DOCTORAL THESIS

Decarbonisation of the Existing Residential Building Stock – Obstacles and Opportunities in Cold Climate Deep Renovation in a High-Emission Energy System

Kadri-Ann Kertsmik

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.

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TALLINNA TEHNIKAÜLIKOOL
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Olemasoleva elamufondi dekarboniseerimine – väljakutsed ja võimalused külmas kliimas, kus on kõrge emissiooniga energiavõrk

KADRI-ANN KERTSMIK

TALTECH KIRJASTUS

Abstract

Decarbonisation of the Existing Residential Building Stock – obstacles and opportunities in cold climate deep renovation in a high-emission energy system

The thesis explores how decarbonising existing residential building stock can help meet the national decarbonisation climate target, with particular focus on the challenges occurring in a cold climate and a carbon-intensive energy source. In this context, the research investigates whether the currently used renovation strategies are sufficient and how these can be improved to deliver both operational and embodied carbon reductions. The thesis is based on four peer-reviewed publications and applies an Estonian life-cycle assessment (LCA) method for buildings' carbon footprint (CF), alongside national-scale scenario modelling, including the most widespread residential building archetypes at the stock and renovation policy analysis level.

The motivation for this research stems from the author's professional background as a practising architect, with experience in apartment building renovations. This perspective raised a central question – how can Estonian residential building stock, largely constructed pre-2000, be transformed so that it will be decarbonised by 2050? The thesis answers this by offering integrated, evidence-based insights that move from single building deep renovations to comprehensive carbon reduction strategies on an urban and national scale.

It is the first study in Estonia to systematically evaluate embodied emissions in residential building renovation, an area previously overlooked in both research and policy. The work shows that building envelope and technical service systems upgrades alone are inadequate if not paired with the decarbonisation of energy sources at the national level. Moreover, the thesis introduces the challenges and opportunities of land use for decarbonisation, highlighting the land area needed for renewable energy generation and carbon offsetting, factors that are currently beyond the scope of Estonia's renovation and land use planning frameworks.

The results confirm that operational energy remains the dominant source of life-cycle emissions, but as the energy source decarbonises, the share of embodied emissions is becoming more significant. It will lead to an urgent need to focus on circular renovation solutions. The most effective carbon reductions are achieved through renovations that incorporate on-site energy generation from renewable sources (e.g., PV panels) and pre-fabricated insulation elements for the building envelope. The analysis shows that Estonia's current policy underestimates the land use impact to achieve declared targets.

In conclusion, this thesis contributes both methodological and strategic knowledge to the field of residential building decarbonisation. It provides a foundation for a national LCA method for building carbon footprint for renovated buildings and offers guidance for realigning Estonia's renovation policy with a whole-life carbon perspective. It also addresses the core challenges expressed in the thesis title: achieving climate ambition under the specific constraints of a cold climate and a high-emission energy system. By demonstrating the land use, technical, and policy-related conditions necessary for success, the study calls for a fundamental rethinking of how renovation targets are defined and implemented to support the climate neutrality goal.

Lühikokkuvõte

Olemasoleva elamufondi dekarboniseerimine – väljakutsed ja võimalused külmas kliima, kus on kõrge emissiooniga energia

Käesolev doktoritöö uurib võimalusi Eesti olemasoleva elamufondi dekarboniseerimiseks, et toetada riikliku kliimaneutraalsuse eesmärgi saavutamist. Seda olukorras kus ilmnevad väljakutsed seoses külma kliima ja kõrge heitmega energiavõrgu kombinatsioonis. Doktoritöö keskendub küsimusele, kas senised renoveerimisstrateegiad on piisavad ning kuidas neid parendada, et vähendada nii hoonete kasutusaegset energiakulu kui ehitusmaterjalidest tulenevat kehastunud süsiniku heidet. Töö tugineb neljale eelretsenseeritud teadusartiklile ning rakendab hoone olelusringi hindamise metoodikat koos Eestis enim levinud elamutüüpide põhjal läbi viidud üleriigilise stsenaariumimudeldamise ja poliitika analüüsiga.

Töö motivatsioon tuleneb autori taustast arhitektina, omades praktilist kogemust korterelamute renoveerimisprojektidega. See vaade projekteerimise ja ehituse tegelikkusele andis tõuke kesksele uurimisküsimusele: kuidas on võimalik Eestis, kus enamik elamufondist on ehitatud enne aastat 2000, toetada kliimaneutraalsuse saavutamist aastaks 2050? Doktoritöö pakub sellele küsimusele vastuseks teaduspõhiseid lahendusi, mis ulatuvad kaugemale tavapärastest üksikhoone energiatõhususe parandamisest ning suunavad terviklikule vaatele süsiniku heitmete vähendamisel.

Töö uudne väärtus seisneb selles, et tegemist on esimese uurimusega Eestis, mis käsitleb olemasolevate elamute renoveerimisega seotud kehastunud süsiniku heidet – valdkond, mis seni on jäänud nii teadusuuringutes kui ka poliitikakujundamises tahaplaanile. Tulemused näitavad, et pelgalt hoonete piirdetarindite energiatõhusamaks muutmisest ei piisa, kui sellega ei kaasne energiavõrgu dekarboniseerimine riiklikul tasandil. Lisaks tuuakse sisse kontseptuaalne raamistik ruumilisteks eeldusteks, mille raames käsitletakse vajadust eraldada piisavalt maapinda kohapealseks taastuvenergia tootmiseks ja süsiniku heitmete kompenseerimiseks. Need aspektid puuduvad praegu Eesti ruumilise planeerimise ja renoveerimispoliitika dokumentides.

Saadud tulemused kinnitavad, et tänasel päeval on renoveeritavate hoonete olelusringi süsiniku heitmetes ülekaalus kasutusaegne energia, kuid energia tootmise süsinikumahukuse vähenedes muutub kehastunud süsiniku osakaal üha olulisemaks. Seetõttu on juba täna oluline rakendada suuremal määral ringse renoveerimise põhimõtteid. Suurimat mõju heitmete vähendamisele avaldavad lahendused, mis sisaldavad kohapealseid PV-paneele ning tehases eeltoodetud välisseina elemente. Analüüs näitab, et Eesti praegune poliitiline raamistik alahindab ruumilisi ja regulatiivseid vajadusi, mis on vajalikud riiklikult seatud kliimaeesmärkide täitmiseks.

Kokkuvõttes pakub doktoritöö nii metoodilisi kui strateegilisi teadmisi olemasolevate eluhoonete dekarboniseerimiseks. Töö loob aluse üleriigilise LCA-metoodika arendamiseks hoonete renoveerimise tarbeks ning annab soovitused, kuidas luua tervikpilt Eesti renoveerimispoliitika eluhoonete olelusringi vaates. Samuti vastab töö otseselt pealkirjas püstitatud küsimusele: kuidas saavutada seotud kliimaeesmärgid külma kliima ja süsinikuintensiivse energiasüsteemi tingimustes? Uuring näitab, et selleks on vaja selget ruumilist, tehnilist ja poliitilist raamistikku ning laiemat arusaama renoveerimise rollist kliimaneutraalsuse saavutamisel.

Contents

List of publications

This thesis has been prepared on the basis of the following publications:

I Kertsmik, K-A., Kuusk, K., Lylykangas, K., Kalamees, T. (2023) Evaluation of renovation strategies: cost-optimal, CO_2e optimal, or total energy optimal, *Energy and Buildings*. Elsevier B.V., 287, p. 112995. doi: 10.1016/j.enbuild.2023.112995

II Kertsmik, K-A., Arumägi, E., Hallik, J., Kalamees, T. (2024) Low carbon emission renovation of historical residential buildings, *Energy Reports.* Elsevier B.V., 11, p. 3836−3847. doi: 10.1016/j.egyr.2024.03.030

III Kertsmik, K-A., Kalamees, T., Arumägi, E., Hallik, J. (2025) The feasibility of zero-emission neighbourhood renovation of apartment buildings in a cold climate, *Building and Environment*. Elsevier B.V., 278, p. 113004. doi: 10.1016/j.buildenv.2025.113004

IV Lylykangas, K., Kertsmik, K-A., Cerrone, D., Walke, P., Kuusk, K., Kalamees, T. (2025) Decarbonisation of Estonia's residential building stock, *Energy and Buildings*. Elsevier B.V., 346, p. 116193. doi: 10.1016/j.enbuild.2025.116193

These publications are referred to in the thesis by their Roman numerals.

Author’s contribution to the publications

The author of the thesis is the principal author at first three publications and second author of the fourth article. All of the following descriptions are presented in exactly the same form as in the articles. Specific contributions to the articles in this thesis are as follows:

I Kertsmik Kadri-Ann was responsible for the entire writing process of the article, including both the manuscript and the revised versions. In addition, all LCA calculations, based on the input data provided in the study, as well as the comparative analyses presented, were conducted by the doctoral candidate. Kuusk Kalle is responsible for calculating the energy performance of building components (walls, windows, and roofs) and total energy demand. Concept development and review of the article was carried out in cooperation with Lylykangas Kimmo and Kalamees Targo.

II Endrik Arumägi: Writing – original draft, Visualization, Methodology, Formal analysis. Kadri-Ann Kertsmik: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Jaanus Hallik: Methodology, Formal analysis. Targo Kalamees: Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

III Kadri-Ann Kertsmik: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. Targo Kalamees: Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition. Jaanus Hallik: Software, Formal analysis, Data curation, Conceptualization. Endrik Arumägi: Software, Data curation, Conceptualization.

IV Kimmo Lylykangas: Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. Kadri-Ann Kertsmik: Writing – review & editing, Methodology, Investigation. Damiano Cerrone: Investigation, Formal analysis, Data curation. Peter Walke: Writing – review & editing, Investigation, Formal analysis. Kalle Kuusk: Writing – review & editing, Validation, Data curation. Targo Kalamees: Writing – review & editing, Validation, Supervision, Funding acquisition.

Abbreviations

BAU	Business-As-Usual (current common practice)
CF	Carbon Footprint,
CO_2eq	Carbon Dioxide Equivalent, unit to describe CF
DC	District Cooling
DH	District Heating
DHW	Domestic Hot Water
EffDH	Efficient District Heating
EHR	Estonian Building Registry (Riiklik Ehitisregister)
EN	European Standard
EPBD	Energy Performance of Building Directive
EPC	Energy Performance Certificate
EPD	Environmental Product Declaration
EPS	Expanded Polystyrene (insulation)
EPV	Energy Performance Value
ETICS	External Thermal Insulated Composite System
EU	European Union
FU	Functional Unit
GHG	Greenhouse gas
GSHP	Ground Source Heat Pump
GWP	Global Warming Potential
HVAC	Heating Ventilation and Air Conditioning
LCA	Life-Cycle Assessment
LTRS	Estonian Long-term Strategy for Building Renovation
nZEB	Nearly zero-energy building
OECD	Organisation for Economic Co-operation and Development
Pre-Fab	Previously Fabricated element
PV-panel	Photovoltaic panel
RES	Renewable Energy System
RKAS	State Real Estate Ltd. (Riigi Kinnisvara AS)
RQ	Research Questions
Q	Quarter
XPS	Extruded Polystyrene (insulation)

Symbols

U	Thermal transmittance, $W/(m^2 \cdot K)$
A	Area, m^2
$Cg(\tau)$	Global cost, €/m^2
ΔCO_2eq	The change of carbon emissions, $kgCO_2eq/(m^2 \cdot a)$
q_{E50}	Air leakage rate of building envelope at 50 Pa pressure difference, $m^3/(h \cdot m^2)$

Introduction

With ambitious goals such as achieving carbon neutrality by 2050, the European Union's Renovation Wave (European Commission, 2020b) initiative has emerged as a pivotal strategy for reducing the environmental impact of the existing residential building stock. This initiative not only seeks to enhance energy efficiency but also aligns with broader goals of resource conservation, improved living standards, and climate resilience. Estonia, as an EU Member State, faces both challenges and opportunities in contributing to this target.

At present, Eastern European countries such as Estonia, Latvia, Lithuania, and Poland remain underrepresented in the scientific literature (Figure 1) concerning life-cycle assessment (LCA) of buildings, based on scholarly analysis (The Lens, 2025). Research is particularly scarce in the field of renovation studies, even though most of the building stock in these countries was constructed before 2000 (MacArthur, 2001) and is urgently in need of energy-efficient retrofitting. The limited number of case studies conducted in the Baltic States and Poland, for example, has primarily focused on operational energy aspects, while broader whole-life carbon perspectives have only recently begun to emerge. This relative lack of scientific evidence creates uncertainties regarding the climate impact of large-scale renovation waves, especially when compared with the ambitious decarbonisation trajectories outlined in EU policy frameworks. By contrast, the Nordic countries, including Finland, Sweden, Norway, and Denmark, possess a far more mature body of research addressing both new construction and renovation through the LCA lens.

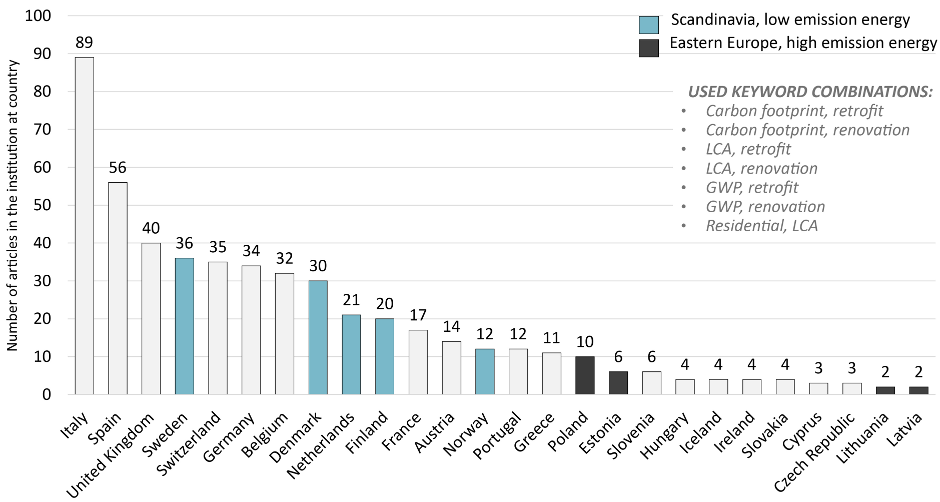


Figure 1. Overview of European scientific studies on life cycle assessment of renovation.

It is important to note that in the scientific literature (Figure 1), studies reported for Poland relate only to emissions from the national or municipal energy grid, with no building-specific analyses available. In the case of Latvia, only grid energy carbon analyses are available, while Lithuania is represented by a single building-level analysis (Chandrasekaran et al., 2021) and grid energy emission data. For Estonia, the only building-level LCA research has been conducted by the author of this doctoral thesis; all other studies focus either on university campuses or on emissions from district heating networks. By contrast, in the Scandinavian countries it is common to find studies in which more than three different buildings are analysed within a single article (Zimmermann, et al., 2023).

However, the asymmetry in the availability of data and studies between Estonia, Lativa, Lithuania, Poland (44.2 million residents) and Scandinavia (27.9 million residents) (Word Population Review, 2025) risks skewing the understanding of the European average residential building stock and its renovation challenges. Without addressing this imbalance, the European discourse on building decarbonisation may understate the unique technical, economic, and policy barriers faced by Eastern European countries.

One of the critical factors in Estonia's and Eastern Europe's path towards decarbonisation is the use-stage operational energy (module B6 in Life-Cycle Assessment (EN 15978:2011, 2011)) of buildings, which directly influences the carbon emissions associated with building whole life cycle. Estonia's energy system is amongst the most carbon-intensive in the Organisation for Economic Co-operation and Development (OECD) countries (Scarlat et al., 2022) driven largely by its historical reliance on oil shale as a primary energy source. However, it is also projected for Estonia to experience one of the most rapid reductions in carbon intensity from a global perspective, marking a significant transition towards renewable energy generation and use. The country's target of integrating 100% renewable energy into the national grid was initially set for 2030, but in June 2025 was postponed to an unspecified date (Eschbaum et al., 2025). This delay highlights the complexities of transitioning to a clean energy system and underscores the importance of complementary measures, such as improving the energy performance of buildings, to achieve climate targets.

Estonia's residential building stock presents a significant opportunity for impactful change, given its historical and demographic context. Nearly 70% (Statistics Board of Estonia, 2025) of Estonians live in apartment buildings, many of which originate from a housing crisis following the Second World War (1940–1990, the Soviet era) (Figure 2). These buildings (Kuusk & Kalamees, 2016) often suffer from poor energy performance, inadequate indoor climate conditions, and outdated insulation and façade materials. Current renovation practice focuses on key measures, such as reducing heat loss through the building envelope (external wall, roof, attic floor, roof, windows, etc.) and the installation of efficient service systems (mechanical ventilation systems with heat recovery, heating systems with thermostats, balancing of the systems, etc.), which substantially reduce energy consumption and therefore operational emissions.

Figure 2. Typical apartment building from the housing crisis following the Second World War. Left before and right after deep renovation.

This work seeks to explore different dimensions of decarbonisation, focusing on the role of renovation in Estonia's residential building stock as a pathway to achieve national and global climate goals. By examining the balance of carbon emissions and energy savings in renovation, it aims to provide an understanding of actions addressing environmental challenges and opportunities. Through this lens, the study contributes to the broader discourse on decarbonized renovation solutions and the urgent need for systematic change in national policy, including on-site renewable energy production and the importance of energy system decarbonisation.

This thesis is a compilation containing four published research articles. The studies were carried out between November 2021 and May 2025. In this thesis, the four articles will be presented to show how they have all aimed towards the same goal of addressing decarbonisation strategies in residential building stock renovation in a cold climate country with high-intensity operational emissions.

Research questions (RQ)

RQ1: Why is a carbon-optimal renovation strategy critical for achieving carbon neutrality in the existing residential building sector instead of cost-optimal?

RQ2: Why do current renovation strategies for historic buildings create challenges for reducing their carbon footprint?

RQ3: Why do climate neutrality targets reshape land-use planning in existing residential building stock areas in the urban areas?

RQ4: Why should Estonia reassess and potentially redefine its residential renovation requirements to support the decarbonisation of the building stock and the achievement of national climate targets?

Argumentation

The thesis argues that carbon footprint assessments of representative renovation cases yield more nuanced insights for implementing the Renovation Wave in Estonia. In particular, the findings point to the need for revised renovation targets, the establishment of a carbon offset mandate within land-use planning, and explicit recognition of the decisive role of energy supply decarbonisation in achieving long-term climate goals.

1.1 The main objectives of the thesis

The overarching objective of this thesis is to develop a comprehensive understanding of how residential building renovation strategies in Estonia can contribute to national and European climate targets:

- **Identify the lowest carbon emission renovation pathway** by comparing cost-optimal, carbon-optimal, and energy-optimal approaches, thereby enabling more effective decarbonisation potential in the residential sector;
- **Analysing historic building challenges for reducing carbon footprint**, seek to demonstrate that deep renovation strategies not only lower emissions from buildings, but also preserve the architectural and cultural value of historic buildings;

- **Ensuring that urban environment land-use perspectives are addressed** with the benefits to the urban area, while evaluating the feasibility of raising the renovation baseline from Energy Performance Certificate (EPC) C to EPC-A class or zero-emission building;
- **Modelling existing residential building stock decarbonisation potential,** with large-scale residential retrofitting using an LCA methodology, with a particular focus on embodied emissions – a crucial aspect that has been until now overlooked in Estonian renovation studies and at Long-Term Renovation Strategy (LTRS).

