based deep renovations. For the scientific community, this points toward a significant area for further development: the need for multi-cycle renovation models that explicitly incorporate sequencing, precondition requirements, and "renovation readiness" dynamics. Such frameworks would enable more realistic decarbonisation pathway analysis, better capture the temporal nature of building improvements, and provide a more accurate assessment of equity impacts. They would also allow researchers to examine how policy instruments, such as staged renovation subsidies or minimum insulation thresholds, shape long-term renovation patterns across successive cycles. In this sense, the single-cycle limitation in the current model not only clarifies why the worst-performing residential units remain excluded under certain schemes but also highlights the broader need for dynamic, iterative renovation modelling capable of reflecting how buildings evolve across multiple intervention rounds.

4.2 Material Inflows, Outflows, and Stock Accumulation of Renovations

4.2.1 Interpretation of Results

The material flows observed under the three prioritisation schemes reflect the renovation packages that each scheme favours. The combination of ESMs for larger renovation packages is the primary driver of material intensity. When the renovation quota pathways have a high quota for deep renovations, the differences between the schemes in terms of material flows are more pronounced, while pathways with a low renovation quota display more uniform material patterns. Therefore, the interaction between renovation rates and prioritisation schemes shapes not only the selection of packages, but also resource consumption, material turnover and net stock accumulation.

4.2.2 Material Intensity Influenced by Prioritisation Schemes

There is a consensus around the scientific community and that is that deep renovation cause large amount of material, the deeper and more thorough the renovation, the more materials are put into the system [81], [82]. This is reflected in this study, as across pathways, the IMP scheme consistently demonstrates the highest material inflows and outflows. This aligns with its strong focus on fabric-intensive renovation packages that incorporate envelope upgrades, high-performance glazing, and renewable heating system replacements (P00 → P02). These actions introduce large quantities of insulation, glazing, and construction materials into the stock, explaining the high inflow totals and the fact that IMP consistently achieves the highest net accumulation, 1.01×10^{8} kg in the NPA pathway and 1.61×10^{8} kg in the MID pathway. BUR and EFF generally show lower material inflows in deeper pathways, reflecting their more incremental focus. Therefore prioritisation schemes do have an influence on the material intensity due to the different adoption of renovation packages.

A consistent trend across pathways is that net material accumulation declines as renovation ambition increases. LOW pathways generate the highest accumulation because they rely heavily on limited renovations that primarily add materials, while removing very little. By contrast, the NPA pathway includes deep renovations that produce significant outflows, including the replacement of heating systems and other building components. These larger removals bring inflow–outflow balances much closer to neutral. Despite involving the most extensive interventions, NPA exhibits the lowest material accumulation, as deeper measures tend to replace existing elements rather than layering additional materials onto the envelope.

Across all schemes and pathways, the analysis reveals a consistent hierarchy in terms of material and component flows. At the material level: Organics (primarily wood-based construction elements) dominate both inflows and outflows, with inflows up to $\sim1.9\times10^{8}$ kg in all pathways. Glazing and construction materials represent the second-largest categories, each contributing around 9×10^{7}–1.06×10^{8} kg in inflows. Plastics and metals form medium-scale flows, generally between 6×10^{7} and 8×10^{7} kg. Refrigerants make up only a negligible share of total flows across all schemes ($<10^{4}$–10^{5} kg). This distribution reflects the centrality of envelope components in most renovation packages. At the component level: Windows and floors are consistently the largest contributors to both inflows and outflows across all pathways. Inflows exceed 2×10^{8} kg in most schemes. Roofs form a significant secondary component inflow, around 1.0×10^{8} kg. Walls contribute moderate flows (1.2×10^{7}–2.0×10^{7} kg). Heating and ventilation systems—despite their strategic importance—represent only a very small share of total mass flows ($<1.5\times10^{7}$ kg). This indicates that most of the material movement in renovation schemes is tied to envelope-related upgrades, not to mechanical system replacement.

4.2.3 Implications for the Scientific Community

This study highlights a methodological gap in current renovation material-flow assessments: the systematic exclusion of heating-system integration material, such as distribution piping, floor-heating components, manifolds, and associated finishing layers. Because these elements were not included, the material burdens of system-oriented upgrades (e.g., heat pumps, district-heating connections) are underestimated, while envelope-based measures appear comparatively more material intensive

4.3 Changes to Energy Burden of Households

How do the different renovation schemes and pathways impact energy costs and affordability for vulnerable households?

4.3.1 Interpretation of Results

The analysis of energy burden, annual energy costs, and energy consumption highlights important trade-offs between energy efficiency, household costs, and energy burden equity. ESMs effectively reduce energy consumption across all pathways. IMP prioritisation, which deploys renewable systems and improvements to the envelop ESMs, consistently achieves the largest reductions in theoretical energy consumption. However, these reductions do not always translate into lower energy burden or costs to the tenants.

Two main factors contribute to this outcome:

- **Higher operational costs of renewable energy sources**: Transitioning from natural gas to renewable heating increases operational energy costs, particularly for lower-income households. While energy consumption declines, the higher price of sustainable fuels offsets some of the financial benefits, leading to an increase in energy burden. This expense it particularly felt in the Netherlands, where district heating has been reported to be 2-3 times more expensive than in its European neighbours Denmark, Sweden, Germany and Finland [83].
- **Electrification of building systems**: Modern renovations often incorporate electrically driven mechanical ventilation systems. While these systems improve indoor air quality and overall energy efficiency, their electricity demand can partially offset reductions from heating energy, further impacting household energy bills.

BUR prioritisation, which targets households with the highest initial energy burden, effectively reduces both consumption and costs, thereby minimizing financial stress. EFF schemes provide a moderate compromise, achieving reductions in energy consumption while limiting increases in costs and burden. These findings highlight the complex interaction between energy efficiency, renewable energy adoption, and building system electrification. Reductions in energy consumption alone are insufficient to ensure lower household costs, and interventions must consider both the type of energy used and operational implications of new systems to avoid inadvertently increasing energy burden, particularly for vulnerable populations. The pathways influence the magnitude of energy savings and cost reductions, but they do not alter the relative performance of the prioritisation schemes: BUR is always the most effective in reducing burden and costs. IMP and EFF consistently risk increasing burden, especially under more ambitious pathways. Thus, pathways amplify the effects of prioritisation rather than fundamentally changing the pattern of outcomes. Higher deep renovation quotas increase overall consumption reductions but also magnifies inequities for schemes not targeted at high energy burden households.

4.3.2 Implications for Policy-making in Amsterdam

The results of this analysis indicate that ambitious renovation and decarbonisation policies that emphasize IMP-like schemes can lead to significant reductions in energy consumption, but their effects on household energy burden and costs are highly dependent on both the prioritisation strategy and the intensity of implementation. Technical improvements alone do not guarantee improved affordability, and interventions that focus solely on energy efficiency or renewable energy adoption may unintentionally increase financial stress for tenants, particularly in social housing.

Considerations for Policy Design

1. *Household Affordability as a Core Criterion:* Renovation programs should consider not only the potential energy savings but also the economic capacity of households to absorb changes in operational costs. Prioritisation schemes targeting households with the highest initial energy burden (BUR) consistently reduce both energy consumption and financial stress, suggesting that equity-sensitive approaches are more effective in protecting vulnerable populations.
2. *Phased or Targeted Implementation:* The intensity of renovation pathways can amplify both the benefits and the potential risks of interventions. Gradual rollouts or burden-sensitive prioritisation can help achieve ambitious energy efficiency or decarbonisation targets while mitigating increases in energy costs for tenants.
3. *Affordability of District Heating: E*nsuring that district heating remains financially accessible. While Amsterdam's heat transition plan emphasises switching households to district heating, several challenges limit its effectiveness. Beyond the risk of increased energy burden due to higher operational costs of this renewable source [83], the expansion of the district heating network is facing technical and logistical hurdles, raising concerns that the current approach may not achieve its intended outcomes. Ensuring affordability and system reliability is therefore essential; without it, district heating risks becoming a "dead end" rather than a viable solution for decarbonising residential heating.

As an example, Amsterdam's Gas-Free Policy (2040) aims to phase out natural gas and transition households to renewable heating. While such a transition reduces overall energy consumption, the analysis shows that without complementary measures, it may increase energy burden and costs for lower-income tenants, particularly under MID and NPA renovation pathways. Reducing the operational costs of the heating and the electrification of the ventilation systems would reduce this burden and collectively aid the adoption of renewables in lower income households. As of today, the renewable sources available are far too expensive.

Achieving a high share of deep renovations can significantly reduce energy consumption. However, under high-intensity pathways and prioritisation schemes focused solely on efficiency (IMP or EFF), household energy burden and costs can increase. So if the Amsterdam SHAs want to follow through with the 85% deep renovation rates, staged, burden-sensitive approaches combined with targeted financial support can balance the technical objectives of deep renovation with tenant affordability.

Overall, these findings highlight the need for renovation and decarbonisation policies to integrate technical, economic, and social objectives. Energy efficiency and renewable energy measures must be complemented by burden-sensitive prioritisation and financial safeguards to prevent unintended negative consequences for vulnerable households, while still achieving ambitious climate and energy goals. Additionally, careful attention must be paid to the affordability and feasibility of district heating networks, as their success is contingent not only on technical deployment but also on maintaining manageable costs for households.

4.3.3 Implications for the Scientific Community

This study underscores a key methodological consideration: the representation of household income. A uniform monthly household disposable income was used for each neighbourhood as a proxy for individual residential units. While practical, this approach does not capture income heterogeneity within neighbourhoods. Lower-income households may reside in higher-MHDI areas, particularly in mixed-income neighbourhoods, which may result in underestimation of energy burden for social housing tenants. Future research should explore alternative approaches, such as:

1. Using household-level income data where available.
2. Integrating demographic or housing tenure information to better represent social housing tenants.

3. Applying probabilistic income distributions within neighbourhoods to reflect real-world heterogeneity.

Refining income representation will improve the accuracy of energy burden assessments and allow researchers to more reliably evaluate social equity impacts of energy efficiency and decarbonisation interventions. This methodological improvement is critical for generating policy-relevant insights and ensuring that energy transitions are both environmentally effective and socially equitable.

In conclusion, the study highlights a fundamental trade-off between reducing energy consumption and managing household energy burden. BUR prioritisation effectively lowers both energy burden and costs, IMP maximizes energy savings but may increase financial stress, and EFF provides a moderate compromise. For both the Amsterdam gas-free policy and AEDES renovation targets, achieving energy efficiency and decarbonisation goals must be complemented by measures that protect low-income households. Furthermore, methodological improvements in income representation are necessary to generate more accurate, socially relevant insights into urban energy transitions.