1.2 Methods to achieve objectives

To achieve the objectives of this thesis, a combinations of quantitative modelling, scenario analysis, and policy alignment assessments were employed:

- **LCA methodology** with the Estonian building carbon footprint (CF) method is used in **all publications**, following the standards EN 15978 and EN 15804+A2. This helps to extend the focus from operational energy to embodied emissions across the whole building life cycle;
- **A comparative analysis between cost-, carbon-, and energy-optimal scenarios was** conducted in **publications I and II.** Assessing the alignment of the results with national energy performance standards and renovation recommendations;
- **The evaluation of building envelope renovation strategies in publications I-III,** such as heat source transitions and the potential for on-site renewable energy integration, was conducted with specific attention to how these measures impact both operational and embodied carbon emissions;
- **The land area planning development** needs were analysed in **publications III and IV**, considering the influence of planning frameworks with carbon emission compensation areas;
- **The national existing residential building stock modelling was** used to identify decarbonisation obstacles and possibilities in **publication IV**, aiming to reach the declared climate neutrality target.

1.3 Scientific novelty and practical application

This thesis makes several contributions to the field of decarbonised residential building stock renovation in a cold climate and high emissions energy system. New knowledge gained from this research includes:

- **The first study in Estonia and Eastern-Europe to systematically incorporate embodied emissions** into renovation assessments, addressing a gap in existing research where operational energy performance has been the sole focus;
- **The first research to evaluate the Estonian national LCA method** for buildings CF, whilst giving input for future development in the renovation LCA method;
- **Cost-optimised renovation alone is insufficient** to meet Estonia’s long-term climate targets;
- **On-site renewable energy production should be mandatory** with renovation projects due to increased - use of electricity after renovation. Achieving a zero-emission building stock requires raising the national renovation ambition from EPC-C to EPC-A class, a shift that has critical implications for renovation grant schemes and national renovation strategies;

- **Deep renovation of heritage buildings can reduce their carbon emissions** without compromising their external appearance, thus aligning national decarbonisation goals with heritage conservation priorities;
- **Providing results that imply circular renovation solutions should be emphasised**, in the future. The thesis offers a more comprehensive understanding of the true climate impacts of renovation activities;
- **Achieving climate-neutral cities requires revising land-use planning measures,** particularly in the context of deep renovation of residential buildings. It emphasises the need to clearly assess urban space requirements for offsetting both – operational and embodied emissions, challenging currently used climate neutrality declarations.

The practical outcomes of this thesis are twofold – they address both technical renovation practices and national-level renovation policy development:

- To reduce operational emissions, **on-site energy production should be integrated into buildings**. This is valid even for those projects that do not yet achieve EPC-C class. This recommendation aligns with the revised EPBD directive "solar-ready" requirement, reinforcing the role of distributed energy generation as an essential complement to deep energy renovation;
- Results indicate the need of to **develop a national CF methodology for building renovation** in Estonia. By demonstrating the necessity of incorporating both operational and embodied carbon emissions into renovation assessments, the thesis provides a scientific foundation for extending Estonia's existing CF practice, which is currently focused only on new constructions;
- **Critical review for policy adjustments**, the need for more integrated planning strategies that consider energy production, carbon offsetting and land-use efficiency in dense residential areas.

This thesis work provides insights into architectural land use planning by evaluating land requirements for zero-emission energy production. The findings contribute to a broader understanding of zero-emission urban development for integrating renewable energy infrastructure into future national planning strategies and addressing area needs to compensate for emissions.

The findings of this thesis not only provide new evidence on the embodied emissions of renovation solutions, an aspect previously overlooked in the Estonian context, but also offer insights into prospective pathways. It becomes increasingly important to consider embodied carbon alongside operational emissions, as the relative significance of material-related impacts will increase in the future. This highlights the need to focus on renovation strategies today, particularly those involving pre-fabricated (pre-fab) external wall elements, which demonstrate significantly lower life-cycle emissions over a 50-year period than the External Thermal Insulated Composite System (ETICS), while offering higher potential for circularity.

Figure 3 presents the graphical abstract of the doctoral thesis, illustrating the content and focus of the individual articles and their contribution to the input for of the thesis.

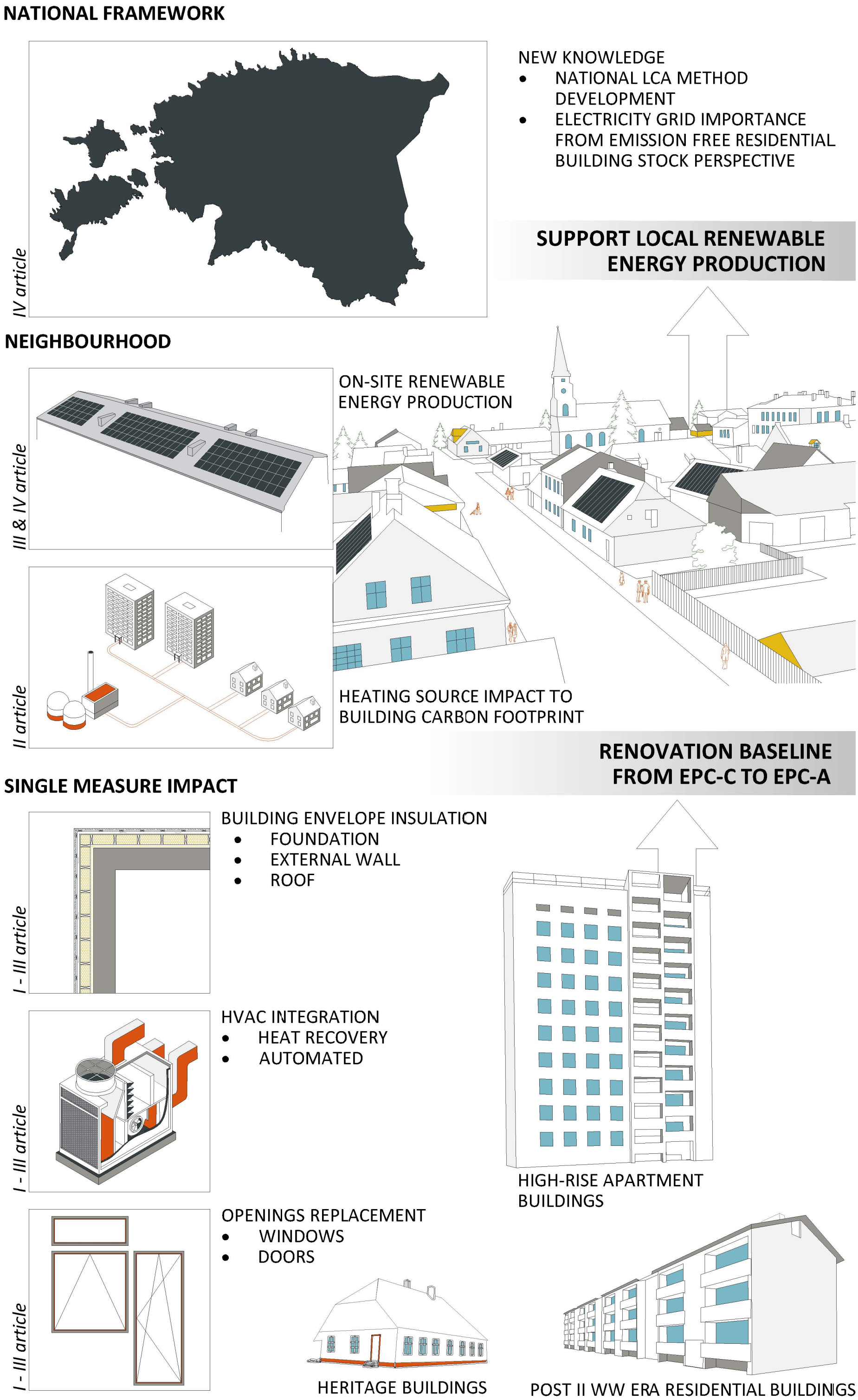


Figure 3. Graphical abstract of the thesis.

1.4 Limitations of the approaches

While this thesis provides valuable insights into the decarbonisation of Estonia's residential building stock which should be renovated by the year 2050, several limitations must be acknowledged:

- Estonia currently lacks a national LCA carbon footprint method suitable for building renovation, which requires adaptations and assumptions within the modelling framework used in this study;
- Upstream emissions associated with operational energy, such as those from fuel extraction and processing, are not systematically included in national emissions databases, restricting the scope of full carbon accounting.
- Renovation solutions should consider more thoroughly the life-span and maintenance costs. Currently only initial cost is considered under cost-optimal solutions.
- Although this research focuses on life-cycle carbon emissions, broader sustainability aspects, including for example biodiversity impacts, circularity of materials, and social impacts, are outside the scope of the LCA applied here, as illustrated in Figure 4, indicating a need for future investigation.

1.5 Built environment sustainability aspects

While the thesis offers new contributions, including the first study in Estonia to evaluate embodied carbon alongside operational carbon within national LTRS and several other proposals, certain limitations should be acknowledged.

Figure 4 illustrates the broader sustainable built environment field within which built environment (thus renovation works) decisions operate. It highlights some factors influencing building sustainability beyond carbon emissions, including aspects such as urban greenery, public space quality, transportation modes, and ecosystem integration. Elements **shown in bold** are those currently incorporated into the LCA approach applied in this thesis.

However, the figure also visualises aspects, such as light pollution, environmental education, and landscape architecture, not yet fully addressed in current LCA (especially carbon emissions focused) renovation assessments but still represent important areas for future methodological development. This emphasises the need for a wider sustainability perspective. Additionally, with the Renovation Wave initiative, reusable/existing building materials topics are increasingly being investigated in order to increase their potential use. This is something which should be included in the LCA method intended for renovation works.

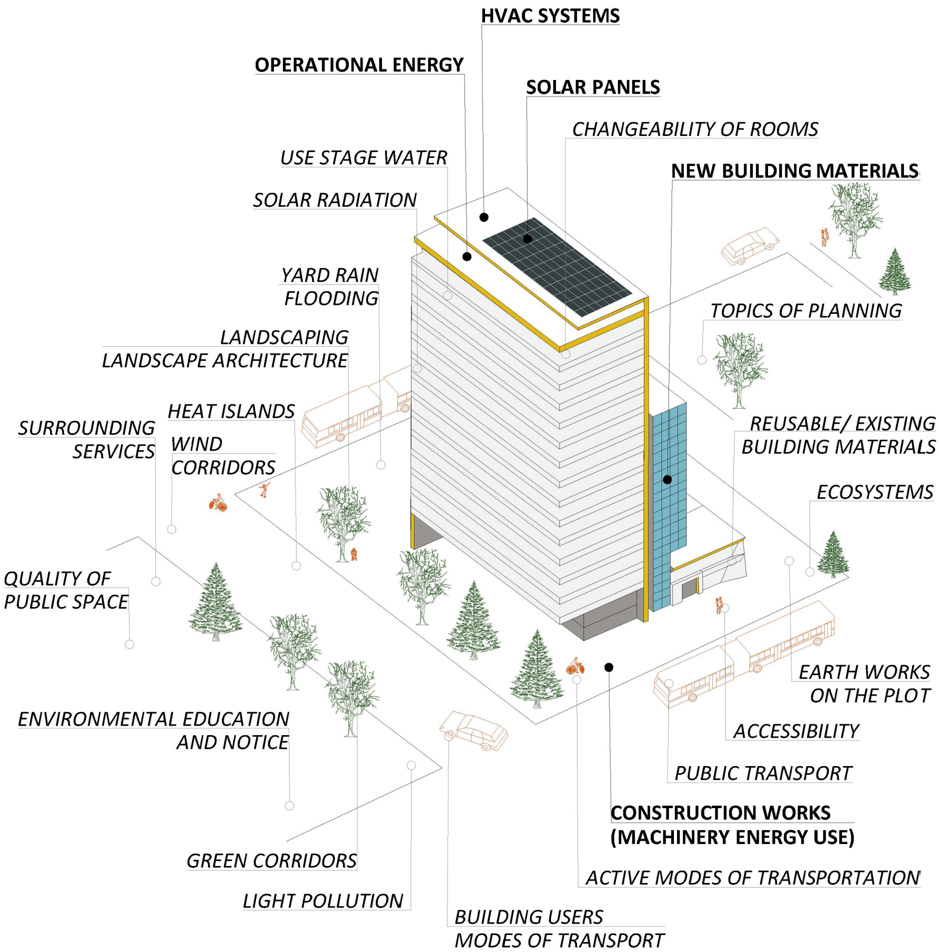


Figure 4. Sustainable built environment field (bold – included at used CF method).

2 Background

2.1 Renovation wave

The need for the large-scale renovation of the existing building stock has emerged as one of the critical challenges (European Commission, 2020b) in addressing the global climate crisis. Approximately 80% of buildings used today are expected to be still in use by 2050 (EEA, 2022). Buildings contribute a substantial share of global carbon emissions, during their construction and operation phases (Ramírez-Villegas et al., 2019). Major energy saving potential lies in the improvement of the existing building stock (Meijer et al., 2009; Mohammadiziazi & Bilec, 2023). To improve the energy performance of the entire existing building stock, the number of building renovations should increase five times over the next ten years (Kuusk et al., 2021; LTRS, 2020).

The 2010 recast of the Energy Performance of Buildings Directive (EPBD) (European Parliament and the Council, 2010) introduced the concept of "nearly zero energy" as the new energy performance benchmark for the construction sector in EU Member States and instructed national authorities to define the concept based on cost-optimal level of energy performance in their respective country. For the EU to meet its 2050 carbon neutrality targets, the EPBD puts the entire EU building stock on a clearly planned trajectory towards deep renovation(European Commission, 2021a). Renovation of existing buildings requires a multi-criteria approach. In addition to technical solutions, financial, social and environmental aspects should be considered (Galimshina et al., 2024; Mjörnell et al., 2019).

EU Member States must set minimum energy performance requirements that aim at least for cost-optimal levels and where relevant, for more stringent standards such as nearly zero-energy or zero-emission buildings. Energy performance must be calculated according to the methodology set out in Article 4 of the (recast) EPBD (European Commission, 2021b). Cost-optimal levels must be determined following the comparative methodology framework in Article 6. (European Commission, 2021b)

The 2022 recast of the EPBD emphasises the Renovation Wave strategy introduced in October 2020 and the assessment of the CF of the buildings. Renovation Wave Initiative (Roscini et al., 2020) aims to increase the renovation rate of buildings to at least 3 % per year with an average energy demand reduction of 75% to achieve climate neutrality by 2050.

Renovating existing buildings to improve energy efficiency and reduce emissions is not only an environmental challenge, but also a complex technical and economic undertaking, particularly when applied to older, inefficient housing stock on a massive scale (Kuusk & Kalamees, 2016). Innovative renovation solutions are essential to meet the dual goals of reducing carbon emissions and enhancing the resilience of buildings against the impacts of climate change (Tisov et al., 2020). Building renovation solutions should follow circular economy principles to meet sustainability goals, with design, material recovery, renovation, and end-of-life actions as the key strategies.

Different studies about building renovation CF - Switzerland (Drouilles et al., 2019), United Kingdom (Collings, 2020), Denmark (Zimmermann, Rasmussen, et al., 2023) have proved the need for a higher focus on older buildings emissions than those in new buildings. Residential building stock renovations should be recognised not only as a technical improvement but as a strategic and major aspect on the decarbonisation pathway that demands flexible methodologies capable of integrating both tangible performance metrics and intangible cultural, architectural, and social values (Thuvander et al., 2012).

The main goal of the LTRS is the full renovation, by 2050, for buildings constructed before 2000. The data show (Figure 5) that residential buildings together (apartment and detached houses) account for approximately 59% of the Estonia's total national renovation need.

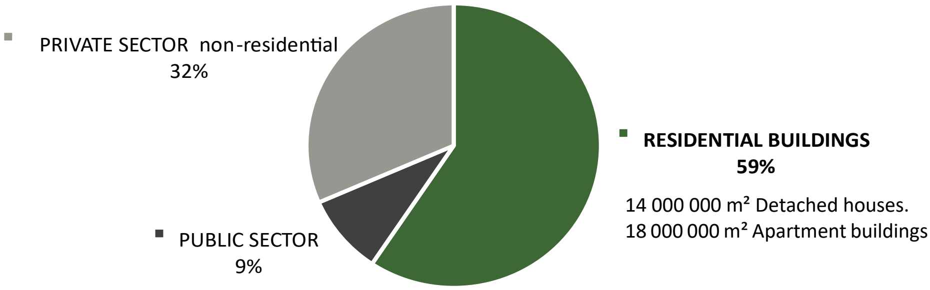


Figure 5. Estonia's building renovation needs (LTRS, 2020)

Figure 5 illustrates Estonia's estimated renovation demand between 2021 and 2050. The Estonian LTRS (LTRS, 2020) forecasts renovation needs, in totalling, 14,000,000 m² of detached houses (approximately 105,000 houses) and 18,000,000 m² of apartment buildings (approximately 14,000 buildings) to be renovated by 2050. This highlights the strategic importance of focusing renovation solutions on the residential building stock to achieve a large-scale impact in decarbonising the national building stock. Brick and prefabricated concrete large panels are the main construction types for apartment buildings, while wood and brick are the main construction types for detached houses.

In Estonia, this challenge is particularly pronounced due to the country's historically carbon-intensive energy system (Melnyk et al., 2020), which has relied heavily on oil shale as its primary source. This reliance has made the Estonian energy system one of the most carbon-intensive among the OECD countries (Unnewehr et al., 2022). However, Estonia also represents a unique case for studying the interplay between building renovations and energy system transitions, as it is projected to achieve one of the fastest reductions in grid carbon intensity worldwide (Melnyk et al., 2020), However, transitioning to 100% renewable energy goals for 2030 was postponed in June 2025 (Eschbaum et al., 2025). Given this context, there is an urgent need for research that supports the decarbonisation trajectory by focusing on the carbon reduction (KLiM, 2025) of renovating Estonia's buildings.

Approximately 20% of European residential buildings date back to the Second World War, which today are often classified as having historical value (Meijer et al., 2009). While these buildings have officially designated architectural or historical values (European Commission, 2018a), they still retain the flexibility to improve energy performance requirements. It has been shown that in cold climates (Alev et al., 2014; Arumägi & Kalamees, 2014), the largest energy-saving potential in deeply renovating historic wooden apartment buildings lies in the heating source.

2.2 Land use planning and climate neutral cities

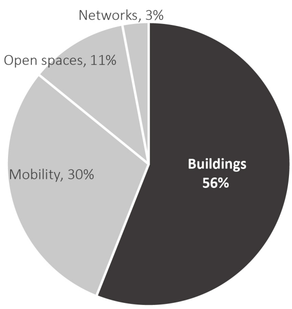
The role of cities is instrumental in achieving the climate neutrality of the building stock by 2050 (Mi et al., 2019). Cities consume up to 65% of the total global energy and cause over 70% of the total global CO_2eq emissions (United Nations, 2019). The challenges of urban density and cold climate are emphasised, representing a vital case for the European Union's "Zero Emission Districts and Neighbourhoods for Sustainable Urban Development" initiative (European Commission, 2020a).

Transitioning urban neighbourhoods into zero-emission districts requires integrated strategies that combine energy-efficient renovations, renewable energy deployment, and strategic land use planning. The steps toward climate neutrality are recommended to start with minimising emissions, for which the most important aspect is the reduction of operational energy use through energy efficiency, followed by the supply of renewable energy and later carbon offsets (Institution of Mechanical Engineers, 2020).

Different analyses show that total emissions are lower for deep renovation than new construction, highlighting the importance of retrofitting buildings to reach net-zero goals (García-López et al., 2024). Although, it was verified (Caruso et al., 2024) that the A1–A3 module has a significant impact at the city scale, operational energy strongly dominates in cold climates. Moisio et al. (2024) studied the environmental impacts of retaining or replacing buildings in Finland and showed that refurbishing and extending existing buildings is worthwhile in terms of GHG mitigation.