4.4 Economic and Environmental Trade-Offs of the Renovations

4.4.1 Interpretation of Results

This section discusses the relationship between renovation costs and environmental performance across the prioritization schemes and renovation quota pathways. The analysis combines total renovation expenditure (materials and labour costs) with both operational and material-embedded CO_2 emissions to evaluate cost-efficiency and environmental trade-offs in achieving deep renovation outcomes.

Environmental Flows and Carbon Trade-offs

The results demonstrate that all renovation schemes achieve net negative CO_2 emissions, confirming that renovation activities significantly improve the environmental performance of Amsterdam's SHA housing stock. Operational CO_2 emissions related to heating demand are consistently reduced in all scenarios, with the IMP scheme delivering the largest overall reduction, while the BUR and EFF schemes achieve more tame reductions. The reductions are smaller in the MID and LOW pathways but still noticeable. However, these operational gains are partially offset by material-embedded CO_2 emissions, which reflect the environmental cost of producing and installing renovation materials. Embedded emissions are particularly pronounced in the IMP scheme compared to the BUR and EFF. Despite these embedded impacts, the operational reductions outweigh material emissions by several orders of magnitude, by a factor of approximately 10^5, indicating that renovation benefits dominate in the long term. A key finding is that IMP's improved operational performance comes at a higher embodied carbon cost, resulting from the intensive use of materials and technologies required for deep heating system upgrades and renewable energy integration (packages P01 and P02). In contrast, BUR achieves a more balanced outcome, combining substantial operational reductions with lower material-embedded emissions. The EFF scheme aligns closely with BUR in terms of environmental performance, although in high renovation quota pathways (NPA and MID) it shows slightly increased material emissions. Reflecting the selection of renovation packages from Section 4.1. This highlights that while deep renovations quotas and more intense packages are effective in reducing operational CO_2, they can also generate larger embodied carbon flows that diminish short-term environmental gains.

Renovation Costs and Economic Implications

Renovation cost analysis reveals clear differences in economic performance across schemes. The EFF scheme demonstrates the lowest total renovation costs in all pathways confirming its focus on cost efficiency. The IMP scheme consistently shows the highest total renovation costs. The BUR scheme occupies an intermediate position balancing affordability and performance. Interestingly, the MID pathway, which represents an even 50:50 split between deep and limited renovation jumps, results in the highest total costs for both BUR and MIP. Material expenditures in this pathway reach €7.94×10^{10} for BUR and €8.82×10^{10} for MIP, while labour costs peak at €3.27×10^{10} and €3.49×10^{10}, respectively. This finding was unexpected, as the MID pathway was designed to represent a cost-moderate balance between the limited and deep renovation quotas. In contrast, the LOW and NPA pathways show better cost performance despite their differing renovation intensities. The LOW pathway benefits from limited intervention costs, while the NPA pathway gains from improving heating efficiencies and reducing per-residential unit costs due to the concentration of deep renovations quota. These results imply that renovation pathway that favours one renovation type, either deep or limited, are more cost-effective than mixed-depth approaches.

Integrating Cost and Environmental Dimensions

When comparing environmental and economic performance, distinct trade-offs emerge between schemes. The IMP scheme offers the strongest environmental benefits, achieving the largest operational CO_2 reductions, but at the highest total cost and with significant embodied carbon inflows. This suggests that achieving deep decarbonization through highly technological or renewable-heavy solutions may come with financial and material burdens. The BUR scheme demonstrates a more balanced outcome, achieving large emission reductions while maintaining moderate renovation costs and lower embodied carbon impacts. This makes BUR an appealing middle-ground option for long-term sustainability and affordability goals. The EFF scheme, although the most financially efficient, achieves slightly smaller operational CO_2 reductions. From a systems perspective, the comparison reveals that while embodied emissions from renovation materials are small relative to operational emission savings, they are not negligible. Over time, as operational emissions decrease due to energy transitions, embodied impacts will become a more dominant share of total life-cycle emissions [84]. Therefore, future renovation schemes should increasingly emphasize low-carbon material selection and circular construction practices to preserve net environmental gains.

4.4.2 Implication for Policy

For policy and planning, these findings imply that large-scale renovation programs should account for embodied carbon impacts alongside operational savings to avoid carbon shifting between energy use and construction materials. However, as of 2025, the material embedded emissions lag the gains from the heating systems, making them insignificant when compared with the emission reduction from using new heating systems. At the same time, prioritization schemes must optimize both cost-effectiveness and carbon performance to ensure a just and sustainable transition of the housing stock toward 2050 climate targets.

4.4.3 Implication for the Scientific Community

While these results highlight important links between renovation quotas and prioritisation schemes with emissions and costs of renovations, further work is needed to refine the model and better quantify the magnitude of impacts. The analysis accounted for basic material-embedded emissions but did not consider the full life cycle of products. For instance, the model included emissions from primary materials (e.g., EPS for insulation) but excluded the production of the final panels and material transportation. A comprehensive life-cycle assessment could reveal higher emissions for some insulation products, depending on processing and manufacturing requirements. Additionally, each ESM was represented by a single insulation material, which oversimplifies reality. Future studies should include market research on commonly used materials and sensitivity analyses to assess how material choice may influence results, potentially more than prioritisation schemes or renovation pathways.

And lastly, the model assumed no changes in occupant behaviour over the 25-year period with regards to their heating and ventilation tendencies. In reality, maintenance and occupant behaviour can strongly affect both energy consumption and associated CO_2 emissions (e.g., thermostat settings, ventilation habits, occupancy patterns) [85], [86]. A thorough assessment of the effectiveness of the prioritisation schemes should therefore include a dedicated analysis of tenant behaviour over time, as this could significantly alter the projected outcomes of renovations.

Overall, these limitations highlight opportunities for future research to adopt a full life-cycle perspective, explore material variability, and incorporate behavioural dynamics to improve the accuracy and robustness of renovation impact assessments.

4.5 General Limitations of the MFA and Modelling

The modelling approach adopted in this study relies on several assumptions and simplifications that, while necessary for consistency and data completeness, introduce a degree of uncertainty to the results. This section discusses the main limitations of the analysis, particularly those related to the estimation of missing energy labels, typological aggregation, and data availability for specific renovation packages and components.

First Round of Renovations Only

As stated in the Section 4.1, this analysis focuses exclusively on the material, economic, and environmental flows associated with the initial round of renovations of the SHA residential units. It does not account for ongoing maintenance activities or component replacements that may occur in the years following the renovation. As a result, components with relatively short service lives, which may require replacement within the 2025–2050 period, are not included in this assessment, and sequential renovation cycles are also not modelled. These aspects should be addressed in future research to provide a more thorough understanding of long-term impacts of on-going sequential improvements and renovations.

Assumptions on Missing Energy Labels

A core assumption in this study concerns the treatment of residential units without registered energy labels. It was assumed that these units have remained in their original condition since construction and therefore correspond to the unrenovated state ES. While this assumption allowed a consistent labelling of all residential units in the dataset, it introduces potential bias. In practice, many of these homes may have undergone partial or undocumented renovations, particularly prior to resale or rental, given that key building components such as windows, boilers, or roofing typically have a technical lifespan of 25–30 years. Consequently, this assumption likely leads to an underestimation of the true energy performance of a portion of the stock. To mitigate this, label-less units were matched with RVO's data to get a proxy energy label. While this approach ensures internal consistency, it may mask small-scale and heterogeneous retrofit activity. Moreover, energy label estimation was based exclusively on space heating demand per square meter, rather than the full Dutch energy label-calculation methodology (NTA 8800). As a result, other relevant factors, such as domestic hot water demand, ventilation losses, internal heat gains, and occupant behaviour, were not considered. This simplification may underestimate or overestimate performance for certain dwelling archetypes.

Data and Typological Limitations

Several typological simplifications were necessary due to data constraints within the BAG and ESRI datasets. All apartments were categorised under the galerijwoning (corridor-access apartment) archetype, despite the RVO classification distinguishing between galerijwoningen, portiekwoningen (stairwell-access flats), and maisonnettes. This aggregation was implemented to maintain consistency but inevitably reduces typological accuracy. These subtypes differ in geometry, envelope area ratios, and internal layout (all factors that influence heating demand and energy performance). Therefore, the assumption introduces uncertainty and may result in typology-driven deviations in the calculated space heating demand. Future analyses with higher-resolution typological data should aim to disaggregate these subtypes for improved representativeness.

Similarly, the construction period category "before 1946" was expanded to include buildings constructed from 1800 onward. This broader grouping may include historical or heritage buildings subject to non-standard renovation restrictions, such as façade preservation or material conservation requirements. These constraints may limit the applicability of conventional ESMs and result in atypical performance characteristics. Future studies should therefore consider separating heritage buildings and integrating regulatory or conservation constraints into their retrofit modelling. Additionally, the "2015–2018" construction period was extended up to 2025, under the assumption that buildings constructed after 2018 follow similar building regulations and thermal standards.

Exclusion of RVO's Renovation Package P03 and Energy Labels Above "A"

The RVO renovation package P03, which includes advanced ventilation upgrades (e.g. transitioning from mechanical exhaust to balanced ventilation with heat recovery), was excluded from the analysis because the energy label ranges, which use the energy index proxy, do not take into account energy labels above 'A'. This means that the potential influence of deeper and available renovations was not considered. This could be addressed in a subsequent study if the calculation and estimation of the energy label were more precise for higher energy labels.

Behavioural and Institutional Constraints

The analysis does not consider tenant willingness or approval for renovation measures. Under the Dutch Civil Code, any energy retrofit project requires at least 70% tenant approval [87]. These social and institutional constraints can significantly delay or restrict the practical implementation of large-scale renovation programmes. Therefore, while the technical potential modelled here is informative, real-world feasibility is dependent upon social acceptance and affordability considerations that fall outside the scope of this analysis.

A further limitation arises from the assumption that the Amsterdam heat transition plan will progress according to its stated timeline and objectives. The renovation modelling and associated energy system transitions in this study are based on the plan's projected phasing out of natural gas and the expansion of district heating and other low-carbon technologies. However, in practice, the rollout of this plan has already experienced delays and logistical challenges, particularly related to funding availability, infrastructure development, and coordination between stakeholders. As noted in the City of Amsterdam's own evaluation report, the municipality has insufficient means to bear the full burden of the district heating network expansion, asking for the national government to step up their financial support. This highlights a critical clash between technical feasibility and financial capacity. The assumption of smooth implementation overlooks these socio-political and financial uncertainties, which could delay or alter the pace at which households transition to low-carbon heating. Therefore, while the current modelling reflects the intended direction of Amsterdam's heat transition, the real-world trajectory is likely to diverge from the planned schedule. This creates a degree of policy-induced uncertainty in the timing and magnitude of operational CO_2 emission reductions modelled here. Future studies should therefore incorporate scenario-based sensitivity analyses that consider varying rates of the plan's implementation or potential deviations in the energy carrier mix (e.g., slower-than-expected district heating expansion or increased reliance on electric heat pumps)

5 CONCLUSION

This study provides a comprehensive analysis of the trade-offs involved in energy renovations of Amsterdam's social housing stock between 2025 and 2050, examining different prioritisation schemes (BUR, IMP, and EFF) across multiple renovation quota pathways (LOW, MID, NPA). The findings reveal how prioritisation schemes, renovation depth quotas, material flows, energy costs, and carbon emissions interact to shape guiding insights for policymakers, housing associations, and the scientific community.