Modelling of a zero-emission neighbourhood in a cold climate (Lausselet et al., 2021) revealed that nearly half of embodied emissions arise from long-term material replacements, highlighting the importance of material efficiency strategies across the entire building life cycle. Carbon footprint analysis (García-López et al., 2024) for the district-scale showed that retrofitting buildings is better for decarbonisation goals than demolishing and building new ones.

Studies from southern Europe (García-López et al., 2024), northern Europe (Lausselet et al., 2021; Moisio et al., 2024) demonstrate that buildings have the highest impact (over 50%) in urban CFs (Figure 6).



BUILDINGS 56%	**Building materials, PV panels, and operational energy**
mobility 30%	Cars, buses, light rail, etc.
open spaces 11%	Roads, parking, green area
networks 3%	District heating, sewage, ground source heat pump systems, etc.

Figure 6. District CF components impact.

The significant environmental differences between neighbourhood design alternatives (Trigaux et al., 2014) were highlighted, underscoring the importance of optimising building layout and density. It was shown (Stephan et al., 2013) that replacing suburban built areas with higher-density apartment buildings reduces per capita energy consumption by 19.6%. Similarly, it was found (Wiik et al., 2019) that developing interconnected buildings into a zero-emission neighbourhood entails higher initial capital costs but significantly lowers operational energy use, reinforcing the pivotal role of buildings in city decarbonisation.

Renovation CF may vary by the local energy system (Grossi et al., 2024) – in fossil-based systems, shifting to electric heating reduces emissions, while in cleaner grids, the added embodied emissions can outweigh operational savings, underscoring the need for region-specific renovation strategies in cold climates. Nevertheless, evaluating whole neighbourhood (García-López et al., 2024) renovation strategies, buildings have the greatest impact and obligation on balancing emissions – both embodied and operational.

2.3 Life-Cycle Assessment method for buildings

A life-Cycle Assessment (LCA) calculation is used to provide objective information on the environmental impact during the building's service life. The LCA methodology, based on ISO 14040, consists of four key analytical steps: 1) Defining the goal and scope, 2) Compiling the life-cycle inventory, 3) Conducting the impact assessment, and 4) Interpreting the results (ISO 14040:2006, 2006). Decarbonising the building stock and climate-targets are increasingly influencing the building industry, governments, designers, and researchers, with LCA widely recognized as a critical tool for obtaining environment-related product information and promoting sustainable building practices (Khasreen et al., 2009). LCA results offer valuable insights for selecting optimal building materials, guiding procurements, and supporting environmentally informed policymaking in the building sector (Hellweg & Canals, 2014).

The LCA method is divided into four stages shown in Figure 7 – product, construction, use and end-of-life. Beyond system boundaries is module D, which describes benefits and loads from the system (EN 15978:2011, 2011).

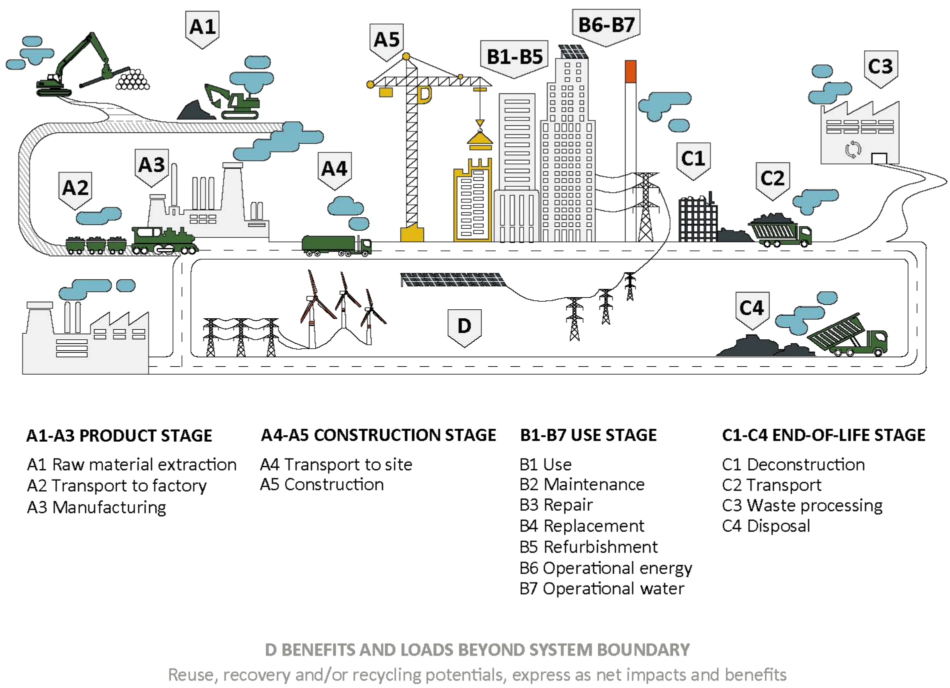


Figure 7. Building LCA overview.

In typical building LCA practice, material quantities are sourced from Bill of Materials (BOMs), while environmental indicators are obtained from national databases (where available), published articles, technical reports, or Environmental Product Declarations (EPDs) for spreadsheet-based assessments, or modelled within specialized LCA software tools (Warrier et al., 2024).

The LCA method has fifteen different environmental impact categories, from which only one –climate change (unit kgCO_2eq) is included in the Estonian building CF method. The first Estonian building Life-Cycle assessment (LCA) calculation methodology development for buildings CF in Estonia started in June 2021 (MKM, 2022). The LCA application in this study aligns with the framework outlined (Lützkendorf & Frischknecht, 2020), providing a comprehensive perspective on the LCA methodology and its relevance to the built environment decarbonisation. The proposed calculation for the LCA method is based on ISO EN 14040 (2006), European standards EN 15804+A2:2019 (2012) and EN15978 (2011), and the European Level(s) framework (European Commission, 2018b), which provide system boundaries. The methodological approach also considers the European Taxonomy Regulations (European Parliament and the Council, 2020), which came into force on July 12, 2020 (2020/852).

2.3.1 Renovation LCA methodology for building CF

The growing emphasis on renovating the existing building stock raises questions about the suitability of current methods and regulations when applied to renovation projects (Zimmermann et al., 2023).

One of the contributions of this thesis is to initiate the development of a nationally suitable LCA approach for building renovation, reflecting the practical and methodological complexities associated with assessing existing building structures.

To start developing the Estonian national method for renovation, research based on examples from other studies (Table 1) was conducted. In the Finnish example (Huuhka et al., 2023), an open-ended study period is assumed, excluding the final C-module emissions, unlike the current Estonian method. This approach, ideal for comparing renovation to new construction, includes C-module emissions from demolished materials, though their impact is minimal and negligible under the 2% rule.

Table 1. Three LCA methodology for building CF comparison.

	ESTONIAN	FINLAND	DENMARK
TYPE	new buildings	renovation	
ANALYSIS	One-phase analysis (after construction)	One-phase analysis (after renovation)	Two-phase analysis (before and after renovation)
LIFE-SPAN	50 years	Open-ended	50 years
FU	kgCO_2eq/(m^2a)	kgCO_2eq/(m^2a)	kgCO_2eq/(m^2a)
EXISTING BUILDING ELEMENTS	Not included in calculations	Partially considered in cases where retained elements contribute to emissions savings	Included in assessment, considers emissions embedded in existing structures
SYSTEM BOUNDARIES	modules A1–A5, B4, B6, and C1–C4	A, B, C, D (all modules)	
EMBODIED CARBON	New building materials used in renovation project	Comprehensive approach, accounting for both retained and new materials	
OPERATIONAL ENERGY B6	Based on EPC	Evaluated in both pre- and post-renovation scenarios	
REUSE BENEFITS	No credit for reuse/recycling	Explicitly models end-of-life scenarios and benefits of material reuse (Module D)	

On the other hand, (Lund et al., 2022) suggest that two separate CFs should be conducted: one for the building before the renovation and another for the building after the renovation. The difference is that the B- and C-modules for the old components are included in the latter CF.

In contrast, the calculations in this thesis follow a net emissions approach, in which the embodied emissions of the existing structures and materials are excluded, and only emissions related to retrofitted components are assessed and averaged over the upcoming 50-year use period. This approach is suited for evaluating the climate neutrality potential of building stock transformation, where operational emissions dominate and embodied emissions from retained structures are considered sunk.

Additionally, LCA methods for renovations could incorporate the consideration of existing materials within buildings, as seen in the Danish and Finnish approaches, thereby creating a stronger incentive for renovation and reuse (Zimmermann et al., 2023). Building materials and construction products whose service life has not yet expired during renovation should be preserved, thereby maximising the initial functional lifespan of already produced materials and products.

2.4 Embodied and operational entire life-cycle emissions

Architects and designers must develop solutions and options to reduce costs and lower environmental impacts (Azari & Abbasabadi, 2018). Kuusk, et al. (2020) analysed nearly zero energy renovation concepts, which included heating, ventilation, envelope insulation, and window replacement. It has been shown that in cold climates (Alev et al., 2014; Arumägi & Kalamees, 2014), to deeply renovate historic wooden apartment buildings, the largest energy-saving potential lies in the heating source. The lower CF of renovated buildings results from two main factors – reduced energy consumption through improved insulation and the replacement of the heating source with lower-emission systems (Wrålsen et al., 2018). However, no environmental aspects or effects of the building materials used for renovation were analysed.

It was found (Lihtmaa & Kalamees, 2020) that the goals of the carbon neutrality target do not consider aspects other than energy efficiency. Hamdy, et al (2013) found that the most optimal solution for environmental benefit and low operating costs tends to require focus on the heating source during the renovation of the building, as it has the highest impact on total energy costs. To achieve carbon neutrality, renewable energy sources with low carbon intensity are needed (Ma et al., 2022).

Considering both embodied and operational carbon emissions is important in building renovation CF calculations, as renovation impacts can offset operational emissions reductions (Mastrucci et al., 2020). Based on several studies which were conducted in cold climate regions, an analysis was carried out to assess the relative share of embodied and operational emissions shown in Figure 8. It presents a comparative overview of emission shares from several international studies. It summarises the proportion of embodied and operational emissions observed in deeply renovated residential buildings across various cold-climate countries. This figure offers a visualisation of the dominant role of operational energy use in current CF assessments, while also indicating the growing relevance of embodied emissions as renovation practices advance and energy systems decarbonise.

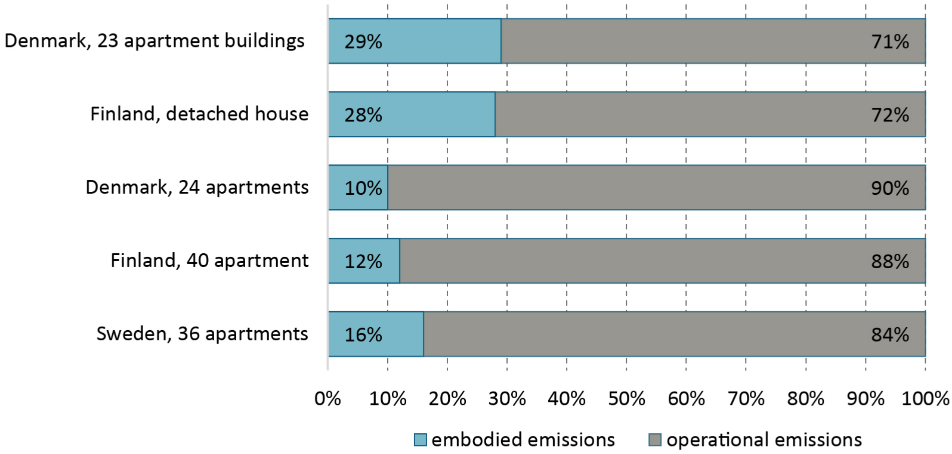


Figure 8. Deeply renovated residential building emissions share (Hirvonen et al., 2020; Montana et al., 2020; Pal et al., 2017; Ramírez-Villegas et al., 2019; Zimmermann, Rasmussen, et al., 2023)

Across all reviewed studies, a consistent pattern emerges, operational emissions currently dominate at the building CF, but as buildings become more energy-efficient and energy source become decarbonised, the share of embodied emissions grows over time. Recent studies underscore the significant role for both – operational and embodied carbon emissions. For instance, Ramírez-Villegas et al. (2019) conducted LCA for multi-family housing in Sweden and found that operational energy use is the primary contributor to environmental impact, particularly in cold climates with low solar radiation during the heating season from October to March. Same study highlighted that building materials and construction processes also contribute substantially to environmental impact.

In addition to operational emissions, embodied emissions associated with building materials and construction processes, are increasingly recognized for their impact. Zimmermann et al. (2023) analysed 23 real-life renovation cases from Denmark and found that these life cycle-embodied impacts were associated with functions beyond energy efficiency, such as land use adjustments and changes in interior layout. Pal et al. (2017) applied a life cycle optimization method to a Finnish townhouse and found that a cost-optimal solution has 28% lower embodied carbon impact than carbon-optimal with 38% from total building CF. Embodied carbon focus was also pointed out in the Denmark apartment building (Montana et al., 2020). Study from Sweden imply that for cold-climate housing the heating systems and occupant practices intervention should be integrated to a whole-carbon perspective, to have a bod embodied and operational emission included (Mjörnell & Johansson, 2024). These findings emphasize the necessity of incorporating both operational and embodied emissions in renovation assessments to achieve comprehensive environmental impact evaluations.

Jochem and Madlener (2003) stated that renovation creates co-benefits at the societal level, such as the impact on climate change. Honarvar, et al. (2022) proposed in his study that to reduce the GHG emissions of an old building, it should be necessary to focus on operational energy (B6) and added new building materials (A1-A3). Matthews et al (2012) showed that the proportion of embodied emissions in the built environment is increasing. As these emissions are cumulative, not annual emissions, it is critical to consider these components in terms of building renovation strategies.

Hirvonen et al. (2020) showed that energy focused renovation has other benefits beyond reduced utility costs, such an increase in property values, air quality, and thermal comfort. Vilches et al. (2017) demonstrated that from the perspective of LCA, the share of embodied carbon dioxide equivalent (CO_2eq) from material production and construction stages (A1–A3, A4, A5) and the use stage (B1–B5), have changed over time due to applications of more energy-efficient solutions. Embodied carbon has a greater influence on construction decisions, when operational carbon emissions decline due to implementing more energy-efficient solutions (Goulouti et al., 2020). Niemelä et al. (2017) stated that it is possible to reduce CO_2eq emissions by 63% when thermal comfort and energy efficiency are considered in deep renovations.

The choice of heat source in a cold climate has a greater influence on primary energy consumption than the efficiency of the building envelope. Therefore, the energy mix of the country in which the building is located strongly influences building CF emissions (Nematchoua et al., 2019). Installing photovoltaic (PV) panels on the roof helps to reduce electricity demand in buildings in cold climates. These systems can complement district heating, but they are not effective when combined with modern heat pump systems due to the already high efficiency of heat pumps (Niemelä et al., 2017).

For renovations, as a large share of building structures will remain, the high impact is from heating, ventilation, and air conditioning (HVAC) systems. A case-study for ventilation ductwork, a building located in Norway, found that embodied emissions, particularly from ventilation ductwork, will gain importance once electricity emission intensity falls below 0.14 kgCO_2eq/kWh (Liu et al., 2024).

2.4.1 Carbon emission optimality over cost optimality

Currently, building renovation decisions are often driven by immediate investment expenses and short-term energy cost savings, rather than long-term optimization and maintenance costs. Currently, cost-optimisation principles guide the climate targets applied in policies driving the energy performance and renovation of buildings. However, more versatile options may be preferred in the future. As a building component, lifespan plays a significant role in decarbonisation goals.

Niemelä et al. (2017) analysed cost-optimal renovation solutions for large-panel apartment buildings in Finland and demonstrated that operational energy consumption accounts for more than 90% of total CO_2eq emissions over a 30-year life cycle. The study also indicated that cost-optimally dimensioned heat pump systems offer significant potential for cost savings and environmental impact reduction.

Article 6 of the calculation of cost-optimal levels aligns with the Green Deal, stating that "the costs of greenhouse gas (GHG) allowances, as well as the environmental and health externalities of energy use, should be considered when determining the lowest costs. The Commission will review the cost-optimal methodology on 30 June 2026" (European Commission, 2021b). The conceptual differences between cost- and carbon-optimal renovation strategies are illustrated in Figure 9, highlighting their implications for policy and practice.

In situations where there are no national grants to support residential building renovations and the energy system has low carbon emission, renovation may not prove beneficial – either economically or environmentally. From the environmental perspective, the emissions created by new construction materials used during renovation may not be offset by the reduction in operational energy use, resulting in a limited overall improvement in the building's life-cycle carbon footprint (Mjörnell et al., 2019).

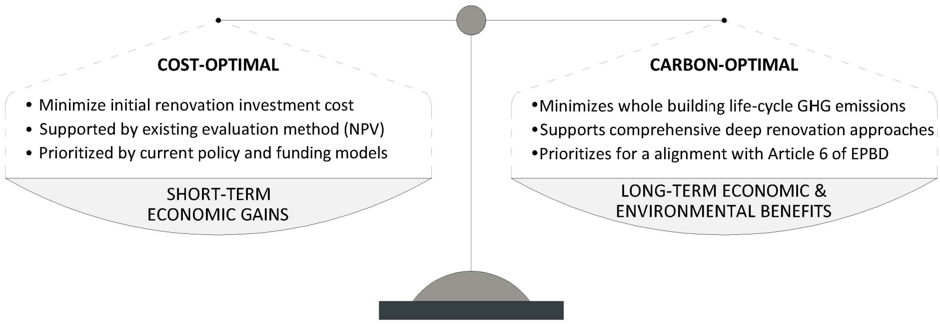


Figure 9. Cost- and carbon-optimal renovation solutions priorities.

As illustrated above, while cost-optimal approaches prioritize short-term economic gains, carbon-optimal strategies offer long-term environmental and systemic benefits, reinforcing the need to re-evaluate renovation metrics beyond immediate cost-efficiency. A study showed that the traditional approach for cost-optimal evaluation for private and public investment projects, Net Present Value (NPV), tends to concentrate only on cost savings from energy-efficient solutions while excluding other non-financial advantages (Bragolusi & D’Alpaos, 2022). Although external wall insulation is identified as the most cost-effective renovation solution in terms of embodied emissions (Hirvonen et al., 2019), the same study shows that operational energy use (stage B6) has a much greater influence on the building life-cycle climate impact than the exact embodied carbon value of materials. The current approach overlooks the significant benefits that a holistic renovation strategy can offer in terms of energy efficiency and long-term financial savings. Therefore, improving energy efficiency is the most critical aspect of residential building renovation to achieve substantial GHG reductions (Arbulu et al., 2025).

While renovating residential buildings, prioritizing only minimal renovation work instead of whole building envelope upgrades (such as insulation, window replacement, and heating source improvements), often results in minimal cost reductions for residents (Teichmann et al., 2025). A cost-efficient energy reduction in GHG emissions has been achieved by improving all large-scale elements in building envelope, except the roof. This is due to the geometrical relation with multi-storey buildings (Montana et al., 2020). One case study from Sweden with a residential building stated that adding more insulation to the external wall and triple-glazed windows is cost-optimal (Avelin et al., 2017). The study demonstrated (Fahlstedt et al., 2024) that renovation solutions focused on minimising carbon emissions yield and reduced energy consumption make these a more suitable benchmark for assessing energy performance in deep renovations compared to cost-optimal solutions.

D’Agostino et al. (2022) found that combining proper insulation with PV panels on the roof will help to offer a cost-effective possibility to reduce net primary energy use in residential buildings after renovation. A study from Germany found the same, shared PV-panel systems should be promoted as standard with deep renovation (Galvin, 2024).

2.5 Estonian national decarbonisation and renovation policy

The ambitious policy measures (Figure 10) aim at the decarbonisation of the building stock and the renewable energy system to support that target. The current 1% annual renovation rate is insufficient to meet declared climate targets (Kuusk et al., 2019). Increasing it up to 3%, with a focus on heating and cooling in older buildings, could reduce CO_2eq emissions in European cities by 30% by 2030 (Pohoryles et al., 2020). According to LTRS roadmaps, full EPBD implementation could reduce building energy use by 41% and direct GHG emissions by 94% by 2050, compared to 2019 (Maduta et al., 2023).

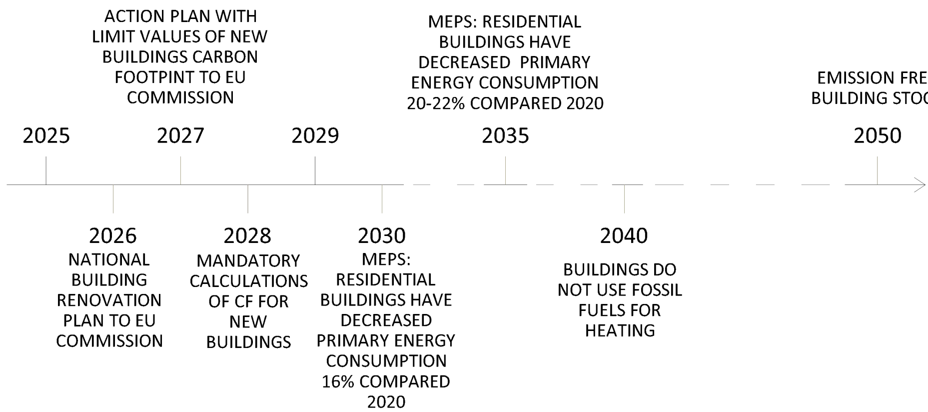


Figure 10. EPBD timeline and goals in Estonia (European Commission, 2021b)

The renovation to Energy Performance Certificate (EPC) EPC-C, representing the current minimum requirement for major renovation and suggested by the Estonian LTRS in 2020 (LTRS, 2020), may be insufficient if effective financial measures are not discovered and the annual renovation rate remains lower than expected. To avoid a lock-in effect, all renovations should be designed to enable further upgrades in energy performance. The United Kingdom building stock was mapped for research utilising LCA to evaluate environmental impacts, analysing fifty-four scientific articles published between 2005 and 2022 (Fahlstedt et al., 2024). The results of the review revealed a steady increase in the use of LCA in building renovation research.

The European Union (EU) aims to achieve a fully decarbonized building stock by 2050, as part of its broader climate goals. The Renovation Wave, launched under the European Green Deal, seeks to at least double annual renovation rates by 2030 and promote deep energy renovations.

Figure 10 outlines Estonia’s roadmap toward a fully decarbonised building stock by 2050. Key milestones include the introduction of national renovation targets, CF limits for new buildings, and the progressive reduction of residential primary energy use by up to 22% compared to 2020 levels. By 2040, residential buildings are expected to no longer use fossil fuels for heating, contributing to the overarching 2050 goal of an emission-free building stock. These targets reflect alignment of Estonia with the revised EPBD directive and the broader ambitions of the EU Renovation Wave.

2.6 Estonian CF method and thesis interaction

The current thesis has been incorporating and testing the newest approved methods and knowledge in Estonia. These efforts have resulted in the establishment of a coherent framework that integrates research, policy, and practice.

The academic trajectory began with the commencement of doctoral studies in November 2021 (Figure 11), focusing on residential building renovations. This research has provided the foundation for analysing and improving the national building LCA methodology. In addition to the validation of the national methodology and the development of proposals for its further advancement, this doctoral research has also contributed to the CF application in the projects of Estonia's largest state-owned real estate developer – State Real Estate Company (RKAS), both at the design and construction stages.

The integration of these pathways (Figure 11) parallels with national methodology development, academic research and RKAS practical implementation, all of which the author of this thesis has been a part of. Scientific articles published and combined for this thesis, during this time, have been prepared using the recently published and accepted Estonian national methodology and database.

The thesis acknowledges the current limitations and gaps in the Estonian building LCA framework, highlighting the need for future development, focusing on renovation LCA methods. While significant progress has been made, the existing methodology contains errors that require correction to ensure accuracy and reliability.

Furthermore, the construction material database remains insufficiently comprehensive. To meet the demands of a diverse and evolving construction sector, the database needs to be expanded by at least two to three times compared to its current size. At the time of writing this thesis it consists of only 124 of the most typical construction products/building materials. Additionally, there is currently no Estonian national EPD register. Addressing these challenges is essential for refining the national LCA methodology, enhancing its applicability, and supporting Estonia's long-term environmental goals for both new construction and renovation projects.

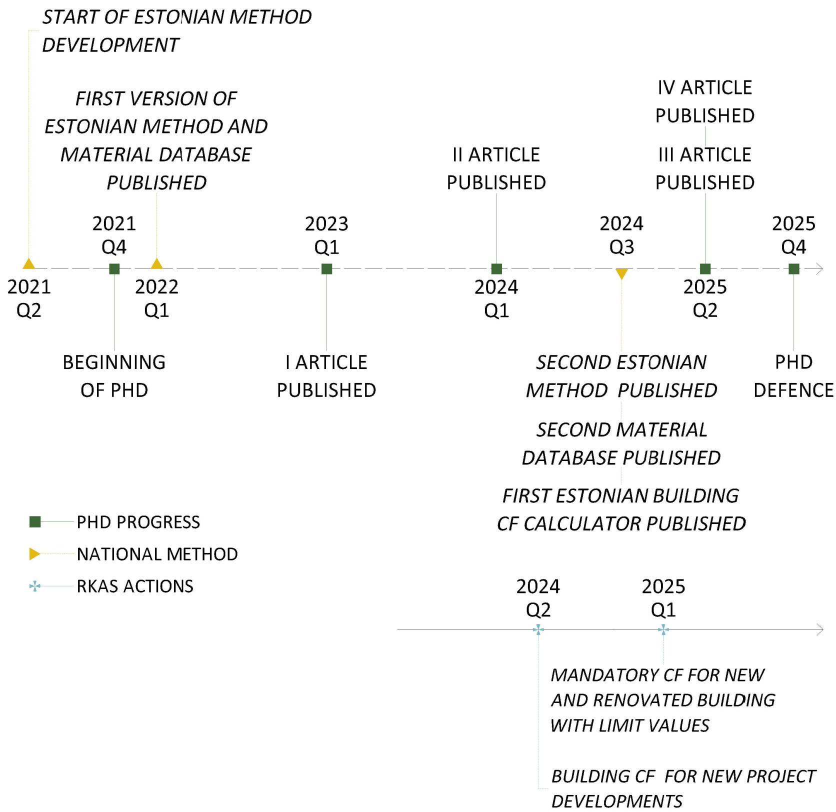


Figure 11. PhD and national methodology timeline.

3 Methods

3.1 Archetypes

The existing residential building stock in Estonia comprises a diverse range of structure types with varying construction periods, materials, and energy performance characteristics. The building category analysed within this thesis (residential buildings), which plays an important role in the country's efforts to achieve carbon neutrality, can be categorised into two main groups based on the architectural form of the residential building: low-rise (up to two floors) and multi-story (more than three floors) residential buildings. The renovation potential of these buildings is highly dependent on their historical construction methods and energy efficiency standards at the time of their construction.

The following tables (Table 2 and Table 3) summarise the key characteristics of the primary building types found in Estonia, providing an overview of their construction periods and materials. Understanding these distinctions is essential for developing tailored renovation strategies that align with the country's long-term decarbonisation goals.

Table 2. Archetypes used in the study – up to two floors.

	RESIDENTIAL BUILDING ARCHETYPES WITH UP TO TWO STORIES		
Picture before renovation			
Used in the article	IV	IV	II & IV
Archetype number	1	2	3
Building type	Detached house		Apartment building
Heating source	Stove & GSHP		Stove, gas, EffDH, GSHP
Construction period	-1945	1946-2000	-1940
% of residential stock	36	29	4
Construction material	Wood	Brick	Wood
Façade material	Wooden cladding	Plaster	Wooden cladding
Number of floors	1	2	2
Number of apartments	1	1	6
Net floor area, m²	100	220	640
Heated area, m²	100	200	620

Detached houses (Table 2 and Table 3) are predominantly composed of brick and timber structures, built pre-2000, with their construction dates registered in the Estonian Building Registry (EHR) (Estonian Building Registry, 2025). The two main types, brick and timber buildings, comprise nearly 65% of all detached houses in need of renovation, thereby justifying their consideration as representative of the majority.

Notably, renovation solutions for detached house concrete structures do not differ from those applied to brick buildings. In detached houses constructed before 1920, wood is the primary structural material, accounting for 75% (Estonian Building Registry, 2025), represented in this case by Archetype 1. This leads to a renovation solution featuring a rear-ventilated façade, which is also addressed in this doctoral thesis. Furthermore, in cases where the construction involves a combination of construction materials, the renovation strategies are typically aligned with those suitable for either wood or brick structures, depending on the predominant material. The dominant façade materials are wooden cladding and plaster (Estonian Building Registry, 2025).

Table 3. Archetypes used in the study – with three and more floors.

	RESIDENTIAL BUILDING ARCHETYPES WITH THREE STORIES OF MORE				
					
Used in the article	IV	I & IV	III & IV		
Archetype number	4	5	6	7	8
Building type	Apartment building				
Heat source	EffDH & gas	EffDH			
Construction period	1951-1980	1951-1980	1981-2000		
% of residential stock	22	35	18		
Construction material	Concrete large panel	Brick, large block	Concrete large panel		
Façade material	Plaster				
Number of floors	5	3	4	6	9
Number of apartments	60	24	32	48	144
Net floor area, m²	3500	2000	2500	4800	9900
Heated area, m²	3300	1800	2400	4600	9580

The selected apartment building types (archetypes 3-8) account approximately 75% of Estonia's total apartment building stock constructed before 2000 based on data from the Estonian Building Registry (EHR) (Table 2 and Table 3). This is to be expected, as the post-Second World War (II WW) housing crisis created an urgent need for rapid residential building development. Consequently, Estonia faces a Soviet-era challenge wherein 80% of total Estonian apartment buildings (Hess & Metspalu, 2019), constructed within the same period (1940–1990), now simultaneously require deep renovation to ensure their usability.

The largest share of apartment buildings consists of brick structures (37%) and large-panel concrete buildings (30%) (Kuusk et al., 2014). These are followed by lightweight concrete buildings at 12% and timber apartment buildings at 8% (Estonian Building Registry, 2025).

Non-renovated residential buildings constructed before the 1990s typically rely on natural passive stack ventilation, while those constructed between 1991 and 2010 are generally equipped with mechanical exhaust ventilation. Kitchens are commonly fitted with extractor hoods, and windows are used for manual airing. However, technical inspections of Estonian dwellings have revealed that natural ventilation systems are often in poor condition (Mikola et al., 2022).

The data available in the EHR confirms that the selected building types are representative of the Estonian residential building stock and cover the principal renovation-related challenges. The renovation approaches and focal areas addressed in the research underlying this thesis provide a comprehensive overview of the issues relevant to the Estonian residential building stock context focusing on challenges and opportunities of decarbonisation.

3.2 Building carbon footprint method

In recent years, Estonia has pursued an intensive development effort to position itself as a forerunner in the field of LCA in the Baltics, aiming to align closely with the advanced practices of Nordic countries. However, the current lack of comprehensive environmental data has hindered progress and slowed the pace of development.

Estonia's current national carbon footprint methodology, officially introduced in 2022 by the Republic of Estonia Ministry of Economic Affairs and Communication, was initially developed for assessing the CF of new buildings (MKM, 2022). As such, its structure (Figure 12), system boundaries, and emission factor database are oriented toward new construction.

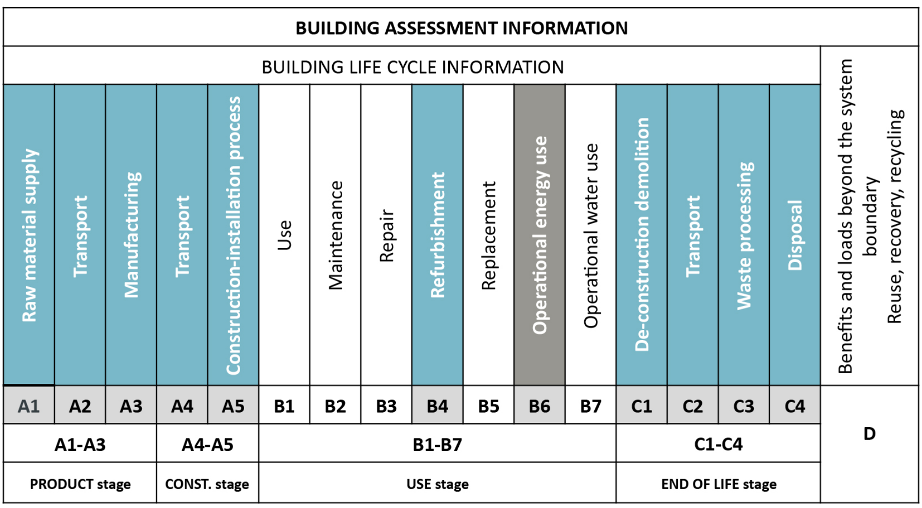


Figure 12. Building LCA methodology EN 15978, coloured in Estonian method. Blue colour indicates embodied and grey colour operational emissions.

The method provides clear guidance on modules A1–A5, B4, B6, and C1–C4. Module D was included in the first method but was left out in the updated version (Republic of Estonia Ministry of Climate et al., 2024) to simplify the calculation, due to the lack of national data on building materials loads and benefits beyond the system boundaries.

However, in the absence of a dedicated framework for renovation works, and with the aim of testing and evaluating the national method, the Estonian CF methodology was applied in this thesis. All LCA calculations were conducted over a 50-year reference study period to objectively evaluate the emissions balance between embodied and operational carbon.

The functional unit (FU) used throughout the study is defined as 1 square metre (m^2) of net floor area over a 50-year reference study period, in accordance with the Estonian CF methodology for construction works and standard EN 15978. This definition enables consistent comparison between renovation strategies with varying scopes and energy performance levels. All environmental impacts, including embodied emissions (modules A1–A3, B4, C1–C4) and emissions from operational energy use (B6), are normalised to this unit.

Existing building structures are considered outside the system boundary, and only additional materials and systems introduced through renovation are included, following the refurbishment modelling principles described in the study (Balouktsi & Lützkendorf, 2022).

3.2.1 Measuring the change in building carbon emissions

To evaluate residential building CF, the equation for the change in carbon emissions was created and used. The aim of this equation (Equation 1) is to compare carbon emissions over a 50-year lifespan before and after renovation. The change in carbon emissions includes the additional carbon emissions related to the renovation solutions and renewable energy solutions needed to meet the requirements of the energy performance level of the building.

Equation 1. The change in carbon emissions.

$$\Delta CO_2eq = \frac{\left(C_G^{target} - C_G^{original}\right)}{A_{floor}}$$

C_G^{target} means the total carbon emissions of the targeted energy performance level according to the renovation solution, $C_G^{original}$ means the total carbon emissions of the original situation before renovation, and A_{floor} means the net area of the rooms.

This equation enables a broader assessment of carbon emissions beyond a simple comparison of pre- and post-renovation states. By establishing a baseline scenario that reflects the emissions of the building in its current condition, it becomes possible to more accurately evaluate how individual renovation measures affect the building's overall CF.

The results will later allow for identifying the minimum scope of renovation works required, specifically in the Estonian context, where operational energy (B6) is strongly dominant, while ensuring that the embodied carbon included in construction materials is compensated by the operational carbon savings achieved through improved energy performance over the building's 50-year use phase.

3.3 Operational energy

Estonia has made notable progress in decarbonisation (Figure 13) since the 1990 baseline, as one of the most rapidly improving countries in the OECD (Melnyk et al., 2020). In terms of national emissions reduction, the operational energy use of buildings (module B6) remains the dominant contributor to GHG emissions in the building sector.

This is particularly evident over a standard 50-year reference period, where B6 continues to outweigh embodied emissions. Consequently, the improvement of operational energy performance through energy-efficient renovation is essential. The transition to deep renovation should be defined according to the EPBD (European Commission, 2018a) as upgrading buildings to zero-emission standards, or initially to nearly zero-energy levels as a first step, and it must be prioritised if Estonia aims to reach net-zero emissions in its building stock by 2050.

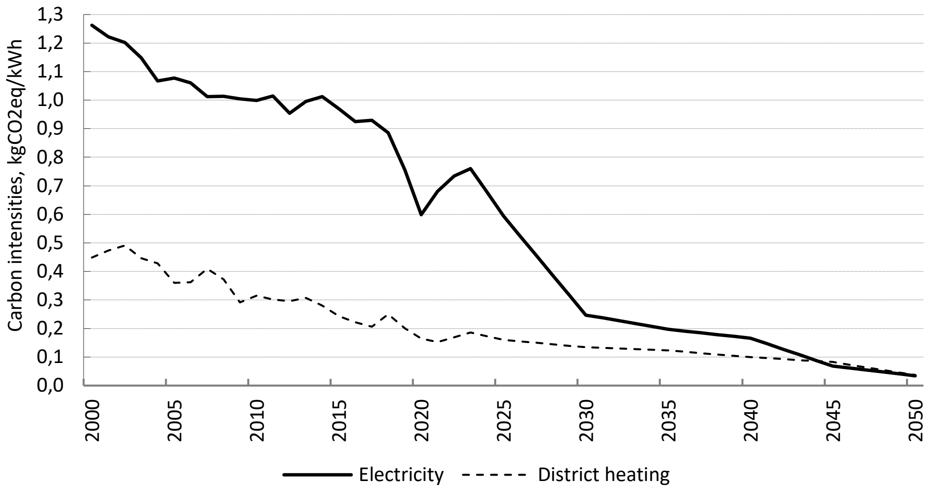


Figure 13. Carbon intensities for the grid electricity and district heating, scenario from 2024 (EKUK, 2024).

Figure 13 illustrates the rapid decrease in carbon intensity, with the scenario starting from the year 2024 and the values for district heating representing a national average. The majority of Estonia's (residential) building stock is in the cities, which makes the role of urban energy infrastructure, particularly district heating, critical for large-scale renovation outcomes. The availability, capacity, and decarbonisation of district heating sources have a major impact on operational emissions at the neighbourhood and city scale. Renovating the building stock plays a central role across all scenarios in reducing overall heating and cooling energy demand. As detached houses are typically situated outside district heating networks, Butt et al. (2022) identify heat pumps, supplemented by bioenergy, as the most suitable solution.

Apartment buildings are predominantly heated with district heating sources combined with one-pipe hydronic radiator networks (Mikola et al., 2017). In detached houses, heating is typically provided by a building-specific heat source, such as a wood-burning stove or a central boiler system (Estonian Building Registry, 2025). Radiators generally lack thermostatic valves, making individual room temperature control impossible. The high energy consumption of Estonian existing residential buildings is largely attributed to significant heat losses (Kalamees et al., 2016) and the presence of critical thermal bridges and air leakage rate q_{50} (Alev et al., 2015; Kuusk et al., 2017).

A further complexity in module B6 assessment lies in its temporal variability. The carbon intensity of operational energy is expected to decline over time due to the increasing share of renewables in both electricity generation and district heating. A building renovated in 2025 will have a higher operational CF emission over 50 years compared to one renovated in 2030, assuming identical energy demand and usage patterns.

3.3.1 Emission factors for energy carriers

A critical methodological limitation in current LCA practices in Estonia is the absence of a nationally maintained and regularly updated emission factor database for energy carriers. Figure 14 outlines the operational emission factors (AS Utilitas, 2025; Gren OY, 2025; Kalamees et al., 2022; Moora et al., 2023) that were used for studies to determine 50-year average operational emissions. However, the lack of transparency and coherence in emission factor datasets introduces uncertainty into long-term assessments.