5.1 Prioritisation Schemes and Renovation Deepness

How are renovation packages distributed across the housing stock renovation prioritisation schemes in different renovation quota pathways? Which dwelling types are prioritized?

The choice of prioritisation scheme shapes the allocation of renovation packages. BUR scheme, oriented toward households with the highest energy burden, consistently prioritises foundational envelope upgrades (P00, P01), ensuring that poorly insulated homes receive essential improvements before system transitions. The scheme does put to aside the renewable energy transition in the residential housing sector but elevates the worst-performing residential units to adequate envelop insulation. IMP schemes, which maximise emissions reductions, favour renewable heating system transitions (P02) and higher-impact packages, often at the expense of homes with low initial energy performance. So whilst there is a push forward on the gas-free movement from Amsterdam, not the most pressing units are prioritised in terms of energy performance, as IMP seems to renovate units that have already had some work done on them. EFF scheme balances cost efficiency and energy consumption reductions, progressively shifting from envelope-focused like the BUR scheme to more system-focused interventions, like the IMP scheme, as renovation quotas increase.

High deep-renovation quotas amplify the differences between the scheme: BUR remains envelope-focused, IMP becomes increasingly selective and the P02 renovation package which is the electrification-driven on dominates, and EFF transitions toward system upgrades while maintaining some envelope improvements. Apartment buildings dominate renovations due to stock composition and cost-effectiveness.

5.2 Material Inflows, Outflows, and Stock Accumulation

What materials are required under each prioritisation scheme, and how do material inflows and outflows differ between renovation depths in terms of quantity at material and component level?

Material consumption is closely linked to the type and depth of renovations jumps. IMP schemes, which favour intensive packages, exhibit the highest material inflows and outflows, while BUR and EFF schemes generally consume fewer resources. Interestingly, net material accumulation declines as renovation package intensity increases: So for IMP where P02 is dominant, the outflows are closer to the inflows than the other two schemes, this is because the approach is more of a "discard the old, put new in" approach where the existing components such as the heating systems are taken out completely and replaced by new ones. BUR and EFF build up on the layering of new materials on top of old one, with the outflows being the envelop insulation materials that are not up to standard or have been damaged, which tends to be a small share of the one staying in. Component-wise, envelope components, particularly windows, floors, and roofs, dominate material flows, whereas heating and ventilation systems contribute minimally by mass alone.

5.3 Energy Burden and Household Affordability

How do the different renovation schemes and pathways impact energy costs and affordability for vulnerable households?

The study reveals a critical tension between energy savings and household affordability. While IMP schemes achieve the largest reductions in energy consumption, operational costs of renewable heating sources and electrified systems can increase household energy burden, disproportionately affecting lower-income tenants. BUR schemes effectively reduce both energy consumption and household energy costs, as it remains sourced by high efficient gas boilers. Gas is still the cheaper option compared to the distric heating costs, which provides a more affordable outcome for the tenants. EFF schemes offer a moderate compromise between IMP and BUR, mixing affordability with slowly transitioning to renewables.

The interaction between renovation pathways and prioritisation schemes scales these effects up: higher deep-renovation quotas improve overall energy performance but can lead to a higher uptake of renewables and therefore higher energy costs, leading to worse energy burdens on the tenants. Policy design must therefore integrate household affordability into renovation programmes, for example through burden-sensitive prioritisation, phased rollouts, and targeted financial support. Affordability and feasibility of district heating, which is currently more expensive than in other European countries, are particularly important to ensure that decarbonisation does not create social regressivity.

5.4 Economic and Environmental Trade-Offs

What are the total renovation costs in the different schemes and pathways and how do these renovations impact both embodied carbon emissions from building materials and operational CO_2 reductions from heating and ventilation?

Renovation cost and environmental performance analyses show the usual trade-offs. IMP schemes deliver the largest operational CO_2 reductions but at the highest total renovation costs and material-embedded emissions. BUR schemes provide a balanced outcome with moderate costs and lower embodied emissions, while EFF schemes prioritise cost efficiency but achieve slightly smaller emissions reductions. Material-embedded CO_2 is currently minor relative to operational savings but will become increasingly significant as energy systems decarbonise, emphasizing the importance of low-carbon material selection and circular construction practices in the future.

An interesting find is that the MID pathway can be less cost-effective than the LOW and NPA pathways dominated by either deep or limited renovations. This shows that the renovation quotas do not simply scale up and down the trade-off depending on the deep renovation share but can have hidden influence on the economic and environmental trade-offs. This case highlighting the importance of carefully aligning renovation schemes and renovation quotas to optimise both financial and environmental outcomes.

5.5 Integrated Conclusion

To what extent do different renovation-prioritisation schemes and renovation quotas influence the trade-offs among energy savings, material use, household energy burden, and carbon emissions in Amsterdam's social housing stock between 2025 and 2050?

In conclusion, renovation schemes for Amsterdam's social housing stock are shaped by a complex interplay of prioritisation schemes and renovation quotas. Their interplay deliver trade-offs within material flows, energy savings, costs, and energy burden of households. BUR prioritisation excels in reducing household energy burden, but has the slowest uptake of renewable heating systems. IMP maximises operational CO_2 reductions but can increase tenant energy costs. And EFF provides a moderate compromise.

High deep-renovation quotas tend to improve decarbonisation but can also increase financial burdens on the tenants if not paired with supportive schemes. Material flows and embodied emissions are closely tied to renovation jump depth, and while currently secondary to operational savings, they will become increasingly significant over time. Effective renovation and decarbonisation strategies must therefore integrate both the quota of deep vs. limited renovations and prioritise in accordance to policies that ensure both ambitious climate goals and fairness for vulnerable populations. This integrated perspective provides a starting point for policymakers and SHAs to start the debate on which houses to prioritise and to what extent they should be renovated to.

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APPENDIX A. DETAILED PRELIMINARY DATA PROCESSING

Appendix A.1. Overview of Datasets and Processing in Model

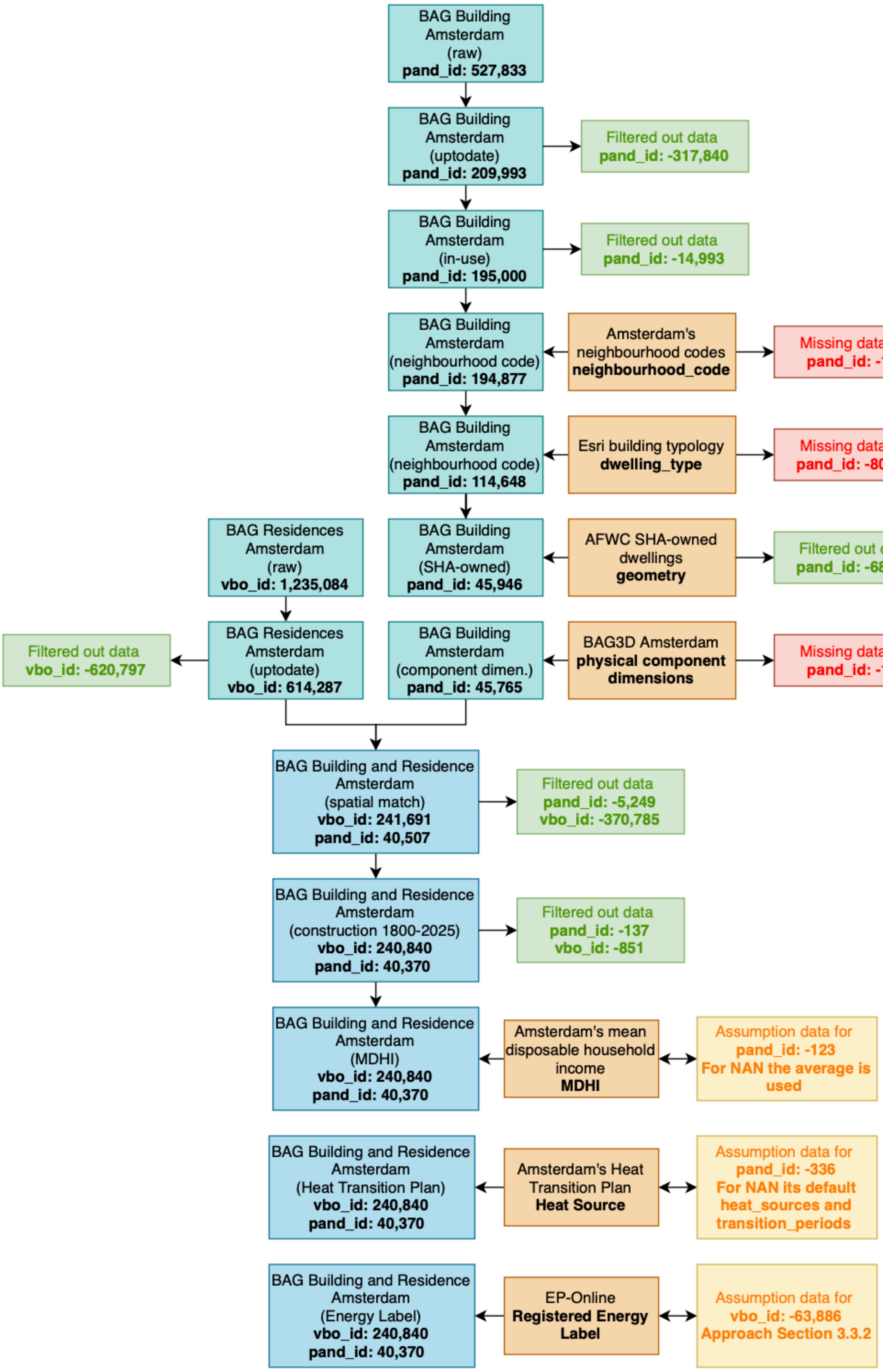

Figure 30: Overview of Dataset Integration in Model

Appendix A.2. BAG Parameters and Data Cleaning Process

For the mapping of the SHA, the BAG was extensively processed to get the most up-to-date in-use buildings in Amsterdam.