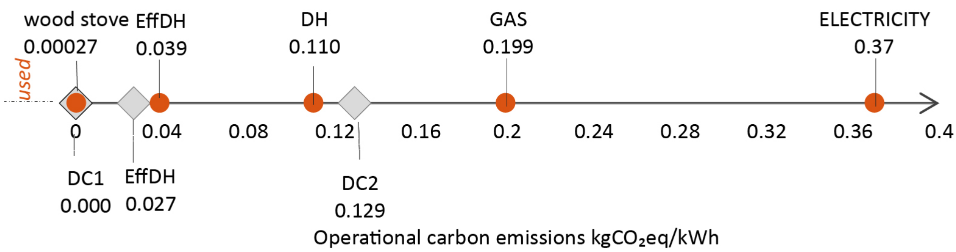


Figure 14. Emission factors for source of operational energy, orange dots represent used values.

As illustrated in Figure 14, electricity has the highest emission factor. DC1 represents the emission factor for district cooling in Tallinn (2024), and DC2 corresponds to Tartu. The graph highlights the critical role of electricity decarbonisation in reducing the CF of the entire national building stock, as it has highest value among currently known emission factors.

Moreover, current estimations do not include upstream emissions, regional energy mixes, or prospective energy policy shifts. This may be partly due to the use of domestic oil shale in electricity production and the difficulties in assessing the global warming potential for the processes included. A nationally endorsed dataset is urgently needed to support consistent, verifiable LCA practices in Estonia.

3.3.2 Energy performance modelling

Indoor climate and energy performance of the reference buildings were modelled using the IDA Indoor Climate and Energy (IDA-ICE) programme (Björsell et al., 1999; Sahlin et al., 2003). The impact of energy renovation measures was simulated according to standard usage and using a unified calculation methodology (Methodology for Calculating the Energy Performance of Buildings, 2020). In practice, the energy consumption of buildings may not correspond to the standardised assumed conditions. This may be expressed in both lower and higher levels of energy use. For comparability, standard usage profiles have therefore been used.

An Estonian Test Reference Year (Kalamees & Kurnitski, 2006) was used for the outdoor climate conditions (design temperature for heating measuring -21 °C, annual heating degree days at temperature 17 °C: 4160 °C·d). Energy simulations were performed for different renovation measures (different thicknesses of additional thermal insulation, improvement of windows, and ventilation systems). The energy-optimal solution was identified based on primary energy and does not include embodied energy. The Energy Performance Value (EPV) measuring the energy intensity was used to gauge the effectiveness of energy management.

Each archetype was analysed under three scenarios:

- Baseline – pre-renovation situation;
- EPC-C – national minimum standards for renovation;
- EPC-B – deep renovation to nearly zero-energy level without local renewable energy production;
- EPC-A – deep renovation to nearly zero-energy level with local renewable energy production.

3.4 Embodied carbon – renovation solutions

The environmental emissions of building materials and systems used in the studies were primarily based on the values provided by the first Estonian building material database (MKM, 2022), and where data were unavailable, values were derived through sensitivity analysis (I).

Estonia's first national database included emission values for 47 different construction materials, and the updated 2024 version contains 127 entries. The Estonian material emissions database, established in 2021, served as the primary source for emission factors (Figure 15). This database provides representative values for typical construction products with a 25% conservativity factor on GWPfossil values, similarly to the national generic construction material emissions databases in Sweden (+25%) (Boverket, 2025) and Finland (+20%) (Finnish Environmental Institute, 2025). Such conservativity adjustments are incorporated to ensure that generic factors do not outperform Environmental Product Declarations (EPDs). As the materials commonly used in renovation works are relatively standardised, most materials were already represented in the first version of the database.

	LAYER	MATERIAL	$kgCO_2eq/kg$
External wall	Insulation	Stone wool	1.6
		Glass wool	2.9
		EPS	3.7
	Façade	Facade board	1.0
		Exetrior paint	3.0
		Cladding	0.1
		Plaster	0.3
Openings	Windows	Double-glazed	2.1
		Triple-glazed	3.5
	Doors	Metal door	3.6

	LAYER	MATERIAL	$kgCO_2eq/kg$
Ground floor foundation	Insulation	XPS	3.5
		EPS	3.7
	Façade	Exetrior paint	3.0
		Plaster	0.4
Roof	Insulation	Blown celluloose	0.1
		Glass wool	2.9
	Covering	Stone tiles	0.4
		Steel sheets	2.8

Figure 15. Embodied carbon emission factors for the building materials used.

To verify and validate the reliability of environmental data, a sensitivity analysis was conducted for all materials used in the studies (Appendix 1). The values from Estonia's first construction material database were compared against other databases for both module A1–A3 material production and replacement, and B4 material service lives. A more detailed description of the information sources used can be found in Appendix 1.

3.4.1 Renovation solutions for heritage residential buildings

For heritage buildings, the requirements from the National Heritage Board were incorporated into the study. Several meetings were conducted (Table 4) with the representatives of the National Heritage Board to discuss and obtain consent for the technical requirements of the building design, such as adding insulation to the external wall sufficient to achieve EPC-A and lifting the roofline to preserve the original building profile, compared with the business-as-usual (BAU) solution.

Table 4. Limitations originating from heritage protection (II).

STAGE	ADDITIONAL INSULATION			WINDOW
	EXTERNAL WALL	ROOF	GROUND FLOOR	
Existing	-	-	-	-
BAU	Up to 5-7 cm	Only attic insulation	No limitation	Must be moved outward
Outcome	Enough to achieve the EPC-A	Can be lifted to insulate roof and attic		

According to EVS-EN 16883 (2017) the renovation of historic buildings should include an assessment of GHG emissions, acknowledging their role in national and European climate objectives. This thesis addresses this gap by exploring how the emission reduction potential of heritage buildings can be unlocked from within the building thermal envelope, focusing on deep renovation measures that consider historical and urban value while reducing carbon emissions over a 50-year lifespan.

3.4.2 External wall insulation

The renovation of exterior walls constitutes a central measure for attaining carbon neutrality in apartment buildings by 2050. Nonetheless, achieving the required increase in renovation rates remains constrained by limited construction capacity and the inefficiencies of conventional on-site renovation practices (Lihtmaa & Kalamees, 2020). In this context, the deployment of prefabricated elements emerges as a critical strategy to overcome these barriers.

Two external wall renovation strategies were analysed: the commonly used (Michalak, 2021) External Thermal Insulation Composite System (ETICS) and contemporary pre-fab insulation element system, respectively. The pre-fab solution involves the off-site production (in a factory) of insulated external wall elements, which are then delivered to the construction site as ready-made modules and installed in a streamlined workflow. This approach significantly reduces on-site construction time and minimises disruption for residents, making it particularly suitable for occupied apartment buildings (Nigumann et al., 2024).

As shown in Figure 16, both strategies result in comparable thermal performance (U-value), but they differ in terms of installation time, cost, and service life, with pre-fab systems offering faster installation and potentially longer durability. For a deeper analysis of building CF, the effect of individual parameters, such as replacing windows and installing extra insulation in the attics and/or foundation needed to be considered. Four of the facade alternatives can be produced as a pre-fab timber element in a factory, and two others are ETICS facade systems, which are currently widely in cold climates (Ilomets & Kalamees, 2013).

All renovation measures analysed among all case-studies included the following: insulating the foundation, replacing windows and exterior doors, adding an extra layer of insulation to the attic with new roof covering and exterior wall insulation to achieve a minimum EPC-C. For guaranteeing hygrothermal performance XPS and EPS insulations were used for the slab on the ground.

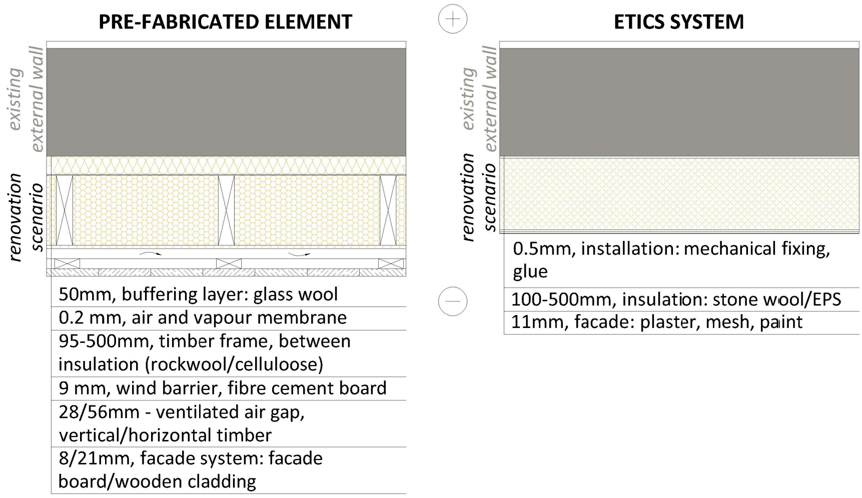


Figure 16. Examples of external wall renovation solutions.

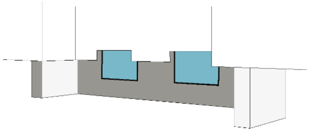
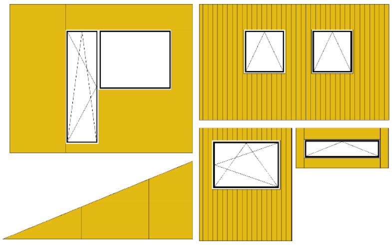
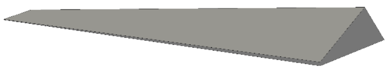
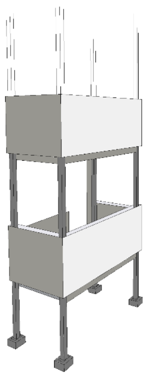
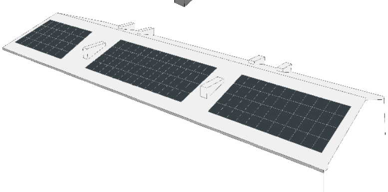
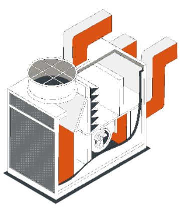
Figure 16 illustrates two renovation approaches for the insulation of external walls, the pre-fab solution and the ETICS, respectively. The first option integrates multiple layers, including a ventilated air gap, timber framing, and fibre cement board or wooden cladding, offering higher durability and improved moisture performance. In contrast, the ETICS applies insulation and a plaster finish directly onto the existing wall, making it a faster and more cost-effective, but less durable, renovation method. These differences are critical in selecting appropriate renovation solutions, especially when considering life-cycle costs and user comfort during the construction period.

Pre-fab external wall elements encompass not only a selection of materials but also the design of connections, positioning, and disassembly options, all of which are essential for enhancing the degree of circularity (Kuusk et al., 2022). This solution (Kuusk et al., 2021) demonstrates a good possibility to increase energy performance by using circularity principles while renovating the existing residential building stock.

3.4.3 Included building components

The CF analyses covered various building components and systems, which can be divided into two main categories. The first category involved the improvement of the building envelope (foundations/floor slabs, external walls, and roofs), and the second included additional components such as HVAC systems, PV panels, and new balconies. A detailed overview of the specific measures and solutions is described in Table 5.

Table 5. Renovation solutions and included materials.

COMPONENT	DESCRIPTION OF WORKS
Building envelope upgrade	
	When **insulating basement floors and foundations** then extruded polystyrene (XPS) and expanded polystyrene (EPS) is used, depending on specific building insulation solution choice
	**Insulation of external walls**. Analysed both – ETICS (refurbishment (B4) after 25 years) and pre-fabricated elements systems (designed service life at least 50 years). **New façade** – plaster (included also mechanical fixing and glue), painted wooden cladding (repainted every 10 years) and fibre cement board solutions (50-year life-span). **Replacement of windows** to improve energy efficiency. Analyses included double-glazed (U=1.4-1.8 W/(m^2K)) and triple glazed (U=1.4-1.1 W/(m^2K))
	**Insulating roofs** with mineral wool (blown cellulose, higher density rock, and glass wool plates were analysed). New roofing cladding (metal sheet) were also added.
New elements and systems	
	**New balconies** for the apartment building, since during renovation loggias were turned into heated rooms. In the case of post II WW housing crisis era apartment buildings with up to four stories, it is technically possible during renovation works to increase the heated area of the building, enlarge individual apartment units, enclose existing balconies, and construct new ones supported by individual foundations.
	**On-site renewable electricity production** integrated to buildings, both roof and façade systems (archetypes 6-8) were analysed. For archetype 3, to achieve EPC-A some PV panels were added to next to the building, since the roof geometry did not provide enough suitable installation area.
	**Heat-recovery HVAC system** added, mandatory to achieve minimum requirements for EPC-C. System will be same for EPC-C, EPC-B and EPC-A class buildings

3.5 Renovation cost

Analysing the energy (heating and electricity) and building materials for a reference study period of 50 years, the average cost values were calculated. The baseline for electricity and district heating was the year 2020. District heating cost was 60 €/MWh and electricity 120 €/MWh, with a linear growth of 3% per year used. To assess the cost effectiveness EN 15459-1:2017 (Energy Performance of Buildings - Economic Evaluation Procedure for Energy Systems in Buildings - Part 1: Calculation Procedures, Module M1-14, 2017), in accordance with the global cost calculations (Equation 2) according to EN 15459-1:2017 were made.

Equation 2. Global cost calculation.

$$C_g(\tau) = \frac{C_i + \Sigma_{i=1}^{20}(C_{ai}(j) \times R_d(i))}{A_{floor}} - \frac{C_g^{ref}}{A_{floor}}$$

Where Cg(τ) is the global cost (referred to the starting year), €/m²; C_i is the initial investment cost (self-financing of a renovation loan), €; $C_{ai}(j)$ is the annual cost of year i for the component j (energy cost and loan payback cost), €; $R_d(i)$ is the discount rate for year i; C_g^{ref} is the global cost of the reference building, €; A_{floor} is the net floor area, m².

Based on current practice, the cost of renovation was calculated considering 85% loan financing and 15% self-financing. A discount period of 20 years was selected because the maximum period for renovation loans for apartment owner associations in Estonia is 20 years. The cost-optimal level was defined as “the energy performance level, which leads to the lowest cost during the estimated economic life cycle, according to the Building Performance Institute Europe (2012).

The costs of the building materials, components and construction work originate from Estonian construction companies. These companies were the main contractors, who renovated the reference buildings (archetypes 1–6). Cost data was analysed using insulation options of the building thermal envelope, where external walls, windows, and roofs are variable parameters. The renovation strategies (Figure 17) were pre-fab timber elements and ETICS. The construction cost for external wall insulation solutions (pre-fab and ETICS) are based on the Archetype 5 building.

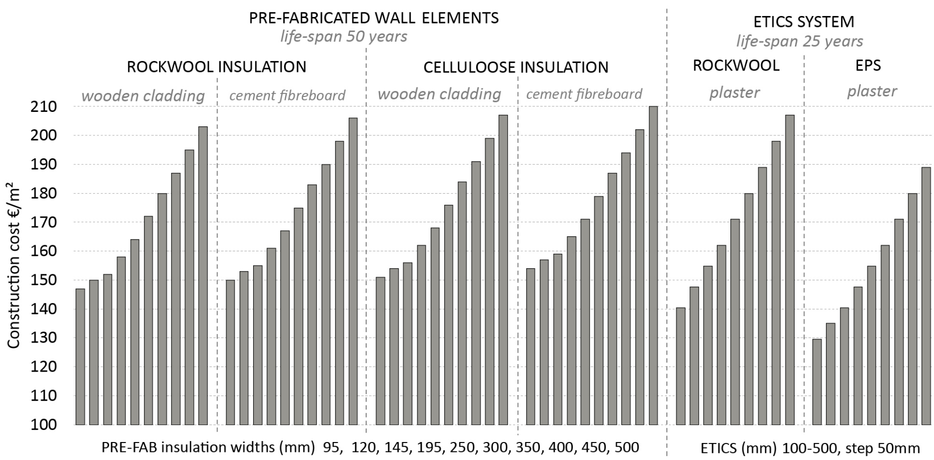


Figure 17. Relation between cost, energy and external wall insulation relation (I).

Figure 17 illustrates the cost comparisons between different renovation scenarios for apartment building external walls. While pre-fab insulation systems are associated with higher initial construction costs compared to ETICS, it is notable that the expected refurbishment module (B4) of ETICS is 25 years (Ximenes et al., 2015), whereas the pre-fab solution offers a lifespan of 50 years (Goulouti et al., 2020), assuming that façade material is maintained regularly. Consequently, despite a higher initial investment, pre-fab systems are likely to incur lower maintenance costs over the long term, making them more cost-effective from a whole life-cycle perspective.

The cost calculations include a range of construction-related works, such as production drawings, material transport to the site, installation, fasteners, crane use, and 30-year façade maintenance. Window replacement costs, calculated using the same principles, were €145/m² for windows with a thermal transmittance (U-value) of 1.1 W/(m²K), and higher (200 €/m²) for windows with improved U-values of 0.8 W/(m²K). The cost of roof insulation with loose-fill cellulose fibre, including new metal sheet roofing, ranged from €18/m² for 800 mm thickness to €22/m² for 1000 mm. As demonstrated by the data, external walls and windows represent the most significant cost components in the overall renovation strategy.

3.6 Enabling deep renovation in detailed planning

Studies included in the thesis show how environmental and energy-related considerations are currently addressed within the framework of detailed spatial planning in Estonia. Current planning practices omit some key aspects arising from climate targets such as the management of localised soil contamination or the integration of infrastructure for electric mobility and cycling. Therefore, a methodological extension in assessment is needed, whereby land use plans are assessed for their capacity to support local renewable energy production and urban decarbonisation goals.

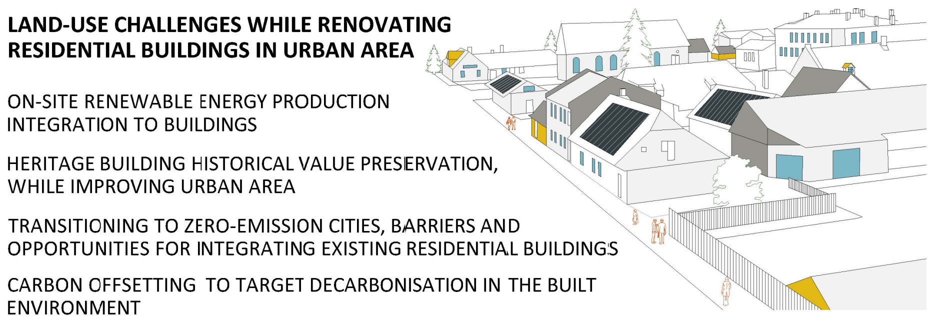


Figure 18. Land use challenges while renovating urban area.

Planning-related challenges in deep renovation of residential buildings occur during large scale residential building renovation (Figure 18), involving the calculation of energy generation potential from building-integrated PV panels, the identification of land suitable for biomass energy cultivation (emission free heating) and the mapping of areas with natural carbon sequestration potential (compensating embodied carbon emissions). These different considerations should be taken into account. These spatially explicit evaluations are part of a broader methodological concept – to establish a process for assessing the carbon offsetting and energy generation capabilities of urban areas at the neighbourhood scale. Such early-stage assessments are essential for aligning detailed planning with intertwined renovation and energy transition strategies.

3.7 Building stock modelling

The methodological framework of this thesis incorporates a policy-level perspective to account for the evolving Estonian national and European directives shaping best renovation practices and climate targets. In the Estonian context, heritage conservation requirements present a barrier to deep renovation, limiting the applicability of typical energy-efficiency renovation solutions.

The national LTRS has provided the methodological choices for this study, guiding the national decarbonisation targets for the renovation of pre-2000 residential buildings. The LTRS, while mandating renovation to an EPC-C as a minimum standard, served as a foundational benchmark for scenario modelling.