Table 21: BAG_PAND, BAG_VBO, and BAG3D_ROOF Database Parameters

Code	Parameter	Description of Values
BAG_PAND	pand_id (‘*identificatie*’)	Unique 16-digit identification number for the building
	version (‘*volgnummer*’)	Ranking digit indicating the version of the registration.
	construction_year (‘*oorspronkelijk_bouwjaar*’)	Year when building was constructed
	status_description (‘*status_omschrijving*’)	building_permit_issued (‘*Bouwvergunning verleend*’) building_in_use (‘*Pand in gebruik*’) building_under_renovation (‘*Verbouwing pand*’) building_demolished (‘*Pand gesloopt*’) construction_started (‘*Bouw gestart*’) building_not_realized (‘*Niet gerealiseerd pand*’) building_in_use_unmeasured (‘*Pand in gebruik (niet ingemeten)*’) building_incorrectly_registered (‘*Pand ten onrechte opgevoerd*’) demolition_permit_issued (‘*Sloopvergunning verleend*’)
	number_of_floors (‘*aantal_bouwlagen*’)	Number of floors in the buildings
	geometry	POLYGON geometry has the coordinate system EPSG:28992. This shows the footprint of the building.
BAG_VBO	vbo_id (‘*identificatie*’)	Unique 16-digit identification number for the residential unit
	version (‘*volgnummer*’)	Ranking digit indicating the version of the registration.
	UFA_m2 (‘*oppervlakte*’)	Usable Floor Area (UFA) in m^2
	geometry	POINT geometry has the coordinate system EPSG:28992. This shows the point location of the residential unit.
BAG3D_ROOF	pand_id (‘*identificatie*’)	Unique 16-digit identification number for the building
	roof_type ('*b3_dak_type*')	The types of roof saved in this parameter are: • pitched (‘slanted’) • flat (‘multiple horizontal’ and ‘horizontal’)
	max_height (‘*b3_h_max*’)	This is the maximum height in a.s.l. meters of the building.
	min_height (‘*b3_h_min*’)	This is the minimum height in a.s.l. meters of the building.
	area_flat_roof_m2 ('*b3_opp_dak_plat*')	Area of flat roof of the **pand_id** (building)
	area_pitched_roof_m2 ('*b3_opp_dak_schuin*')	Area of pitched roof of the **pand_id** (building)
	facade_area_m2 (‘*b3_opp_buitenmuur*’)	Area of façade (external wall) of the **pand_id** (building)

From the Amsterdam Gemeente API data platform [1], both the GeoJSON files for *BAG pand* (building-level registrations) and *BAG vbo* (residential unit-level registrations) are accessible. A preliminary data cleaning step was applied to remove outdated registrations, retaining only the most recent record for each unique building. This filtering process reduced the dataset to *209,993* valid, up-to-date **pand_id** entries. The dataset was further refined based on the **status_description** attribute, which indicates the current registration status of each building. Only buildings registered as '*building_in_use*' were retained for further analysis, resulting in a final subset of *195,000* buildings. This step was needed to ensure that only active, inhabited buildings were considered in the assessment.

Buildings with statuses such as '*demolition_permit_issued*', '*construction_started*', or other non-operational classifications were excluded, as their inclusion could skew the estimation of existing energy conditions and future renovation flows. Additionally, buildings currently under renovation ('*building_under_renovation*') were excluded based on the assumption that such residential units are likely undergoing long-term interventions, which will extend their renovation cycles by more than 30 years, and therefore fall outside the scope of the 2025–2050 renovation timeline considered in this study. The filtering of old registrations was also conducted in the reisdential units BAG dataset.

Each residential unit's POINT geometry was spatially joined to the most relevant building's POLYGON geometry using an intersection-based approach, followed by a proximity refinement using centroid distances. To reduce minor misalignments between geometries, a buffer of 0.1 meters was applied around the residential unit points prior to the spatial join. In cases where multiple buildings intersected with a single residential unit, the building polygon with the nearest centroid was selected to ensure a unique one-to-one matching between residential units (**vbo_ids**) and buildings (**pand_ids**). This approach respects the hierarchical nature of the data: buildings can contain multiple residential units, whereas each residential unit is associated with only one unique building.

Appendix A.3. CBS Socio Economic Data and AFWC SHA Stock Location

The Dutch National Statistics Office CBS (*Centraal Bureau voor de Statistiek*), provides a geospatial database illustrating all neighbourhoods and districts across municipalities in the Netherlands. To later integrate neighbourhood-level data to the analysis, the CBS neighbourhood codes and names were spatially joined to the BAG dataset described above [40]. Using a *'within'* spatial predicate, each building in Amsterdam (represented as a POLYGON geometry) was assigned the corresponding neighbourhood code and name based on its location within the boundaries of the CBS-defined neighbourhood POLYGON geometries. This link ensured that each building has accurate neighbourhood dwelling data for aggregation and analysis at the neighbourhood level.

Table 22: CBS_NEIGHBOR, AMS_MDHI, AFWC_SOCIAL Database Parameters

Code	Parameter	Description of Values
CBS_NEIGHBOR	neighbourhood_code (‘*buurtcode*)	4-digit identification number for the neighbourhood. Ex. AA01, NK03
	neighbourhood_name (‘*buurtnaam’*)	Full name of the neighbourhood. Ex. Weesp Dichtersbuurt
	geometry	POLYGON geometry has the coordinate system EPSG:28992. This shows the footprint of the neighbourhood.
AMS_MDHI	neighbourhood_code (‘*buurtcode*)	4-digit identification number for the neighbourhood. Ex. AA01, NK03
	neighbourhood_name (‘*buurtnaam’*)	Full name of the neighbourhood. Ex. Weesp Dichtersbuurt
	mean_disposable_household_income	This is the mean disposable household income average in each neighbourhood.
AFWC_SOCIAL	geometry	POLYGON and MULTIPOLYGON geometry has the coordinate system EPSG:28992. This shows the footprint of the social housing corporation owned building blocks.

For 123 buildings in the BAG processed data, there is no corresponding neighbourhood code, these were dropped from the analysis.

Neighbourhood-level Mean Disposable Household Income (MDHI) was incorporated into the building stock dataset to support socioeconomic analyses of renovations. Sourced from the Municipality of Amsterdam’s open data platform [42], MDHI values were linked to each residential unit using the unique neighbourhood codes provided by CBS. This approach assumes a uniform income level across all residential units within a neighbourhood, introducing some generalisation but allowing for consistent, spatial-based comparisons between income and building renovations.

The AFWC social housing geospatial data, containing POLYGON and MULTIPOLYGON geometries representing the building blocks owned by the SHAs, was overlaid on the processed BAG dataset. This spatial intersection extracts the social housing buildings based on their spatial location**.** As a result, the total number of buildings included in the social housing analysis amounts to 45,946.

Appendix A.4. Amsterdam's Heat Transition Plan

The geo-spatial and temporal details of Amsterdam's gas-free transition are available through the Gemeente Amsterdam open data API, where a GeoJSON dataset provides information on neighbourhood-level transition planning (See Table 23) [43].

Table 23: Amsterdam's Heat Transition Plan Database and Parameters

Code	Parameter	Description of Values
AMS_HTP	neighbourhood_code (buurcode)	10-digit identification number for the neighbourhood in CBS.
	neighbourhood_name (buurnaam)	Full name of the neighbourhood. Ex. Weesp Dichtersbuurt

	transition_explanation (‘toelichting’)	Description of the heating source that the neighbourhood currently has and wants to transition to, along with the time period this will be accomplished by.
	share_cooking_gas_type (‘aandeel_kookgas’)	Share of cooking gas in the neighbourhood after transition to sustainable heat source
	geometry	POLYGON geometry has the coordinate system EPSG:28992. This shows the footprint of the neighbourhood.

Using the different POLYGON geometries representing different neighbourhood boundaries, a spatial join was performed to associate building-level data from the BAG dataset with the Heat Transition Vision’s heat source information. A ‘*left’* spatial join with the predicate ‘*within’* was executed. This join assigned heat source attributes from neighbourhood polygons to individual building polygons that spatially fell entirely within them. Which integrated analysis of current and target heat sources at the building scale within their respective neighbourhoods. This spatial join allows for a building-level analysis, associating each structure with its respective "from" and "to" heating source according to the municipality’s transition roadmap.

After the spatial joint, there are 336 unmatched buildings that have no data on their heat sources (current and future), however the following default heat sources have filled the rows up. It is assumed that these unknowns transition from a convectional gas network to fully electric heat pump between the years 2025-2050.

Current share of electric heat pumps in Amsterdam

According to CBS, approximately 6.1% of the national social rental residential units are already equipped with electric heat pumps as of 2025. The applicability of eHP is based on the envelop insulation of a dwelling. Given that the only difference between P02 and P01 renovation package is only the adoption of an eHP system, it is assumed that for a house to adopt eHP heating, the envelop insulation must reach a renovation package of P01 to be viable. Therefore, 6.1% of all residential units categorized as P01 were randomly reassigned to P02 and given eHP as their current heating system.

APPENDIX B. RENOVATION PACKAGES

Appendix B.1. RVO’s Adjusted Renovation Packages

Table 24. RVO's Adjusted Renovation Packages

Construction Period	Renovation Status	Dwelling Typology	Heating Demand	UFA	Floor RC	Roof Pitched RC	Roof Flat RC	Wall RC	Window U	Window Type	Window-Facade Ratio	Heating System Type	Energy Index	Energy Label	Ventilation System Type	Ventilation Electricity Use
			kWh/m2]	[m2]	[m2K/W]				[W/m2K]		[m2/m2]					
before_1946	ES	DH	287,73	153,28	0,15	0,35	0,35	0,35	5,10	PVC_1G	0,41	CR-ketel	1,88	D	natural	0
1946_1964	ES	DH	287,73	153,28	0,15	0,35	0,35	0,35	5,10	PVC_1G	0,41	CR-ketel	1,88	D	natural	0
1965_1974	ES	DH	224,85	174,92	0,17	0,43	0,86	0,86	5,10	PVC_1G	0,41	CR-ketel	1,29	B	natural	0
1975_1991	ES	DH	166,91	161,00	0,52	1,30	1,30	1,30	5,10	PVC_1G	0,41	CR-ketel	1,04	A	natural	0
1992_2005	ES	DH	122,16	178,60	2,50	2,50	2,50	2,50	2,90	PVC_2G	0,45	HR107-ketel	0,68	A	type_c	569,4
2006_2014	ES	DH	104,39	201,98	2,50	2,50	2,50	2,50	1,80	ALU_3G	0,45	HR107-ketel	0,52	A	type_c	569,4
2015_now	ES	DH	91,37	194,25	3,50	4,50	6,00	6,00	1,80	ALU_3G	0,45	HR107-ketel	0,47	A	type_c	569,4
before_1946	P00	DH	213,58	153,28	0,15	2,50	0,85	0,35	1,80	ALU_3G	0,41	HR107-ketel	1,39	B	natural	0
1946_1964	P00	DH	213,58	153,28	0,15	2,50	0,85	0,35	1,80	ALU_3G	0,41	HR107-ketel	1,39	B	natural	0
1965_1974	P00	DH	204,89	174,92	0,17	0,43	0,86	0,86	2,90	PVC_2G	0,41	HR107-ketel	1,17	A	natural	0
1975_1991	P00	DH	157,33	161,00	0,52	1,30	1,30	1,30	2,90	PVC_2G	0,41	HR107-ketel	0,98	A	natural	0
1992_2005	P00	DH	122,16	178,60	2,50	2,50	2,50	2,50	2,90	PVC_2G	0,45	HR107-ketel	0,68	A	type_c	569,4
2006_2014	P00	DH	104,39	201,98	2,50	2,50	2,50	2,50	1,80	ALU_3G	0,45	HR107-ketel	0,52	A	type_c	569,4
2015_now	P00	DH	91,37	194,25	3,50	4,50	6,00	6,00	1,80	ALU_3G	0,45	HR107-ketel	0,47	A	type_c	569,4
before_1946	P01	DH	79,46	153,28	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,41	HR107-ketel	0,52	A	type_c	569,4
1946_1964	P01	DH	79,46	153,28	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,41	HR107-ketel	0,52	A	type_c	569,4
1965_1974	P01	DH	72,80	174,92	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,41	HR107-ketel	0,42	A	type_c	569,4
1975_1991	P01	DH	75,34	161,00	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,41	HR107-ketel	0,47	A	type_c	569,4
1992_2005	P01	DH	69,97	178,60	3,50	2,50	3,50	3,50	1,40	PVC_3G	0,45	HR107-ketel	0,39	A	type_c	569,4

2006_2014	P01	DH	68,79	201,98	3,50	2,50	3,50	3,50	1,40	PVC_3G	0,45	HR107-ketel	0,34	A	type_c	569,4
2015_now	P01	DH	64,31	194,25	3,50	4,50	6,00	6,00	1,40	PVC_3G	0,45	HR107-ketel	0,33	A	type_c	569,4
before_1946	P02	DH	79,46	153,28	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,41	ASHP	0,52	A	type_c	569,4
1946_1964	P02	DH	79,46	153,28	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,41	ASHP	0,52	A	type_c	569,4
1965_1974	P02	DH	72,80	174,92	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,41	ASHP	0,42	A	type_c	569,4
1975_1991	P02	DH	75,34	161,00	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,41	ASHP	0,47	A	type_c	569,4
1992_2005	P02	DH	69,97	178,60	3,50	2,50	3,50	3,50	1,40	PVC_3G	0,45	ASHP	0,39	A	type_c	569,4
2006_2014	P02	DH	68,79	201,98	3,50	2,50	3,50	3,50	1,40	PVC_3G	0,45	ASHP	0,34	A	type_c	569,4
2015_now	P02	DH	64,31	194,25	3,50	4,50	6,00	6,00	1,40	PVC_3G	0,45	ASHP	0,33	A	type_c	569,4
before_1946	P03	DH	62,30	153,28	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,41	ASHP	0,41	A	type_d	569,4
1946_1964	P03	DH	62,30	153,28	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,41	ASHP	0,41	A	type_d	569,4
1965_1974	P03	DH	56,01	174,92	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,41	ASHP	0,32	A	type_d	569,4
1975_1991	P03	DH	58,51	161,00	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,41	ASHP	0,36	A	type_d	569,4
1992_2005	P03	DH	54,17	178,60	3,50	2,50	3,50	3,50	1,40	PVC_3G	0,45	ASHP	0,30	A	type_d	569,4
2006_2014	P03	DH	52,73	201,98	3,50	2,50	3,50	3,50	1,40	PVC_3G	0,45	ASHP	0,26	A	type_d	569,4
2015_now	P03	DH	48,69	194,25	3,50	4,50	6,00	6,00	1,40	PVC_3G	0,45	ASHP	0,25	A	type_d	569,4
before_1946	ES	SDH	253,23	122,89	0,15	0,35	0,35	0,35	5,10	PVC_1G	0,41	CR-ketel	2,06	D	natural	0
1946_1964	ES	SDH	253,23	122,89	0,15	0,35	0,35	0,35	5,10	PVC_1G	0,41	CR-ketel	2,06	D	natural	0
1965_1974	ES	SDH	204,90	133,99	0,17	0,43	0,86	0,86	5,10	PVC_1G	0,41	CR-ketel	1,53	C	natural	0
1975_1991	ES	SDH	150,49	129,80	0,52	1,30	1,30	1,30	5,10	PVC_1G	0,41	CR-ketel	1,16	A	natural	0
1992_2005	ES	SDH	107,98	143,90	2,50	2,50	2,50	2,50	2,90	PVC_2G	0,45	HR107-ketel	0,75	A	type_c	569,4
2006_2014	ES	SDH	96,38	152,35	2,50	2,50	2,50	2,50	2,00	ALU_3G	0,45	HR107-ketel	0,63	A	type_c	569,4
2015_now	ES	SDH	75,41	159,89	3,50	4,50	6,00	6,00	1,80	ALU_3G	0,45	HR107-ketel	0,47	A	type_c	569,4
before_1946	P00	SDH	197,00	122,89	0,15	0,35	0,72	2,50	1,80	ALU_3G	0,41	HR107-ketel	1,60	C	natural	0
1946_1964	P00	SDH	197,00	122,89	0,15	0,35	0,72	2,50	1,80	ALU_3G	0,41	HR107-ketel	1,60	C	natural	0
1965_1974	P00	SDH	183,50	133,99	0,17	0,43	0,86	0,86	2,90	PVC_2G	0,41	HR107-ketel	1,37	B	natural	0
1975_1991	P00	SDH	139,06	129,80	1,30	1,30	1,30	1,30	2,90	PVC_2G	0,41	HR107-ketel	1,07	A	natural	0
1992_2005	P00	SDH	107,98	143,90	2,50	2,50	2,50	2,50	2,90	PVC_2G	0,45	HR107-ketel	0,75	A	type_c	569,4
2006_2014	P00	SDH	94,34	152,35	2,50	2,50	2,50	2,50	1,80	ALU_3G	0,45	HR107-ketel	0,62	A	type_c	569,4
2015_now	P00	SDH	72,24	159,89	3,50	4,50	6,00	6,00	1,80	ALU_3G	0,45	HR107-ketel	0,45	A	type_c	569,4

before_1946	P01	SDH	70,58	122,89	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,41	HR107-ketel	0,57	A	type_c	569,4
1946_1964	P01	SDH	70,58	122,89	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,41	HR107-ketel	0,57	A	type_c	569,4
1965_1974	P01	SDH	65,77	133,99	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,41	HR107-ketel	0,49	A	type_c	569,4
1975_1991	P01	SDH	68,13	129,80	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,41	HR107-ketel	0,52	A	type_c	569,4
1992_2005	P01	SDH	62,32	143,90	3,50	2,50	3,50	3,50	1,40	PVC_3G	0,45	HR107-ketel	0,43	A	type_c	569,4
2006_2014	P01	SDH	62,28	152,35	3,50	2,50	3,50	3,50	1,40	PVC_3G	0,45	HR107-ketel	0,41	A	type_c	569,4
2015_now	P01	SDH	51,57	159,89	3,50	4,50	6,00	6,00	1,40	PVC_3G	0,45	HR107-ketel	0,32	A	type_c	569,4
before_1946	P02	SDH	70,58	122,89	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,41	ASHP	0,57	A	type_c	569,4
1946_1964	P02	SDH	70,58	122,89	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,41	ASHP	0,57	A	type_c	569,4
1965_1974	P02	SDH	65,77	133,99	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,41	ASHP	0,49	A	type_c	569,4
1975_1991	P02	SDH	68,13	129,80	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,41	ASHP	0,52	A	type_c	569,4
1992_2005	P02	SDH	62,32	143,90	3,50	2,50	3,50	3,50	1,40	PVC_3G	0,45	ASHP	0,43	A	type_c	569,4
2006_2014	P02	SDH	62,28	152,35	3,50	2,50	3,50	3,50	1,40	PVC_3G	0,45	ASHP	0,41	A	type_c	569,4
2015_now	P02	SDH	51,57	159,89	3,50	4,50	6,00	6,00	1,40	PVC_3G	0,45	ASHP	0,32	A	type_c	569,4
before_1946	P03	SDH	53,29	122,89	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,41	ASHP	0,43	A	type_d	569,4
1946_1964	P03	SDH	53,29	122,89	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,41	ASHP	0,43	A	type_d	569,4
1965_1974	P03	SDH	49,38	133,99	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,41	ASHP	0,37	A	type_d	569,4
1975_1991	P03	SDH	51,35	129,80	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,41	ASHP	0,40	A	type_d	569,4
1992_2005	P03	SDH	46,40	143,90	3,50	2,50	3,50	3,50	1,40	PVC_3G	0,45	ASHP	0,32	A	type_d	569,4
2006_2014	P03	SDH	46,32	152,35	3,50	2,50	3,50	3,50	1,40	PVC_3G	0,45	ASHP	0,30	A	type_d	569,4
2015_now	P03	SDH	34,86	159,89	3,50	4,50	6,00	6,00	1,40	PVC_3G	0,45	ASHP	0,22	A	type_d	569,4
before_1946	ES	AP	176,37	72,75	0,15	0,35	0,35	0,35	5,10	PVC_1G	0,46	CR-ketel	2,42	F	natural	0
1946_1964	ES	AP	176,37	72,75	0,15	0,35	0,35	0,35	5,10	PVC_1G	0,46	CR-ketel	2,42	F	natural	0
1965_1974	ES	AP	144,52	84,00	0,17	0,43	0,86	0,86	5,10	PVC_1G	0,46	CR-ketel	1,72	C	natural	0
1975_1991	ES	AP	104,50	67,25	0,52	1,30	1,30	1,30	5,10	PVC_1G	0,44	CR-ketel	1,55	C	natural	0
1992_2005	ES	AP	75,36	76,70	2,50	2,50	2,50	2,50	2,90	PVC_2G	0,48	HR107-ketel	0,98	A	collective_type_c	3723
2006_2014	ES	AP	68,32	87,55	2,50	2,50	2,50	2,50	2,00	ALU_3G	0,48	HR107-ketel	0,78	A	collective_type_c	3723
2015_now	ES	AP	56,08	82,13	3,50	4,50	6,00	6,00	1,80	ALU_3G	0,48	HR107-ketel	0,68	A	collective_type_c	3723
before_1946	P00	AP	144,55	72,75	0,15	0,35	0,72	0,72	2,90	PVC_2G	0,46	HR107-ketel	1,99	D	natural	0
1946_1964	P00	AP	144,55	72,75	0,15	0,35	0,72	0,72	2,90	PVC_2G	0,46	HR107-ketel	1,99	D	natural	0