Building stock modelling utilises comprehensive data provided by the EHR – the Estonian digital twin encompassing the entire residential building stock. This database facilitated the creation of archetype-based scenarios and enabled the differentiation of renovation solutions. Consequently, the data used from the EHR database confirmed the relevance of the LTRS strategy and the data applied therein.

Considerations are aligned with the latest revision of the EPBD, which extends the scope of building performance beyond operational energy emissions to include embodied carbon. Dong et al. (2023) emphasise that archetype-based LCA models enable a more comprehensive assessment of policy measures by providing realistic representations of building stock, thereby reducing the risk of overestimating environmental benefits. This reflects a more holistic understanding of climate impacts throughout the whole building life cycle.

Until now, Estonian national policy has focused on operational energy consumption, without any evaluation of the embodied carbon impact of building materials and maintenance/replacement loads. The estimation supporting the Estonia LTRS target to renovate the entire building stock by 2050 was primarily based on projected reductions in operational energy use, along with assumptions about the decarbonisation of the national energy system, thus focusing solely on operational emissions while excluding embodied impacts. As a result, life-cycle emissions are excluded from strategies and have remained unaddressed in both legislation and planning practice.

The building stock model consists of the pre-2000 residential stock nationwide for 2020–2050 in annual time steps. The stock is disaggregated by dwelling type (detached houses; apartment buildings) and territorial category used in the LTRS (regional centres, second-tier centres, immediate hinterlands, transitional zones, peripheral areas). This matches the LTRS projections that underpin demolition, and renovation flows and ensures policy consistency across scenarios.

The current LTRS (LTRS, 2020) expects that 4.8 million m² of detached houses and 5.0 million m² of apartment buildings will fall out of use by 2050, mainly in peripheries and transition zones. In this study, the expected demolition of the abandoned residential buildings is anticipated to occur according to a non-linear scenario presented by the LTRS (LTRS, 2020). The resulting development in the residential building stock constructed pre- 2000 is presented in Figure 19.

The baseline stock comes from the Estonian Building Registry (EHR, 2025) digital twin (net floor area, construction decade, construction type, and location). Records with missing or conflicting area/type attributes were dropped, while incomplete heating-system fields were imputed using typology-by-decade patterns reported in national surveys and prior studies (Butt et al., 2022). The cleaned EHR dataset is then mapped to the archetype set used for LCA and scenario construction

To situate the stock dynamics underpinning the scenario analysis, Figure 19 compiles EHR-based baseline areas with LTRS projections for the pre-2000 residential stock. It disaggregates detached houses and apartment buildings and distinguishes two flows

1. Renovated floor area (minimum renovation requirements EPC-C);
2. Floor area remaining in use without renovation;

The figure thus visualises the assumed pace and sequencing of renovation, the progressive contraction of peripheral stock, and the evolving composition of the national dwelling area to 2050, providing the quantitative boundary condition for the subsequent national scenarios and indicating when embodied renovation flows are expected to peak and subside.

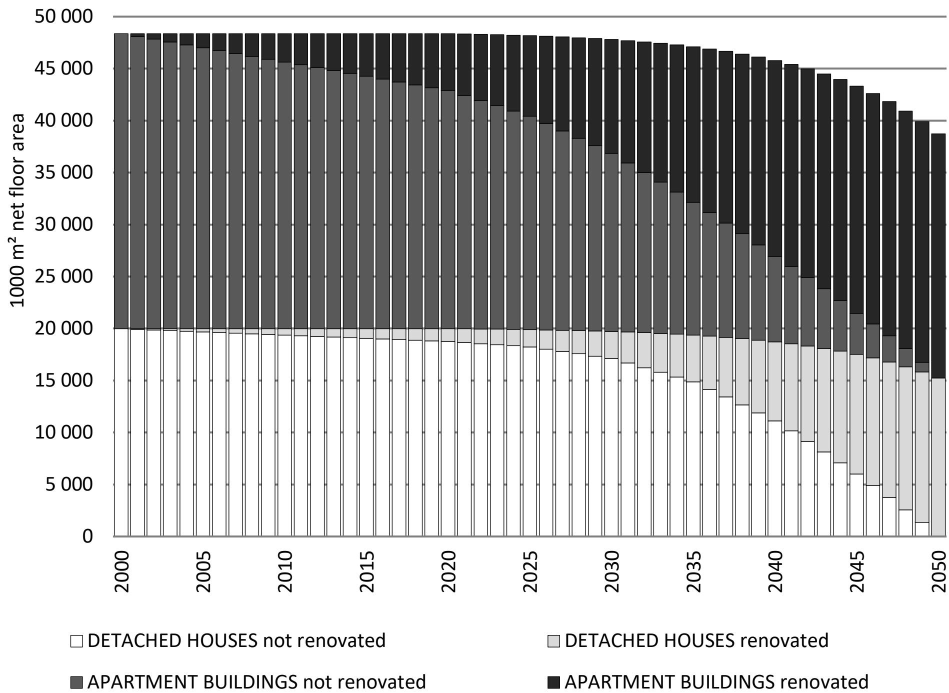


Figure 19. Projection of the residential building stock constructed before 2000 according to LTRS (IV) (2020).

Renovation activities outside of large urban centres often face additional economic challenges, warranting higher financial incentives to enable equitable participation in national climate agenda activities. The calibration to 2020 delivered energy against Odyssee-Mure household statistics (2025) tested sensitivity to (a) pre-renovation demand, (b) EKUK (2025) decarbonisation speed, and (c) B4 replacement cycles.

The baseline (BAS) scenario served as a policy-neutral reference, assuming no systematic acceleration of deep renovation, no additional decarbonisation of electricity or district heat beyond current practice, and stock evolution driven only by natural attrition; the LTRS out-of-use pathway for abandoned/peripheral buildings was retained for consistency. Policy-active comparisons included:

1) **C scenario**, with full implementation of the LTRS to EPC-C by 2050 combined with EKUK decarbonisation;
2) **B scenario**, identical to C-scenario but targeting EPC-B;
3) **C_CI2023 scenario** assumes that the entire residential building stock constructed before 2000 is renovated to an EPC-C by 2050, in line with the LTRS projections.
4) **B_CI2023 scenario** mirrors the assumptions of the C_CI2023 scenario but assumes that all buildings are renovated to an EPC-C, with carbon intensities remaining constant at 2023 levels.
5) **C_43–43 scenario,** which renovates only the worst-performing 43% of the stock to EPC-C constructed before year 2000, paired with EKUK decarbonisation targets.
6) **C_HS2023 scenario** models the full renovation of the pre-2000 residential building stock to an EPC-C, while maintaining the current distribution of heating sources.

Calculations of land-use changes to provide local renewable source energy production such as PV-panels and the required area of biomass for efficient district heating to compensate for the emissions generated in the study area were conducted. Current GHG practices utilise greenery as passive carbon sequestration, such as forest carbon sinks, to achieve net-zero targets (Hudiburg et al., 2019). On the other hand, Havu et al. (2022) showed that typically trees in an urban context are not carbon sinks as within their total lifespan, emission and sequestration balance to zero. Additionally, it is argued (Allen et al., 2024) that this is misleading, as passive sinks result from natural processes rather than active climate action. Relying on them allows residual emissions to continue warming the climate, potentially delaying effective mitigation efforts. This argument is supported by Brunner et al. (2024), who state that only permanent carbon removals, lasting at least 1000 years, can offset fossil emissions. Natural sinks, like forests, do not meet this criterion, making geological storage essential for credible carbon sequestration.

Evidence on one-stop-shop (OSS) renovation services indicates that, when supported by municipalities, OSS models provide proactive, end-to-end assistance across the critical phases of the renovation project and reduce (Pardalis et al., 2022) information and transaction costs for owners. In building stock modelling, these findings justify treating renovation uptake as policy-sensitive – OSS should be interpreted as an enabling mechanism that can sustain the LTRS-consistent renovation rates assumed in the scenarios and improve sequencing and standardisation of envelope and systems upgrades.

4 Results and discussion

4.1 Residential building renovation carbon footprint

In Estonia's cold climate, operational energy use (module B6) is the most dominant total life-cycle emission source (Figure 20), making energy efficiency and heating source critical factors for the decarbonisation of the existing residential building stock.

This scenario-based approach allows for the quantification of carbon reduction potential across typologies and provides insight into the interplay between building geometry, construction period and heating source (embodied and operational carbon relation).

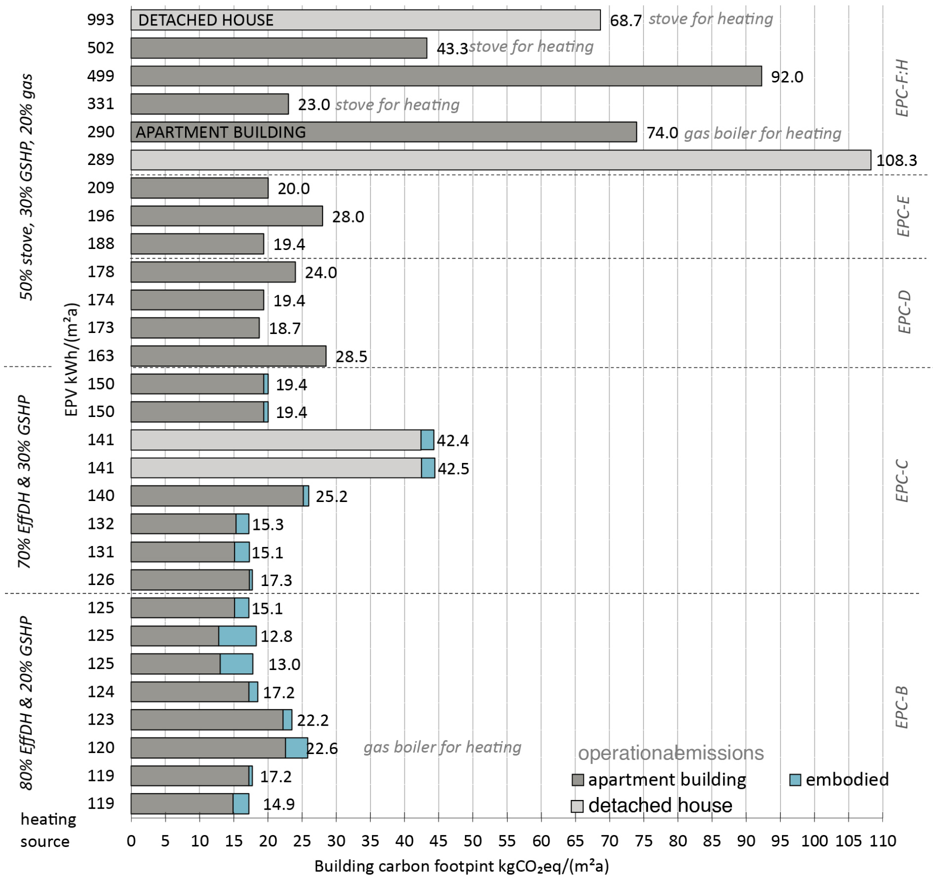


Figure 20. Residential buildings energy performance (vertical axes) and carbon footprint (hor. axes) before and after renovation.

The comparative assessment (Figure 20) reveals that apartment buildings' renovation measures consistently demonstrate a lower CF compared to detached houses. This trend is largely attributed to more efficient building geometry, compact layout, and a higher energy efficiency. Among apartment buildings, a clear correlation is observed between building height and emissions, the greater the number of stories, the lower the CF per net floor m².

However, the analysis also demonstrates that the type of heating source is a critical determinant of use phase operational emissions (B6). For instance, although the five-story building (EPV 120 kWh/(m²·a)) accommodates many dwellings, its reliance on natural gas in combination with district heating results in a substantially higher carbon footprint compared to similar buildings using efficient district heating (EffDH) alone. This underscores a conclusion – the environmental impact of residential buildings is strongly influenced by the heating source, and minimising carbon intensity in the energy system is essential for reaching climate targets.

The results indicate (I) that from a circular renovation perspective, deep renovation is preferable, as it helps to achieve lower operational emissions. However, it is achievable in locations where the energy system has high emissions. Also, using pre-fab elements reduces refurbishment needs (module B4) l leading to lower embodied carbon emissions over the total building lifespan, as these elements have a longer life-span than ETICS.

While cost-optimal solutions focus on minimising expenses (renovation to EPC-C), they do not always align with the most effective strategies for reducing carbon emissions. In contrast, CF optimal approaches prioritize long-term emission reductions, which can lead to lower energy demand in buildings over time (Figure 21) and tackle the challenges in refurbishment (B4). This suggests that integrating carbon considerations into renovation planning can result in more sustainable and energy-efficient outcomes, even if initial investments are higher.

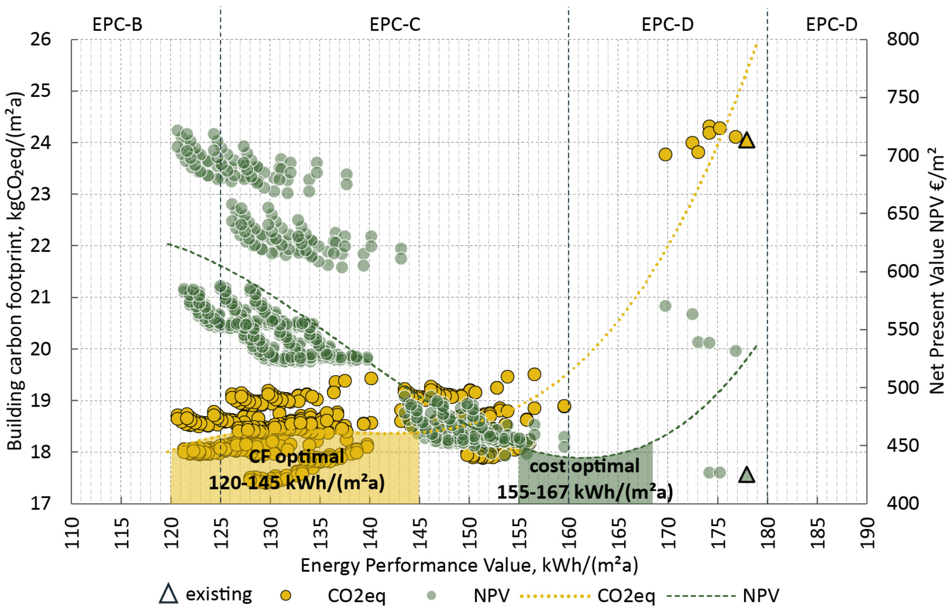


Figure 21. Carbon footprint and cost optimality relation (I).

The solutions that achieve both cost-optimal and CF optimal outcomes are mineral-wool insulation systems with total thicknesses of 145–500 mm. Within this optimum range, the façade may be covered with wooden cladding or fibre-cement panels, both satisfying the optimal CF and cost criteria. The carbon-footprint optimum sits around EPV 120–145 kWh/(m²·a), while the cost optimum lies around 155–167 kWh/(m²·a);

their overlap defines the recommended design space. None of the ETICS solutions are included here, due to their short service life (25 years).

As the EPBD aims to reduce GHG emissions, it is essential to prioritize carbon optimised solutions (I). This approach is necessary to achieve the decarbonisation of the existing building stock, aligning with the national long-term renovation strategy. The (I) study shows that an CF optimal solution can be considered a more relevant carbon neutrality benchmark for deep renovations, instead of a cost optimal solution.

4.1.1 Operational energy development relation to heating source

In the (II) study, time-dependent energy emission factors were modelled based on national decarbonisation scenarios, allowing for a dynamic representation of operational emissions across the 50-year period. For the future, a standardised approach is needed, one that clearly defines whether static average, time-weighted average, or year-by-year dynamic factors should be used for B6 calculations. The wood stove heating factor should be overlooked (Figure 22), as currently does not take into account emissions which are occurring after burning. The analysis is based on the Archetype 3 heating source change, without implementing any other renovation measure (insulating the building envelope or changing openings).

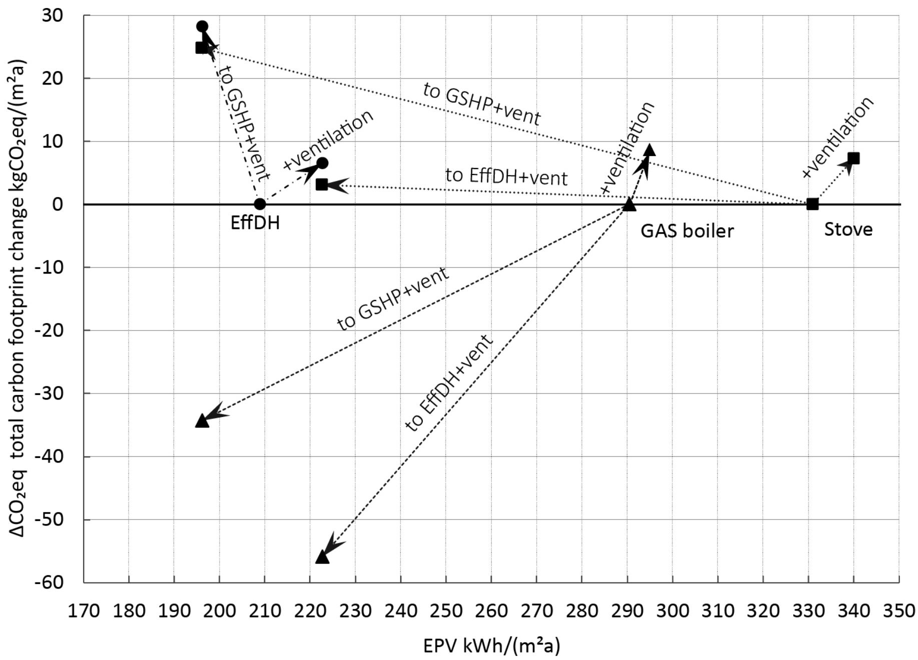


Figure 22. Heating source change impact to building CF (II).

The addition of HVAC alone results in an increase in emissions due to the higher need for electricity. The analysis shows that due to the currently low emission factor for stove heating in Estonia, switching to Efficient District Heating (EffDH) or Ground Source Heat Pump (GSHP) may increase the building CF. In contrast, for buildings that are heated with natural gas, both EffDH and GSHP offer environmentally beneficial alternatives. From a CF perspective, it is essential that renovation efforts not only include a modern HVAC system after renovation but also improve the energy performance of the building envelope. In the Estonian context, EffDH is one of the most suitable solutions (II).

4.1.2 The effect of the change of carbon emissions

Improving energy performance to this level ensures a lower energy need with greater reduction in operational emissions, thereby decreasing the building's CF. However, it does not include renewable energy production which would further help achieving national climate commitments (especially decarbonisation goals).

To evaluate the long-term carbon implications of the renovation strategy, a case study was constructed using the Archetype 3 building. The ΔCO_2eq calculation (Equation 1) was applied, to compare total emissions over a 50-year lifespan between the existing condition, renovation as BAU and renovation to EPC-A. This equation enables a clear visualisation of how carbon emissions accumulate across the building's whole life cycle, considering both operational and embodied emissions. The example presented in Figure 23 illustrates this for the Archetype 3 (Table 2), reflecting an apartment building under heritage protection built before the year 1930. The indoor environmental conditions of the existing building are insufficient (HVAC systems are not renovated). After the improvement of indoor climate systems, emissions from electricity will increase.