1965_1974	P00	AP	111,30	84,00	0,17	0,43	0,86	0,86	2,90	PVC_2G	0,46	CR-ketel	1,32	B	collective_type_c	3723
1975_1991	P00	AP	90,17	67,25	0,52	1,30	1,30	1,30	2,90	PVC_2G	0,44	HR107-ketel	1,34	B	collective_type_c	3723
1992_2005	P00	AP	75,36	76,70	2,50	2,50	2,50	2,50	2,90	PVC_2G	0,48	HR107-ketel	0,98	A	collective_type_c	3723
2006_2014	P00	AP	66,04	87,55	2,50	2,50	2,50	2,50	1,80	ALU_3G	0,48	HR107-ketel	0,75	A	collective_type_c	3723
2015_now	P00	AP	35,03	82,13	3,50	4,50	6,00	6,00	1,80	ALU_3G	0,48	HR107-ketel	0,43	A	collective_type_c	3723
before_1946	P01	AP	42,62	72,75	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,46	HR107-ketel	0,59	A	collective_type_c	3723
1946_1964	P01	AP	42,62	72,75	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,46	HR107-ketel	0,59	A	collective_type_c	3723
1965_1974	P01	AP	39,30	84,00	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,46	HR107-ketel	0,47	A	collective_type_c	3723
1975_1991	P01	AP	43,23	67,25	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,44	HR107-ketel	0,64	A	collective_type_c	3723
1992_2005	P01	AP	38,97	76,70	3,50	2,50	3,50	3,50	1,40	PVC_3G	0,48	HR107-ketel	0,51	A	collective_type_c	3723
2006_2014	P01	AP	40,53	87,55	3,50	2,50	3,50	3,50	1,40	PVC_3G	0,48	HR107-ketel	0,46	A	collective_type_c	3723
2015_now	P01	AP	34,85	82,13	3,50	4,50	6,00	6,00	1,40	PVC_3G	0,48	HR107-ketel	0,42	A	collective_type_c	3723
before_1946	P02	AP	42,62	72,75	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,46	ASHP	0,59	A	collective_type_c	3723
1946_1964	P02	AP	42,62	72,75	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,46	ASHP	0,59	A	collective_type_c	3723
1965_1974	P02	AP	39,30	84,00	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,46	ASHP	0,47	A	collective_type_c	3723
1975_1991	P02	AP	43,23	67,25	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,44	ASHP	0,64	A	collective_type_c	3723
1992_2005	P02	AP	38,97	76,70	3,50	2,50	3,50	3,50	1,40	PVC_3G	0,48	ASHP	0,51	A	collective_type_c	3723
2006_2014	P02	AP	40,53	87,55	3,50	2,50	3,50	3,50	1,40	PVC_3G	0,48	ASHP	0,46	A	collective_type_c	3723
2015_now	P02	AP	34,85	82,13	3,50	4,50	6,00	6,00	1,40	PVC_3G	0,48	ASHP	0,42	A	collective_type_c	3723
before_1946	P03	AP	26,43	72,75	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,46	ASHP	0,36	A	collective_type_d	3723
1946_1964	P03	AP	26,43	72,75	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,46	ASHP	0,36	A	collective_type_d	3723
1965_1974	P03	AP	23,07	84,00	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,46	ASHP	0,27	A	collective_type_d	3723
1975_1991	P03	AP	24,76	67,25	3,50	1,70	3,50	3,50	1,40	PVC_3G	0,44	ASHP	0,37	A	collective_type_d	3723
1992_2005	P03	AP	22,25	76,70	3,50	2,50	3,50	3,50	1,40	PVC_3G	0,48	ASHP	0,29	A	collective_type_d	3723
2006_2014	P03	AP	24,14	87,55	3,50	2,50	3,50	3,50	1,40	PVC_3G	0,48	ASHP	0,28	A	collective_type_d	3723
2015_now	P03	AP	17,78	82,13	3,50	4,50	6,00	6,00	1,40	PVC_3G	0,48	ASHP	0,22	A	collective_type_d	3723
before_1946	ES	MT	234,06	108,96	0,15	0,22	0,22	0,19	5,10	PVC_1G	0,46	CR-ketel	2,15	E	natural	0
1946_1964	ES	MT	199,62	97,87	0,15	0,35	0,22	0,35	5,10	PVC_1G	0,5	CR-ketel	2,04	D	natural	0
1965_1974	ES	MT	163,16	114,90	0,17	0,86	0,22	0,43	5,10	PVC_1G	0,66	CR-ketel	1,42	C	natural	0
1975_1991	ES	MT	121,31	113,60	0,52	1,30	0,22	1,30	5,10	PVC_1G	0,48	CR-ketel	1,07	A	natural	0

1992_2005	ES	MT	92,04	124,45	2,50	2,50	2,50	2,50	2,90	PVC_2G	0,48	CR-ketel	0,74	A	type_c	569,4
2006_2014	ES	MT	74,45	119,13	2,50	2,50	2,50	2,50	1,80	ALU_3G	0,48	HR107-ketel	0,62	A	type_c	569,4
2015_now	ES	MT	68,83	117,00	3,50	6,00	6,00	4,50	1,80	ALU_3G	0,43	HR107-ketel	0,59	A	type_c	569,4
before_1946	P00	MT	160,74	108,96	0,15	2,00	0,35	0,35	2,90	PVC_2G	0,46	HR107-ketel	1,48	C	natural	0
1946_1964	P00	MT	162,53	97,87	0,15	0,72	0,35	0,35	2,90	PVC_2G	0,5	HR107-ketel	1,66	C	natural	0
1965_1974	P00	MT	141,92	114,90	0,17	0,86	0,35	0,43	2,90	PVC_2G	0,66	HR107-ketel	1,24	B	natural	0
1975_1991	P00	MT	108,38	113,60	0,52	1,30	0,35	1,30	2,90	PVC_2G	0,48	HR107-ketel	0,95	A	type_c	569,4
1992_2005	P00	MT	81,44	124,45	2,50	2,50	2,50	2,50	1,80	ALU_3G	0,48	HR107-ketel	0,65	A	type_c	569,4
2006_2014	P00	MT	74,45	119,13	2,50	2,50	2,50	2,50	1,80	ALU_3G	0,48	HR107-ketel	0,62	A	type_c	569,4
2015_now	P00	MT	68,83	117,00	3,50	6,00	6,00	4,50	1,80	ALU_3G	0,43	HR107-ketel	0,59	A	type_c	569,4
before_1946	P01	MT	55,84	108,96	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,46	HR107-ketel	0,51	A	type_c	569,4
1946_1964	P01	MT	53,57	97,87	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,5	HR107-ketel	0,55	A	type_c	569,4
1965_1974	P01	MT	51,28	114,90	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,66	HR107-ketel	0,45	A	type_c	569,4
1975_1991	P01	MT	51,36	113,60	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,48	HR107-ketel	0,45	A	type_c	569,4
1992_2005	P01	MT	51,01	124,45	3,50	3,50	3,50	2,50	1,40	PVC_3G	0,48	HR107-ketel	0,41	A	type_c	569,4
2006_2014	P01	MT	49,63	119,13	3,50	3,50	3,50	2,50	1,40	PVC_3G	0,48	HR107-ketel	0,42	A	type_c	569,4
2015_now	P01	MT	46,78	117,00	3,50	6,00	6,00	4,50	1,40	PVC_3G	0,43	HR107-ketel	0,40	A	type_c	569,4
before_1946	P02	MT	55,84	108,96	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,46	ASHP	0,51	A	type_c	569,4
1946_1964	P02	MT	53,57	97,87	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,5	ASHP	0,55	A	type_c	569,4
1965_1974	P02	MT	51,28	114,90	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,66	ASHP	0,45	A	type_c	569,4
1975_1991	P02	MT	51,36	113,60	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,48	ASHP	0,45	A	type_c	569,4
1992_2005	P02	MT	51,01	124,45	3,50	3,50	3,50	2,50	1,40	PVC_3G	0,48	ASHP	0,41	A	type_c	569,4
2006_2014	P02	MT	49,63	119,13	3,50	3,50	3,50	2,50	1,40	PVC_3G	0,48	ASHP	0,42	A	type_c	569,4
2015_now	P02	MT	46,78	117,00	3,50	6,00	6,00	4,50	1,40	PVC_3G	0,43	ASHP	0,40	A	type_c	569,4
before_1946	P03	MT	39,02	108,96	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,46	ASHP	0,36	A	type_d	569,4
1946_1964	P03	MT	37,16	97,87	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,5	ASHP	0,38	A	type_d	569,4
1965_1974	P03	MT	34,88	114,90	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,66	ASHP	0,30	A	type_d	569,4
1975_1991	P03	MT	34,45	113,60	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,48	ASHP	0,30	A	type_d	569,4
1992_2005	P03	MT	34,96	124,45	3,50	3,50	3,50	2,50	1,40	PVC_3G	0,48	ASHP	0,28	A	type_d	569,4
2006_2014	P03	MT	33,46	119,13	3,50	3,50	3,50	2,50	1,40	PVC_3G	0,48	ASHP	0,28	A	type_d	569,4

2015_now	P03	MT	30,41	117,00	3,50	6,00	6,00	4,50	1,40	PVC_3G	0,43	ASHP	0,26	A	type_d	569,4
before_1946	ES	ET	312,84	110,75	0,15	0,22	0,22	0,19	5,10	PVC_1G	0,33	CR-ketel	2,82	G	natural	0
1946_1964	ES	ET	258,12	100,90	0,15	0,35	0,35	0,35	5,10	PVC_1G	0,31	CR-ketel	2,56	F	natural	0
1965_1974	ES	ET	205,35	115,96	0,17	0,86	0,35	0,43	5,10	PVC_1G	0,41	CR-ketel	1,77	C	natural	0
1975_1991	ES	ET	144,97	112,97	0,52	1,30	0,35	1,30	5,10	PVC_1G	0,28	CR-ketel	1,28	B	natural	0
1992_2005	ES	ET	110,73	128,79	2,50	2,50	2,50	2,50	2,90	PVC_2G	0,3	CR-ketel	0,86	A	type_c	569,4
2006_2014	ES	ET	91,77	136,67	2,50	2,50	2,50	2,50	1,80	ALU_3G	0,32	HR107-ketel	0,67	A	type_c	569,4
2015_now	ES	ET	79,35	119,70	3,50	6,00	2,50	4,50	1,80	ALU_3G	0,27	HR107-ketel	0,66	A	type_c	569,4
before_1946	P00	ET	259,57	110,75	0,15	0,22	0,35	0,35	2,90	PVC_2G	0,33	HR107-ketel	2,34	E	natural	0
1946_1964	P00	ET	208,22	100,90	0,15	0,85	0,35	0,35	2,90	PVC_2G	0,31	HR107-ketel	2,06	D	natural	0
1965_1974	P00	ET	183,59	115,96	0,17	0,86	0,35	0,43	2,90	PVC_2G	0,41	HR107-ketel	1,58	C	natural	0
1975_1991	P00	ET	132,32	112,97	0,52	1,30	0,35	1,30	2,90	PVC_2G	0,28	HR107-ketel	1,17	A	type_c	569,4
1992_2005	P00	ET	110,73	128,79	2,50	2,50	2,50	2,50	1,80	ALU_3G	0,3	HR107-ketel	0,86	A	type_c	569,4
2006_2014	P00	ET	91,77	136,67	2,50	2,50	2,50	2,50	1,80	ALU_3G	0,32	HR107-ketel	0,67	A	type_c	569,4
2015_now	P00	ET	79,35	119,70	3,50	6,00	2,50	4,50	1,80	ALU_3G	0,27	HR107-ketel	0,66	A	type_c	569,4
before_1946	P01	ET	73,82	110,75	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,33	HR107-ketel	0,67	A	type_c	569,4
1946_1964	P01	ET	70,49	100,90	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,31	HR107-ketel	0,70	A	type_c	569,4
1965_1974	P01	ET	65,02	115,96	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,41	HR107-ketel	0,56	A	type_c	569,4
1975_1991	P01	ET	66,26	112,97	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,28	HR107-ketel	0,59	A	type_c	569,4
1992_2005	P01	ET	64,81	128,79	3,50	3,50	3,50	2,50	1,40	PVC_3G	0,3	HR107-ketel	0,50	A	type_c	569,4
2006_2014	P01	ET	61,54	136,67	3,50	3,50	3,50	2,50	1,40	PVC_3G	0,32	HR107-ketel	0,45	A	type_c	569,4
2015_now	P01	ET	55,42	119,70	3,50	6,00	3,50	4,50	1,40	PVC_3G	0,27	HR107-ketel	0,46	A	type_c	569,4
before_1946	P02	ET	73,82	110,75	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,33	ASHP	0,67	A	type_c	569,4
1946_1964	P02	ET	70,49	100,90	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,31	ASHP	0,70	A	type_c	569,4
1965_1974	P02	ET	65,02	115,96	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,41	ASHP	0,56	A	type_c	569,4
1975_1991	P02	ET	66,26	112,97	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,28	ASHP	0,59	A	type_c	569,4
1992_2005	P02	ET	64,81	128,79	3,50	3,50	3,50	2,50	1,40	PVC_3G	0,3	ASHP	0,50	A	type_c	569,4
2006_2014	P02	ET	61,54	136,67	3,50	3,50	3,50	2,50	1,40	PVC_3G	0,32	ASHP	0,45	A	type_c	569,4
2015_now	P02	ET	55,42	119,70	3,50	6,00	3,50	4,50	1,40	PVC_3G	0,27	ASHP	0,46	A	type_c	569,4
before_1946	P03	ET	56,60	110,75	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,33	ASHP	0,51	A	type_d	569,4

1946_1964	P03	ET	53,89	100,90	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,31	ASHP	0,53	A	type_d	569,4
1965_1974	P03	ET	48,71	115,96	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,41	ASHP	0,42	A	type_d	569,4
1975_1991	P03	ET	49,40	112,97	3,50	3,50	3,50	1,70	1,40	PVC_3G	0,28	ASHP	0,44	A	type_d	569,4
1992_2005	P03	ET	48,87	128,79	3,50	3,50	3,50	2,50	1,40	PVC_3G	0,3	ASHP	0,38	A	type_d	569,4
2006_2014	P03	ET	45,75	136,67	3,50	3,50	3,50	2,50	1,40	PVC_3G	0,32	ASHP	0,33	A	type_d	569,4
2015_now	P03	ET	39,24	119,70	3,50	6,00	3,50	4,50	1,40	PVC_3G	0,27	ASHP	0,33	A	type_d	569,4

APPENDIX C. MATERIAL COMPOSITION AND RENOVATION TYPES FOR ENVELOP COMPONENTS

Appendix C.1. Envelop Component Material Inventory

Table 25. Envelop Component Material Density and Thermal Conductivity

Comp.	Comp. specifics	Renovation type	Material	Density kg/m^3	Thermal conductivity W/mK
wall	No cavity	External wall insulation	Glass wool	26,5	0,034
wall	No cavity	Internal wall insulation	Rock wool	57,5	0,034
wall	cavity	Cavity wall insulation	White eps	15,8	0,038
roof	pitched	Cold roof insulation	PUR or PIR	31,5	0,026
roof	pitched	Warm roof insulation	Glass wool	26,5	0,034
roof	Flat	Cold roof insulation	PUR or PIR	31,5	0,026
roof	Flat	Warm roof insulation	PUR or PIR	31,5	0,026
floor	No crawl space	Floor overlay insulation	White eps	15,8	0,038
floor	Crawl space available	Floor crawl space insulation	PUR or PIR	31,5	0,026
floor	Likely no crawl space	Floor overlay insulation	White eps	15,8	0,038
floor	Likely no crawl space	Floor crawl space insulation	PUR PIR	31,5	0,026

Comp.	Comp. specifics	Renovation type	Insulation Mat.	Description	Add. Mat	Weight kg/m^2
wall	No cavity	External wall insulation	Glass wool	Render	Silicone	2,5
wall	No cavity	External wall insulation	Glass wool	Primer	Cerplast	0,3
wall	No cavity	External wall insulation	Glass wool	Reinforcing mesh	Glass fiber	0,165
wall	No cavity	Internal wall insulation	Rock wool	Plasterboard	Plasterboard	0,2016
wall	No cavity	Internal wall insulation	Rock wool	Metal studs	steel	0,58
wall	No cavity	Internal wall insulation	Rock wool	Vapor barrier	polyethylene	0,75
wall	cavity	Cavity wall insulation	White eps	Adhesive	EPS bonding agent	0
roof	pitched	Cold roof insulation	PUR or PIR	Ceiling board	Plasterboard	0,1008
roof	pitched	Cold roof insulation	PUR or PIR	Breathable membrane	Polyethylene	0,75
roof	pitched	Warm roof insulation	PUR or PIR	Tiles	Clay	45,65
roof	pitched	Warm roof insulation	PUR or PIR	Battens tiles support	Wood	2,08
roof	pitched	Warm roof insulation	PUR or PIR	Vapor barrier	Polyethylene	0,75
roof	pitched	Warm roof insulation	PUR or PIR	Decking	OSB	9
roof	Flat	Cold roof insulation	PUR or PIR	Roof membrane	Bitumen	5
roof	Flat	Cold roof insulation	PUR or PIR	Ceiling board	Plasterboard	0,1008
roof	Flat	Warm roof insulation	PUR or PIR	Roof membrane	Bitumen	5
roof	Flat	Warm roof insulation	PUR or PIR	Vapor barrier	Polyethylene	0,75
roof	Flat	Warm roof insulation	PUR or PIR	Roofing	PVC	3,5

roof	Flat	Warm roof insulation	PUR or PIR	Decking	OSB	9
floor	No crawl space	Floor overlay insulation	White eps	Chipboard overlay	Wood	9
floor	No crawl space	Floor overlay insulation	White eps	Damp proof layer	Polyethylene	0,75
floor	No crawl space	Floor overlay insulation	White eps	Floor finish	Laminate	4
floor	Crawl space available	Floor crawl space insulation	PUR or PIR	Support mesh	Galvanized steel	0,3
floor	Crawl space available	Floor crawl space insulation	PUR or PIR	Vapor barrier	Polyethylene	0,75
floor	Crawl space available	Floor crawl space insulation	PUR or PIR	Subfloor	OSB	9
floor	Likely no crawl space	Floor overlay insulation	White eps	Chipboard overlay	Wood	9
floor	Likely no crawl space	Floor overlay insulation	White eps	Damp proof layer	Polyethylene	0,75
floor	Likely no crawl space	Floor overlay insulation	White eps	Floor finish	Laminate	4
floor	Likely no crawl space	Floor crawl space insulation	PUR or PIR	Support mesh	Galvanized steel	0,3
floor	Likely no crawl space	Floor crawl space insulation	PUR or PIR	Vapor barrier	Polyethylene	0,75
floor	Likely no crawl space	Floor crawl space insulation	PUR or PIR	Subfloor	OSB	9

Appendix C.2. Windows Material Inventory

Table 26. Material Composition of Windows

Material	PVC3G	PVC2G	PVC1G	ALU3G
Glass	19,61	13,07	6,53	22,52
PVC	12,44	12,44	12,44	0,39
Galvanized steel	7,98	7,98	7,98	2,02
TPE	0,40	0,40	0,40	0,40
Aluminum	0,66	0,33	0,00	9,97
Stainless steel	0,20	0,20	0,20	0,20
Artificial integrated abs copolymer	0,00	0,00	0,00	2,26
Polyurethane foam	0,00	0,00	0,00	0,60

Appendix C.3. Heating and Ventilation Systems Material Inventory

The material composition and associated environmental impacts of the heating systems are based on data derived from Neumann et al. (2022) an LCA study of heating technologies in Germany [88]. It is assumed that the material composition of the CR boiler is the same as that of the HR107. Additionally, the HIU's material composition was based on the total weight of the unit and the common types of material used for its different components. There is unfortunately a lack of detailed data on HIU material composition and weight distribution, therefore assumptions had to be made. The material composition estimates for HIU weight of approximately 35 kg [89], which is representative of a standard indirect 40-plate HIU with integrated control valves, metering, and casing)

The breakdown assumes a typical distribution of materials according to the functional components of the unit.

- Copper is primarily used in electrical wiring and brazing within the heat exchanger, accounting for roughly 3% of the total mass.
- Brass, present in valves, strainers, and fittings, constitutes an estimated 9% due to its common use in plumbing-grade components.
- Steel, mainly in the mounting plates and fasteners, contributes approximately 6% of the total weight. The most significant material by mass is stainless steel, used in the plate heat exchanger core and internal pipework, making up around 43% of the HIU.
- Silicone, often used for wire sheathing or sealant purposes, is assumed to be negligible in mass due to its minimal volume and weight contribution.
- EPDM rubber, used in gaskets and O-rings, represents about 0.5% of the total weight.
- Plastics such as ABS and PVC are used in valve caps, electronic enclosures, and some insulation, contributing approximately 1.5% and 0.5% of the total weight respectively.
- Electronic components, including PCBs, flow sensors, control meters, and wiring, are estimated to comprise around 3% of the total mass.