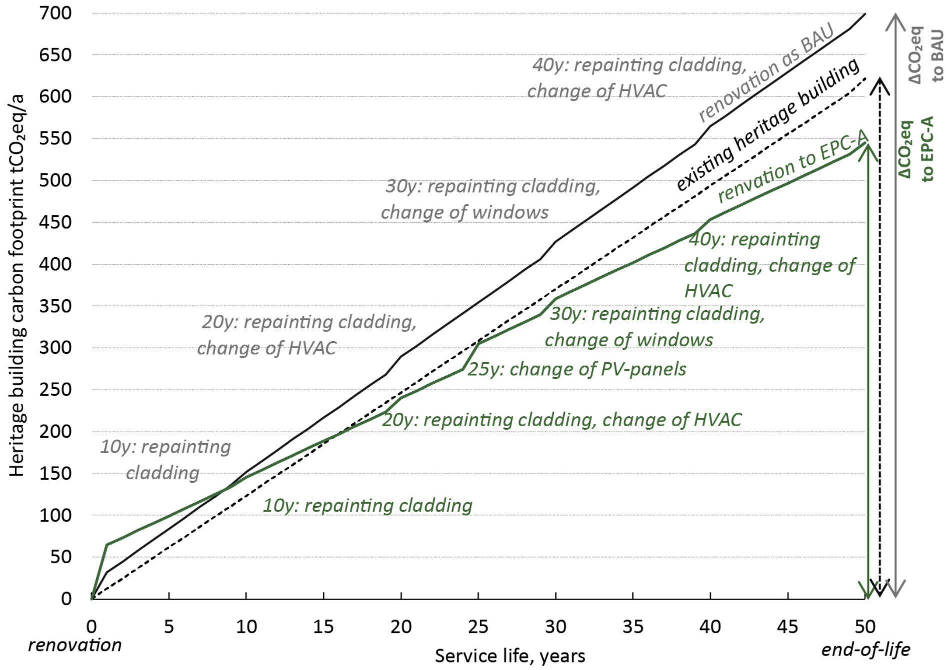


Figure 23. Illustration of ΔCO_2eq change.

This example (Figure 23) demonstrates that renovating the building to EPC-A results in a total carbon emission reduction of over 10% across a 50-year period, whereas typical BAU situation for the same building increases carbon emissions by 10% compared to the existing condition. In this context, such renovation is possible when the original heritage value is not altered, when the identified values allow for intervention (i.e., there are indications that no significant restrictions apply), and when the original building materials cannot be restored or have deteriorated beyond repair, meaning these must be replaced with new materials in any case.

In the heritage building (II) renovation (Figure 24), if there is evidence indicating that the current building generates more emissions than it would if it were energy-efficiently renovated, and it can be achieved without compromising building's external appearance, then deep renovation should be considered.

The results support (II) the broader conclusion of this thesis – such renovation not only reduces emissions but also contributes to improving the overall urban environment, by restoring deteriorated buildings and revitalizing city centres as active, lived-in spaces. Deep renovation combined with thoughtful life-cycle planning, is necessary to meet national climate targets and ensure the long-term decarbonisation of Estonia's existing residential building stock. The results of the publications (I-III) indicate that for achieving carbon neutrality, the renovation target should be set higher than the currently required minimum requirement for the renovation (EPC-C).

Figure 24. Heritage building before and possible outcome after renovation (render). Right: K. Tõra & K. Kalda.

4.2 Land use planning development during renovation wave

Planning is an important aspect of how renovation strategies affect spatial requirements for energy production and emission compensation perspective (III-IV), this is just one aspect from a larger perspective.

Low-carbon renovation measures are particularly relevant for multi-story apartment buildings in regional centres, where widespread application can significantly reduce building stock emissions. On-site electricity generation (requirement for EPC-A) further amplifies these reductions by lowering grid electricity demand (IV). However, adding HVAC systems can increase operational emissions if national grid electricity remains carbon-intensive. While PV panels can offset this additional demand, their effectiveness is constrained in dense urban areas and varies seasonally, with most production occurring from March to October.

The area needed to compensate CO_2eq emissions analysis (Figure 25) is based on a case study consisting of 22 multifamily apartment buildings in Tartu city (total case-study area 13 ha), most of which are currently categorised as EPC-D and F class buildings.

To assess the implications of different renovation levels on the built environment and surrounding land use, three scenarios (Figure 25) were analysed, incorporating both operational and embodied carbon emissions compensation:

1. existing condition;
2. renovation to EPC-C (current renovation requirements);
3. renovation to EPC-A (nZEB standard).

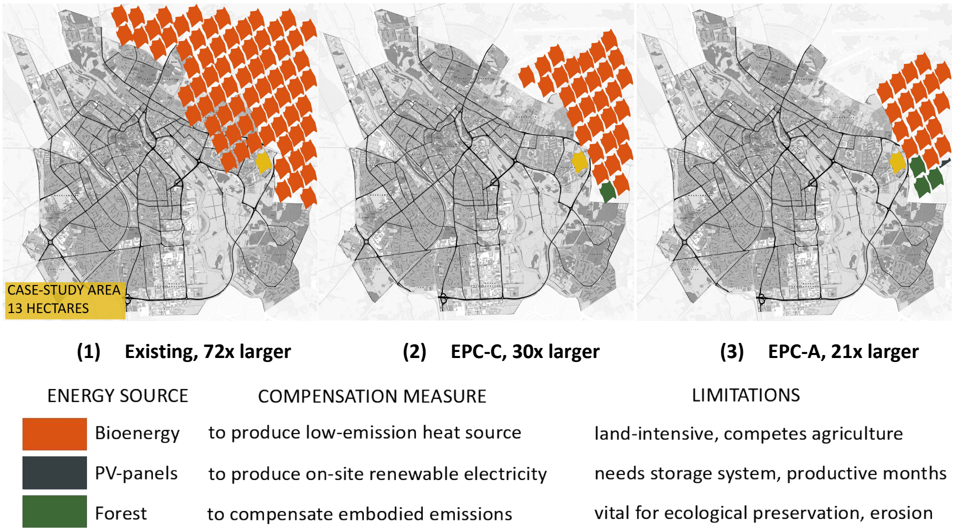


Figure 25. Urban land area needs to compensate emissions (III).

The study focuses on the land use area dimension of urban energy planning by estimating the land area required for local renewable energy production (energy bush, PV panels) and carbon offsetting (new forest) under each scenario. Figure 25 illustrates the scale and composition of these land use requirements, including allocations for heat production, on-site electricity generation, and carbon sequestration, comparing case-area size (ha) with different areas required to compensate emissions.

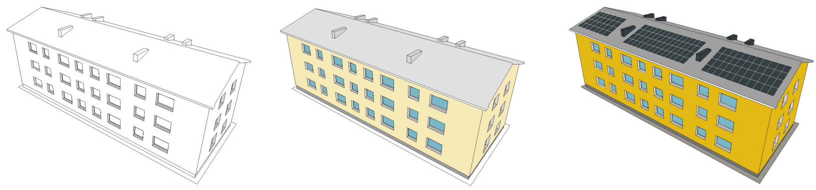
The results indicate (III) that among the three analysed scenarios, renovation to EPC-A requires the least amount of land area to meet the energy demand and carbon offset targets. Analysis reveals that the greatest land demand is consistently linked to the production of energy biomass (current alternative – energy bush), across all categories. This finding underscores the critical importance of reducing emissions from district heating sources. Upgrading the efficiency and decarbonisation level of urban (heating) infrastructure therefore represents a key strategic pathway for supporting sub-national emission reduction targets.

Finally, findings from the Estonian (III) study revealed that the current renovation minimal requirement scope (EPC-C) remains insufficient considering national and European climate neutrality goals. The overarching methodological proposition is that climate-responsive urban planning should include both land use energy potential analysis and comprehensive life-cycle emission accounting as integral components of planning and buildings renovation processes.

4.3 National residential renovation policy measure development

Studies and analyses conducted for this thesis have found that achieving EPC-C through renovation is not sufficient on its own. National strategic documents should emphasise the importance of combining energy efficiency improvements with the integration of on-site (Figure 26) renewable energy systems.

This analysis supports the statement that the cost-optimal renovation criteria, as defined in current national policy for renovated buildings at the EPC target level, are not sufficient to meet long-term climate goals. The findings of this thesis suggest that renovation measures should instead be evaluated based on their whole-life carbon performance, placing the buildings CF at the centre of renovation assessment frameworks.



	EXISTING	EPC-C	EPC-A
Building envelope	*U*≈1,0 – 0,8 W/(m²·K) 2-pane windows Leaky building envelope	Well insulated (foundation, external walls and roof), triple-glazed windows	Highly insulated foundation, external walls and roof, triple-glazed windows
HVAC	-Natural passive stack ventilation that does not provide sufficient air change indoors Hydronic radiators without thermostats that do not provide an operative room temperature change No mechanical cooling	Yes Ventilation heat recovery Hydronic radiators with thermostats Balanced heating system New pipes for the water and sewerage system Metering of consumption	yes
On-site energy production from renewable sources	-	no	On-site renewable energy production (PV panels) Solar collectors for DHW

Figure 26. Energy performance development.

As illustrated in Figure 26, achieving EPC-A not only improves energy efficiency through a highly insulated building envelope and modern HVAC systems but also drives the integration of on-site renewable energy production, such as PV panels. This dual approach significantly reduces operational emissions (module B6), especially in the case of Estonia's high grid electricity emission factor (Figure 14). From a carbon perspective, on-site electricity generation is a critical advantage that EPC-C scenarios are missing. Estonia's national building stock analyses found (IV) strong evidence supporting the recommendation of including PV-panel's, even for buildings not yet meeting EPC-C. This aligns with the EPBD requirement that all new buildings must be "solar-ready", designed to optimise the solar generation potential based on the site's solar irradiance, according to the Article 10 of the EPBD (*Directive - EU - 2024/1275*, 2024).

The results show that most of the energy-related emissions originate (IV) from apartment buildings located in regional centres, where district heating is the primary energy source. While these buildings play a central role in the overall emissions profile, the inclusion of embodied emissions in the life-cycle assessment appears to have only a modest influence (Figure 27) on the overall decarbonisation trajectory, as operational energy use remains the dominant factor in this context. However, as operational emissions decline over time, embodied emissions will gain more focus.

Furthermore, the studies proved (IV) that improvement in building energy class is correlated with reductions in the whole CF. Buildings with better energy performance classes consistently fall into lower emissions (I), demonstrating that carbon-optimal renovation increases a building's energy efficiency compared to a cost-optimal solution. Therefore, shifting from a cost-based to a carbon-based renovation criterion would not only align with national policy but also with the revised EPBD. While increased embodied emissions may partially offset the gains from ambitious renovation targets, the integration of on-site PV panels offers a significant opportunity to lower overall emissions and support the decarbonisation of the residential building stock.

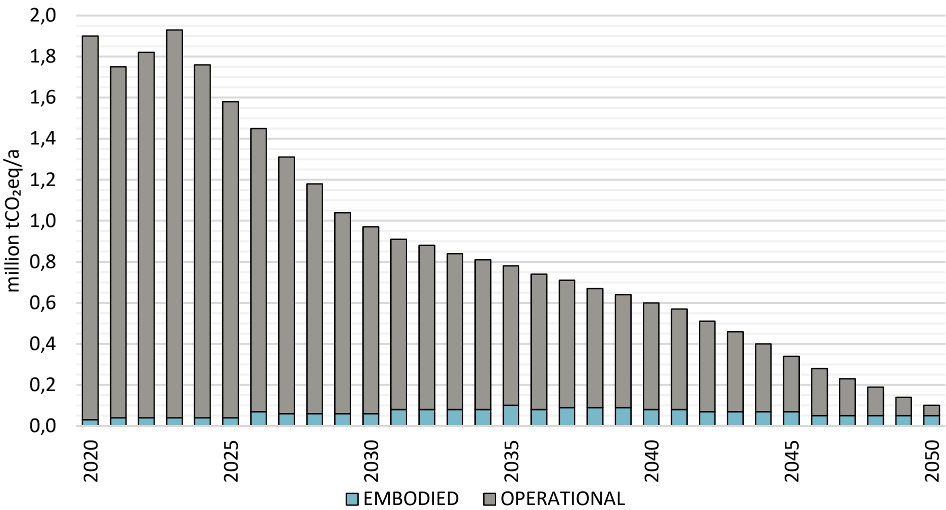


Figure 27. Annual GHG emissions from residential building stock, if 43% is renovated (IV).

The results indicate that the full implementation of national building decarbonisation strategies could reduce annual GHG emissions from Estonia's existing residential building stock by up to 95% (IV) compared to the year 2020. When the decarbonisation of electricity and district heating follows the scenarios, renovating 43% of the residential building stock will cut the total emissions by 87%, which is almost as much as the renovation of the entire residential building stock. While the LTRS projected a 90% emission reduction, a study with more detailed analysis, including embodied emissions, shows an 95% reduction from the 2020 level.

However, if the fuel mix for electricity and district heating remains unchanged, large-scale renovation could paradoxically lead to higher total emissions than in the baseline scenario due to increasing electricity demand. This underscores the need for policy to address not only energy efficiency but also the decarbonisation of energy supply.

Improving the EPV and installing PV panels are environmentally beneficial in situations where grid electricity has high emission intensity, such as in Estonia.

While study (IV) shows that renovating 43% of the residential building stock to EPC-C can already add up to 85% of GHG reduction, this assumes parallel decarbonisation of the energy supply. If grid carbon intensity does not decrease, deep renovations alone will be insufficient to achieve climate targets, a dependency that should be reflected upon in policy design.

In Estonia, the projected emission intensity of electricity by 2048 is expected to align with Sweden's current levels (IV). Under such conditions in the future, the primary challenge in building stock decarbonisation will shift from operational emissions to embodied carbon, emissions originating from construction materials. Prefabricated external wall elements stand out (I) here as a key strategy to mitigate future risks related to the handling, processing, and decreasing emissions from buildings.

4.4 Results comparison with similar studies

In Estonia, operational energy remains the principal driver of whole-life carbon until the energy system decarbonises substantially. By contrast, Nordic literature reports a greater relative focus on embodied impacts, reflecting lower-carbon energy system. Swedish and Danish renovation LCAs consistently highlight significant material-related contributions alongside operation emissions (Ramírez-Villegas et al., 2019; Zimmermann, Rasmussen, et al., 2023) while Norwegian neighbourhood studies show that replacements over time account for a large fraction of embodied emissions in low-carbon contexts (Lausselet et al., 2021; Wiik et al., 2019). These patterns do not align with Estonia's results, as the balance between operational and embodied carbon is shifted in the Nordic cases by their cleaner energy systems (Wrålsen et al., 2018). However, a study from Lithuania supports current thesis findings, indicating that operational emissions have the largest impact on building CF(Chandrasekaran et al., 2021).

Nordic casework indicates that the existing residential stock is generally in better condition than in Estonia, with stronger baselines for building envelope thermal values and services (Avelin et al., 2017; Mjörnell et al., 2019). Consequently, the literature often examines incremental upgrades and optimisation of HVAC systems, rather than the deep renovation solutions which are needed by Estonia's pre-2000 stock. Where deep renovations are made, they are framed as ambitious exemplars rather than typical needs (Wrålsen et al., 2018).

Across Finland and Denmark, studies demonstrate that cost-optimal packages can deviate from carbon-optimal pathways over multi-decade horizons, even in comparatively efficient stocks (Montana et al., 2020; Niemelä et al., 2017; Pal et al., 2017). This validates the thesis finding that relying on cost-optimal solutions (EPC-C as an end-point) risks misalignment with long-term climate goals (I). With a lower-carbon energy system in Scandinavia, the operational energy emissions penalty for stopping at cost-optimal levels is smaller than in Estonia, so Nordic debates emphasise embodied-carbon boundaries and replacement cycles earlier than the current phase in Eastern-Europe (Lund et al., 2022; Zimmermann, Rasmussen, et al., 2023).

4.5 Further LCA methodology development

The studies in this thesis applied and tested the current Estonian LCA methodology in a new context, renovation, but also identified its limitations and necessary extensions. It provides a methodological example for national LCA methodology development. Addressing this issue requires national-level policy alignment and financial mechanisms to support low-income or structurally disadvantaged building owners.

During the thesis process, the Estonian CF method description and the supporting national material emissions database have been revised. To evaluate the differences between the two versions of the calculation method, a comparative analysis (Table 6) was conducted using the Archetype 4 (Table 3) as-built version. This involved applying both, the previous and updated versions of the LCA methodology and database. The calculation period remained consistent at 50 years. The primary change in the updated methodology concerns the construction materials database, which now relies on Estonian manufacturer-specific data, replacing the earlier approach that was based on the conversions of the Finnish national database. This adjustment allows for a more accurate representation of local material production and its associated environmental impacts.

Table 6. Building carbon footprint change between two methods.

version	FIRST	UPDATED	%	WHAT CHANGED
	01.2022	09.2024		
indicator	GWP_{total}	GWP_{fossil}		
	$kgCO_2eq/(m^2a)$			
A1-A3 Material production	**2.78**	**2.96**	**+6**	**Country based material producers' emission factors**
A4 Transport	**0.04**	**0.09**	**+44**	**Added empty run transport emissions from the construction site, and the accuracy of estimating on-site travel has been improved.**
A5 Construction site	**0.06**	**0.72**	**+120**	**Added construction site energy and machinery emissions, based on net m²**
B4 Replacement	2	1.25	-37	The remaining product life is calculated out from the emissions
B6 Operational energy	12.92		-	Emission factors did not change, Figure 14
Electricity	*4.63*		-	
Heating	*8.27*		-	
C1-C4 End-of-life	0.71	0.4	-44	Local material producers in Estonia, particularly EPD declarations, the share of materials ending up as waste (C4) has decreased, and circular use has increased. However, this area likely still contains a degree of uncertainty.
SUM	18.5	17.7	-4	
D loads and benefits	-0.01	not included	-	Excluded from the updated method

Both, first and updated, Estonian CF methodologies (Table 6) have been designed for new construction, with clear guidance for calculating cradle-to-grave climate change impacts across the 50-year reference study period. The comparison illustrates the changes in building CF between two methodological versions, with particular emphasis on updates introduced in September 2024. Although the total value has slightly decreased (from 18.7 to 17.7 $kgCO_2eq/(m^2a)$), this reduction is largely based on assumptions about future improvements, particularly in material replacement (B4) and end-of-life scenarios (C1–C4).

In contrast, present-day emissions recorded at the construction stage (A1–A5) have significantly increased compared to the previous method. For instance, construction site emissions (A5) rose by 120%, and transport emissions (A4) by 44%, indicating a growing recognition of on-site energy and logistical impacts. These changes underscore the increasing importance of selecting low-impact, long-lasting solutions today, as current emissions from construction activities and material production are substantial and more influential than previously estimated.

This suggests a clear need to prioritise materials with both minimal environmental footprint and long service life in today's renovation and construction practices. However, as demonstrated in this thesis, there is a need to extend and adapt the methodology to suit the existing buildings and renovation decisions, particularly in the context of the renovation wave.

4.5.1 Towards an Estonian CF assessment method for renovation

As existing method is tailored for new buildings, it will leave out some renovation project aspects, which will create blind spots. The following suggestions and proposals (Figure 28) are based on studies from this thesis (from single external wall construction type solution to national existing residential building stock analysis).

The application of LCA method depends on its intended purpose. It may focus on reducing operational energy consumption, extending the longevity of buildings or supporting deconstruction practices to increase the proportion of components and materials suitable for circularity. Options

- Comparison between renovation and new construction;
- Evaluation of renovation options;
- Evaluation after renovation;
- Evaluation before and after renovation,

The proposed improvements have been designed in such a way that the Estonia national LCA method would not require the introduction of new modules, but rather extend the principles already established within the existing structure. All suggestions adhere to the logic and structure of the currently included modules, ensuring consistency and compatibility with the current methodology (Figure 28).