Table 27. Material Composition of Heating Systems

Material	CR-ketel	HR107-ketel	HR107-ketel RG	ASHP	ASHP RG	DistH
Copper	2,290	2,290	2,290	36,600	36,600	1,000
Brass	3,215	3,215	3,215	0,000	0,000	3,000
Aluminium	1,905	1,905	1,905	0,000	0,000	0,000
Steel	22,879	22,879	22,879	32,000	32,000	2,000
Stainless steel	6,736	6,736	6,736	0,000	0,000	15,000
Silicone	0,115	0,115	0,115	0,000	0,000	0,000
EPDM	0,064	0,064	0,064	0,000	0,000	0,200
ABS	1,171	1,171	1,171	0,000	0,000	0,500
PVC	0,005	0,005	0,005	1,600	1,600	0,200
Electronic components	0,248	0,248	0,248	0,000	0,000	1,000
HDPE	0,000	0,000	0,000	0,500	0,500	0,000
Rock wool	0,000	0,000	0,000	0,000	0,000	0,000
Reinforcing steel	0,000	0,000	0,000	120,000	120,000	0,000
Elastomer	0,000	0,000	0,000	16,000	16,000	0,100
Polyester oil	0,000	0,000	0,000	2,700	2,700	0,000
R 134a	0,000	0,000	0,000	4,900	4,900	0,000

Table 28. Material Composition of Ventilation Systems

Material	Natural	Type c	Collective type c
Galvanized steel	0,00	0,25	55,69
Polypropylene	0,00	1,55	4,03
ABS	0,00	0,25	0,30
Aluminium	0,00	0,10	1,77
Polystyrene	0,00	1,10	0,00

HDPE	0,00	0,20	0,30
Steel	0,00	0,53	0,89
Stainless steel	0,00	0,09	0,15
Copper	0,00	0,46	1,03
Polyamide	0,00	0,22	0,30
PWB	0,00	0,10	0,71
Electronic components	0,00	0,25	1,96
EPDM	0,00	0,00	0,71

APPENDIX D. ECONOMIC AND ENVIRONMENTAL IMPACTS OF ESMS

Appendix D.1. Material Environmental and Economic Factors

Table 29. Environmental Factor and Economic Factor of Insulation Materials from Ecoinvent

Material	EF [CO_2/kg]	Cost [€/kg]	Reference Product	Unit	Time	Sector	Geo	Ref.
Glass wool	0,633	1,770	glass wool mat, uncoated, Saint-Gobain ISOVER SA	kg	2018-2024	Cement & Concrete	CH	[90]
PUR or PIR	4,230	1,290	polyurethane production, rigid foam	kg	1997-2024	Chemicals	RER	[91]
EPS	0,267	1,770	expanded perlite production	kg	1995-2024	Cement & Concrete; Minerals	CH	[92]
Rock wool	1,099	0,650	stone wool	kg	2000-2024	Cement & Concrete	CH	[93]
White EPS	0,267	1,770	expanded perlite production	kg	1995-2024	Cement & Concrete; Minerals	CH	[92]

Table 30. Environmental Factor and Economic Factor of Additional Materials from Ecoinvent

Material	EF [CO_2/kg]	Cost [€/kg]	Reference Product	Unit	Time	Sector	Geo	Ref.
Silicone	2,97	0,47	silicone product production	kg	1997-2024	Chemicals	RER	[94]
Cerplast	0,40	0,09	pultrusion, thermoset resins	kg	2019-2025	Chemicals	RoE	[95]
Glass fiber	2,12	0,80	glass fibre	kg	2000-2024	Minerals	RER	[96]
Plasterboard	0,14	0,18	gypsum plasterboard	kg	1997-2024	Cement & Concrete	CH	[97]
Steel	1,74	0,47	steel production, converter, unalloyed	kg	2013-2024	Metals	RER	[98]
Polyethylene	3,40	2,97	packaging film production, low density polyethylene	kg	1993-2024	Chemicals	RER	[99]
EPS bonding agent	4,16	2,54	non-ionic surfactant production, ethylene oxide derivate	kg	2015-2024	Chemicals	GLO	[100]
Clay	0,36	0,09	clay roof tile production	kg	1992-2024	Minerals; Cement & Concrete	RER	[101]
Wood	0,01	0,00	wood chipping, industrial residual	kg	1996-2024	Wood	RER	[102]

			wood, stationary electric chipper					
OSB	0,39	0,97	oriented strand board production	m3	2012-2024	Wood	RER	[103]
Bitumen	1,15	1,28	bitumen seal	kg	1992-2024	Cement & Concrete	RER	[104]
PVC	2,36	1,29	polyvinyl chloride, emulsion polymerised	kg	2021-2026	Chemicals	RER	[105]
Laminate	0,06	0,11	anhydrite floor	kg	2000-2024	Cement & Concrete; Minerals	CH	[106]
Galvanised steel	4,62	0,47	steel, chromium steel 18/8	kg	2013-2024	Metals	RER	[107]

Appendix D.2. Labour Costs for Envelop ESMs

Table 31. Labour cost for installation of envelop insulation

Component	Component specifics	Renovation type	Material	Labour costs per m^2	Ref
wall	No cavity	External wall insulation	Glass wool	140	[108]
wall	No cavity	Internal wall insulation	Rock wool	82,5	[108]
wall	cavity	Cavity wall insulation	White eps	20	[109]
roof	pitched	Cold roof insulation	PUR or PIR	50	[110]
roof	pitched	Warm roof insulation	Glass wool	17,5	[110]
roof	Flat	Cold roof insulation	PUR or PIR	50	[110]
roof	Flat	Warm roof insulation	PUR or PIR	17,5	[110]
floor	No crawl space	Floor overlay insulation	White eps	100	[111]
floor	Crawl space available	Floor crawl space insulation	PUR or PIR	25	[111]
floor	Likely no crawl space	Floor overlay insulation	White eps	100	[111]
floor	Likely no crawl space	Floor crawl space insulation	PUR PIR	25	[111]

Table 32. Labour cost for windows, heating systems, and ventilation systems

Material	Heating system cost per unit	Window cost per m2	Ventilation cost per unit	Heating system installation cost per unit	Window installation cost per m2	Ventilation installation cost per unit	Heating system co2 per unit	Window co2 per m2	Ventilation co2 per unit
PVC 1G	0.00	30.00	0.00	0.00	30.00	0.00	0.00	31.60	0.00
PVC 2G	0.00	95.00	0.00	0.00	39.00	0.00	0.00	63.20	0.00
PVC 3G	0.00	140.00	0.00	0.00	72.00	0.00	0.00	73.13	0.00
ALU 3G	0.00	140.00	0.00	0.00	72.00	0.00	0.00	73.13	0.00
CR-ketel	1200.00	0.00	0.00	750.00	0.00	0.00	500.00	0.00	0.00
HR107-ketel	2200.00	0.00	0.00	750.00	0.00	0.00	700.00	0.00	0.00
ASHP	10000.00	0.00	0.00	5750.00	0.00	0.00	400.00	0.00	0.00
DistH	2459.37	0.00	0.00	0.00	0.00	0.00	80.00	0.00	0.00
HR107-ketel RG	2200.00	0.00	0.00	750.00	0.00	0.00	0.00	0.00	0.00

ASHP RG	10000.00	0.00	0.00	5750.00	0.00	0.00	400.00	0.00	0.00
Natural	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Type c	0	0.00	750.00	0.00	0.00	2000.00	0.00	0.00	73.70
Collective type c	0.00	0.00	10068.75	0.00	0.00	26850	0.00	0.00	516.00

APPENDIX E. HEATING SYSTEMS, VENTIALTION SYSTEMS, AND WINDOWS SPECIFICS AND MATERIALS

Appendix E.1. Heating Systems

Table 33. Efficiency of heating systems and the calorific values and EFs

Type	Eff.	Unit	Ref	Calorific value	Unit	Ref	EF	Unit	Ref.
CR-ketel	0,80	-	[112]	9,77	kWh/m3	[113]	1779,00	g CO2eq/m3	[1]
HR107-ketel	1,07	-	[112]	9,77	kWh/m3	[113]	1779,00	g CO2eq/m3	[114]
HR107-ketel RG	1,07	-	[112]	9,94	kWh/m3	[113]	0,00	g CO2eq/m3	[114]
ASHP	3,72	*SCOP of ASHP	[115]	0,00	kWh/m3		370,00	g CO2eq/kWh	[116]
DistH	0,80		*	0,00			108,00	g CO2eq/kWh	[117]
ASHP RG	3,72	*SCOP of ASHP	[115]	0,00	kWh/m3		370,00	g CO2eq/kWh	[116]

Table 34. Environmental factors and economic factors of the materials in heating systems

Material	EF	Reference Product	Unit	Time Period	Sector	Geo	Ref
Copper	6,814	copper, cathode	kg CO2 per kg	1994-2024	Metals	GLO	[118]
Brass	5,694	brass	kg CO2 per kg	2000-2024	Metals	CH	[119]
Aluminium	19,213	aluminium alloy production, Metallic Matrix Composite	kg CO2 per kg	2013-2024	Metals	ROW	[120]
Steel	1,737	steel production, converter, unalloyed	kg CO2 per kg	2013-2024	Metals	RER	[98]
Stainless steel	4,617	steel, chromium steel 18/8	kg CO2 per kg	2013-2024	Metals	RER	[107]
Silicone	86,904	silicon, electronics grade	kg CO2 per kg	1992-2024	Chemicals; Electronics	DE	[94]
EPDM	2,760	synthetic rubber	kg CO2 per kg	1995-2024	Chemicals	RER	[121]
ABS	4,539	acrylonitrile-butadiene-styrene copolymer production	kg CO2 per kg	1996-2024	Chemicals	RER	[122]
PVC	2,066	polyvinyl chloride production, suspension polymerisation	kg CO2 per kg	2021-2026	Chemicals	RER	[123]
Electronic components	1.205,500	electronic component production, active, unspecified	kg CO2 per kg	1994-2024	Electronics	GLO	[124]

HDPE	2,281	polyethylene, high density, granulate	kg CO2 per kg	2011-2024	Chemicals	RER	[125]
Rock wool	1,099	stone wool production	kg CO2 per kg	2000-2024	Cement & Concrete	CH	[93]
Reinforcing steel	2,130	reinforcing steel production	kg CO2 per kg	2000-2024	Metals	EUR wo. AT	[126]
Elastomer	4,681	tube insulation, elastomere	kg CO2 per kg	1997-2024	Chemicals	DE	[127]
Polyester oil	1,544	lubricating oil	kg CO2 per kg	2000-2024	Chemicals	RER	[128]
R 134a	19,906	refrigerant R134a production	kg CO2 per kg	1999-2024	Chemicals	RER	[129]

Appendix E.2. Fuel Costs

Table 35. Fuel Costs in Netherlands

Energy fuel type	Fuel cost per unit
Electricity	0,32
Gas	1,41
District heating	0,50
RG gas	0,08