BUILDING ASSESSMENT INFORMATION											
BUILDING LIFE CYCLE INFORMATION											
A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1-C4	D
PRODUCT stage	CONSTRUCTION stage		USE stage							END OF LIFE stage	
ESTONIAN METHOD DEVELOPMENT FOR RENOVATION LCA											
TYPICAL RENOVATION CONSTRUCTION TYPE VALUES, BASED ON M²		INCLUDING BUILDING PARTS, WHICH WILL BE DISASSEMBLED DURING RENOVATION				PREVIOUS WORK TIMELINE, EXISTING COMPONENTS LIFE-SPAN		HEATING SOURCE CHANGE IMPACT TO CARBON FOOTPRINT		EXTENDING LIFE-SPAN BENEFITS ADDED IN THE CALCULATION	
NEW DATA NEEDS											
Elevators and staircases based on floors		Existsting staircase demolition				Existing openings, insulation, façade components emission balance		Wider operational energy emission factor database		C3: Reusable components and materials benefits	
HVAC for renovated apartment buildings		Roof demolition									
		Loggia demolition									

Figure 28. Estonian LCA methodology development for renovation.

Further development of **Module A1–A3** requires modifications to the methodology that allow for the inclusion of reused elements. Specifically, there is a need to establish a verification procedure and documentation under which the environmental impact of material may be accounted as zero. To enable a high-quality and practical CO_2eq impact assessment methodology for the renovation of Estonian existing (residential) building stock, some new data inputs are required. In the A1–A3 module, typical emission values must be expanded to include elevators and staircases introduced through vertical extensions, as well as HVAC systems commonly used in apartment building retrofits.

For Module A5, it is necessary to refine the accounting of emissions generated on-site during the renovation process. This concerns building components that are removed during renovation works (e.g., when loggias are enclosed, and the room is converted into a heated room). The criteria and methodology for assessing emissions related to both materials and construction equipment at this stage require further development. The A5 module should include for major demolition works linked to renovation, including the removal of existing staircases to allow elevator installation, roof demolition for vertical extensions (new floor) and loggia enclosure, often leading to new, separate balcony areas.

Within **Module B4**, a methodological solution should be developed to account for previous interventions (e.g., window replacements). Renovated buildings may already include components that do not require immediate replacement, but which need to be addressed later, for example 20 years after the current renovation. Therefore, a clear guideline should be established for how the timeline of previous works interacts with new renovation activities. In B4, emissions from retained materials and components whose service lives have not yet ended, for example windows, should be included, even in comprehensive renovation scenarios.

For **Module B6,** Equation 1 may be used as one option to assess the impact of different heating sources. Unlike in new buildings, where the heating source is predefined by building location and EPV requirements, renovations often present an opportunity to change the heating source type. As shown in Figure 14, the carbon impact of different heating options varies considerably. To assess the usefulness of these solutions, there is a need to extend and refine the emission factor database for operational energy, including upstream emissions, to support accurate evaluation. The B6 module requires a harmonised national operational energy emission factor database, reflecting the 50-year average and a clear update system.

Finally, within the **end-of-life stage (C1–C4),** particular attention should be given to module C3, which supports the accounting of reusable components and materials to foster circular renovation practices. In Modules C2–C4, the current methodology only accounts for materials added during the renovation. However, in the case of existing buildings, a large share of materials already exists and will eventually be deconstructed or demolished. These materials must also be considered when evaluating the end-of-life emissions for renovated buildings. Especially in the context where the lifespan of building materials or elements is not ended.

In summary, the findings of this thesis support the conclusion that a renovation-specific carbon footprint methodology is needed. This kind of framework would allow more accurate and dynamic assessments, including the timing of key interventions and their environmental impact. Importantly, it would serve not only policymakers but also building owners and managers, by providing a tool for evaluating both current and future investment needs and operational costs. When properly tailored, LCA can become a practical decision-support instrument for planning renovation works, aligning carbon reduction with building functionality and financial feasibility.

5 Conclusions

This thesis set out to examine how under the specific constraints of a cold climate, a historically carbon-intensive energy system can decarbonise the existing residential building stock. All observed results and scenario outcomes are calibrated to Estonian data and regulations. The conclusions below are bounded to these national conditions. While the analytical framework is transferable, the quantitative effects should not be generalised to countries with different climates, energy mixes, urban forms or heritage establishments.

RQ1. Carbon-optimal versus cost-optimal renovation. Under Estonian conditions, cost-optimal renovation (EPC-C) produces a higher whole-life carbon emissions than carbon-optimal renovation. The latter integrates low-carbon heat, energy efficient and low carbon footprint building envelope solutions and therefore delivers the greater emission reduction over 50 years. Cost-optimality if used as the principal policy measure, risks locking in energy performance that is inconsistent with Estonia's long-term climate targets.

RQ2. Historic buildings and carbon reduction. Current Estonia heritage practice limits building envelope upgrades, keeping operational emissions elevated. Where building values can be preserved (form, façade, original profile), deep renovation to EPC-A is feasible and results in lower carbon footprint emissions than either the BAU or existing as it is situations. These findings apply to the Estonian stock typologies and protection rules examined; different heritage standards elsewhere may alter the feasible scope.

RQ3. Climate-neutrality targets and land use in the urban area. In cold climate and high energy emission system cities, climate-neutral neighbourhoods require considerable land for zero-emission energy supply and for remaining-emission compensation. Deep renovation reduces that land demand relative to limited upgrades, because it lowers operational energy first. Consequently, land-use plans should clearly allocate areas for on-site or near-by energy generation and, where justified, for durable carbon-removal solutions. These spatial requirements were quantified for Estonian urban morphology and densities.

RQ4. Rethinking national renovation requirements. Building-stock modelling shows that, in Estonia, current EPC-C requirements are misaligned with a whole-life carbon pathway. When paired with energy-system decarbonisation consistent with national projections, carbon-optimal deep renovation yields emission cuts approaching ~80% by 2050. If energy-system and minimum requirements will be as it is, reductions are limited to ~33–46%. Accordingly, minimum requirements and grant schemes should prioritise carbon-optimal targets (EPC-A with on-site renewable energy creation), sequencing measures with the decarbonisation of electricity and district heating. These recommendations are framed for Estonia's policy, market and grid trajectories.

Within Estonia's specific context, meeting national climate targets requires moving from cost-optimal to carbon-optimal renovation benchmarks, enabling deep renovation of historic and standard residential building stock, while integrating on-site renewable energy sources to grid system. Urban planning must accommodate the land-use area of carbon neutral target strategies. Taken together, these Estonia-specific findings provide a robust, evidence-based basis for re-designing national renovation policy and for sequencing investments so that the existing residential stock can credibly progress towards climate neutrality.

5.1 Renovation CF calculations and reporting

To support the achievement of national decarbonisation targets and enable systematic monitoring of its progress, it would be reasonable to develop a user-friendly tool. It should be accessible to both energy calculation assessors and private homeowners.

Such solution (Figure 29) would help to simplify the evaluation of carbon emissions associated with renovation works and where necessary, support better-informed decision-making and policy guidance.

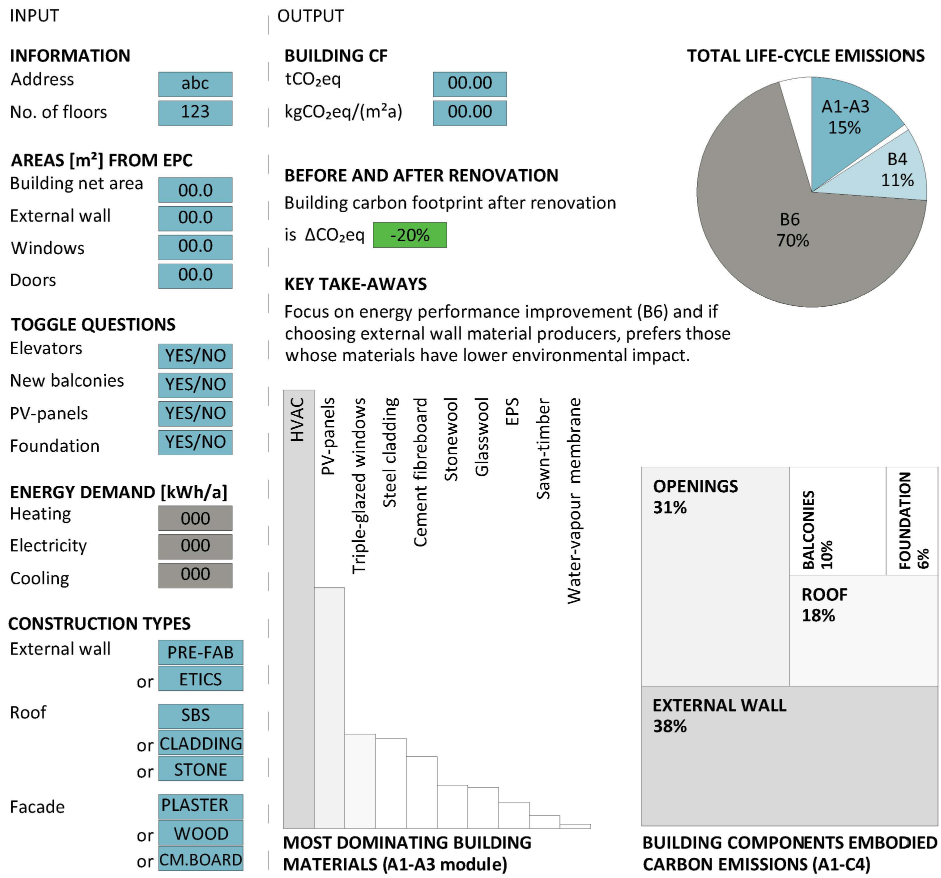


Figure 29. Renovation LCA – template example.

The indicative renovation template presented in Figure 29 includes 16 toggle or drop-down input fields that assist homeowners in calculating the CF of their residential building. This simplification is feasible in the Estonian context, as demonstrated in the current doctoral thesis, operational energy use (module B6) clearly dominates the overall life-cycle impact.

The template questions, combined with numerical values derived from the building actual and calculated EPC-s, enable a straightforward comparison between the current state and potential post-renovation outcomes (ΔCO_2eq). This reporting cand be extended, to have Life-Cycle Costing and larger variety of sustainability aspects cover similarly to Renobuild decision tool (Malmgren & Mjörnell, 2015).

6 Future research

This thesis introduces a novel framework for assessing renovation-related carbon emissions in Estonia and Eastern-Europe more broadly than previous studies. Therefore, it would be important as a next step to assess the carbon footprint of the existing residential building stock of all Eastern Europe (Latvia, Lithuania and Poland), as these countries have challenges (energy system and residential building archetypes) like Estonia.

The revised EPBD extends requirements beyond energy use to include embodied carbon and building material durability. The framework developed in this thesis supports this transition by broadening the focus from EPC ratings to whole life-cycle impacts while supporting on-site renewable energy. Currently, Estonian national operational energy emission factors include only direct emissions. Including upstream emissions in the future emission factors, especially for operational energy, could lead to more comprehensive and accurate results.

Estonia lacks mandatory and/or baseline CF values for buildings. This study demonstrates how different residential building renovation scenarios could inform CO_2eq benchmarks, supporting evidence-based policy and guiding renovation grants. Although, focusing only on carbon risks ignoring broader environmental issues such as biodiversity loss or mobility. Renovation strategies must consider total sustainability impacts. The findings also raise concerns for the forest sector, where rising demand for wood (pre-fab solution) requires transparent carbon accounting and sustainable sourcing, while Estonian forests remain carbon sinks and habitats of biodiversity.

Lastly, the current Estonian LCA methodology designed for new buildings CF lacks guidance for renovation. As a result, renovation assessments rely almost solely on Module B6, overlooking material impacts – replacement and existing components. A renovation-specific LCA methodology is needed to support accurate emissions tracking and inform building maintenance planning. Further development should aim for integrated, transparent, and policy-aligned solutions, that support both climate neutrality and broader environmental goals, while also helping building owners plan maintenance and ensure the long-term durability of buildings.

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Evaluation of renovation strategies: cost-optimal, CO_2e optimal, or total energy optimal?

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ABSTRACT

Currently, building renovation decisions are often driven by immediate investment expenses and short-term energy cost savings, rather than long-term optimisation. The difference between the national carbon footprint (CF) methodologies and the LEVEL(s) framework methodology is significant in relation to the application of energy scenarios. Energy scenarios are created at the national level and are not harmonised. CO_2e emission factor of Estonian grid electricity is among the highest in Europe and carbon footprints of Estonian buildings are typically dominated by operational energy use (B6) in Life-Cycle Assessment methodology. Therefore, carbon optimisation leads to better energy performance, than the previous cost-optimal benchmark. The application of the LEVEL(S) methodology would further emphasize the dominance of operational energy stage (B6) in Estonian results and guide towards even higher energy efficiency targets.

This study shows, that CF optimal renovation solutions differ from cost-optimal solutions and that CF optimal can be considered a more relevant energy efficiency benchmark for deep renovations, instead of cost optimal. It provides an analysis of different renovation solutions for a typical apartment building renovated in 2021. These solutions were examined using three parameters: life-cycle costs, total energy demand, and CF by applying the Estonian assessment method for ŧhe CF of construction works.

The results of this case study indicate that the renovation options for both CO_2e optimal end operational energy use (B6) throughout the life cycle provide similar results. The CO_2e optimal solution leads to lower building energy performance indicator level, than conditioned by cost optimal solution.

The current increasing energy prices are more substantially supporting solutions with lower CF, as total energy demand is an important economic factor not only in operational energy stage (B6), but also in material production, which was also investigated in this study. The results show that, if operational energy (B6) is excluded, there are significant differences in embodied carbon between the materials used for renovation. Lower carbon footprint renovation strategy involves the usage of pre-fabricated timber frame elements, mineral wool for insulation, wooden cladding or cement fibreboard in the facade. The prevalent External Thermal Insulation Composite System (ETICS) had the highest CF value and maintenance requirements during the building's lifetime. As the main objective of the Energy Performance of Buildings Directive is to drive greenhouse gas reductions, then the steering mechanism should be based on CO_2e optimal instead of cost optimal.

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1. Introduction

1.1. Demand

Collectively, buildings in the EU are responsible for 40% of the energy consumption and 36% of greenhouse gas (GHG) emissions, which mainly stem from construction, usage, renovation, and demolition [1]. If examined only from the perspective of resource efficiency, new construction should be considered as the last option and renovation as the first and main solution [2]. Approximately 80% of buildings used today are expected to be in use in 2050 [3]. To improve the energy performance of a building, the number of building renovations should be doubled over the next ten years [4]. If operational energy (B6) performance is improved during renovation, it can lead to lower carbon footprint (CF) results than new construction, because the amount of material used in renovation is usually less than that used in new construction [2].

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Based on the objective of reducing GHG emissions from construction work, it is urgent to evaluate CF in renovation strategies [5]. Currently, cost-optimization principle will guide the climate targets applied in steering mechanisms and policies driving the energy performance and renovation of buildings. However, more versatile options may need to be preferred in the future. As a building component, life age plays a significant role in sustainability.

The Energy Performance of Buildings Directive (EPBD) [6] targets the minimum requirements for the building energy performance. Annex 56 of the IEA EBC infers, that when the objective of the building sector is to reduce carbon emissions, it is necessary to use renewable energy with energy savings [7]. Although better energy performance of buildings improves energy security, thermal comfort, and financial situation, one of the main reasons for improving energy efficiency is the reduction in CO_2 emissions. It influences the effect of the whole picture, especially when operational energy (B6) is decreasing as it is nowadays in nearly zero-energy buildings. This led to a new focus on measuring the impact of embodied carbon [5]. With the future renovation wave, a new approach is necessitated, and cost-effective solutions alone cannot be the only criteria to measure the effectiveness of the renovation [4].

The 2010 recast of Energy Performance of Buildings Directive (EPBD) introduced the concept "nearly zero energy" as the new energy performance benchmark for the construction sector in the EU member states and instructed national authorities to define the concept in each member state based on cost-optimal level of energy performance [8]. For the EU to meet it's 2050 carbon neutrality targets, the EPBD puts the entire EU building stock on a clearly planned trajectory towards comprehensive renovation.

The 2022 recast of the EPBD emphasises the Renovation Wave strategy introduced in October 2020 and the assessment of the CF of the buildings. According to Article 7, "the life-cycle Global Warming Potential (GWP) of new buildings will have to be calculated as of 2030 in accordance with the Level(s) framework, thus informing on the whole-life cycle emissions of new construction." [9].

'Article 6 of the calculation of optimal cost levels aligns with the Green Deal, stating that "the costs of greenhouse gas allowances, as well as the environmental and health externalities of energy use, should be considered when determining the lowest costs. The Commission will review the cost-optimal methodology on 30 June 2026". [10].

1.2. Review of previous studies

Joelsson and Gustavson [11] found that homeowners have a higher interest in economic aspects than in environmental ones, when making renovation decisions. Pikas, *et al.* [12] stated that homeowners tend to be not interested in renovation, because it does not lead to a proportionate increase in their property value. Also, mechanical cooling was deemed as a non-cost-optimal solution because it increases both initial investment and operational costs [13]. Bonakdar, *et al.* [14] found that the cost-optimal parameter for renovation is closely related to the energy efficiency measure, as the majority share of energy is expressed in the heating demand. It has been proven that measurement of energy efficiency may depend on building allocation, therefore affect the total investment cost of a building renovation [14].

Recent study showed that the traditional approach for cost optimality evaluation for private and public investment projects, Net Present Value (NPV), tends to concentrate only cost savings from energy-efficient solutions excluding other non-financial advantages [15]. Almeida and Ferreira [16] declared that the Annex 56 now focuses on energy reduction. However, this does not cover the entire process of reducing carbon emissions. Farsätern, *et al.* [17] concluded that the choice of renovation strategy is important when total energy demand during building lifetime is being investigated. Kuusk, *et al.* [18] analysed nearly zero energy renovation concepts, that included heating, ventilation, envelope insulation and window replacement. However, no environmental aspects or effect of building materials used for renovation were analysed. Heinonen, *et al.* [19] applied a tiered hybrid LCA method to show that emissions from the construction phase can outweigh the operational energy (B6) during the lifetime of a building, depending on the building energy efficiency. Adamski [20] suggested that the building form should more thoroughly optimized in the early design phase, as this leads to significantly lower operational energy (B6) demand. Lihtmaa and Kalamees [21] stated that the goals of the carbon neutrality target do not consider aspects other than energy efficiency. Hirvonen, *et al.* [22] proved that energy retrofitting has other benefits beyond reduced utility costs, such as increase in property values, air quality and thermal comfort. Bragolusi and D'Alphapos [15] claimed that building inhabitants, who were willing to invest more in energy-efficient solutions, had higher levels of social and environmental awareness. Hamdy, *et al* [13] found that the most optimal solution for environmental benefit and low operating costs tend to require focus on the heating system during renovation of the building, as it has the highest impact on total energy costs.

Jochem and Madlener [23] stated that renovation creates co-benefits at the societal level, such as impact on climate change. Honarvar, *et al.* [24] proposed in his study that in order to reduce the GHG emissions of an old building, it should be necessary to focus on operational energy (B6) and added materials. Matthews *et al.* [25] indicated that the proportion of embodied emissions in built environment is increasing. As these are cumulative not annual emissions, it is critical to consider these components in terms of renovation strategies. Vilches, *et al.* [26] demonstrated that from the perspective of Life-Cycle Assessment (LCA), share of CO_2 emissions from material production and construction stage (A1-A3, A4, A5) and use stage (B1-B7), have changed over time due to applications of more energy-efficient solutions. Four retrofitting case-studies in Finnish example showed that CO_2 emissions can be reduced by around 50–75% by 2050 [27]. Niemelä, *et al.* [28] stated that it is possible to reduce CO_2 emissions by 63% when thermal comfort and energy efficiency are taken into account in deep renovations.

1.3. Purpose

Architects and designers are required to develop solutions and options to reduce costs and lower environmental impacts [29]. These financial and environmental aspects can be calculated from the used energy or the produced emissions during the entire building life cycle. For LCA analysis the replacement rate for building components is required. Embodied carbon has a greater influence on construction decisions, when operational carbon emissions decline as a result of implementing more energy-efficient solutions [30].

Earlier life-cycle assessment analyses for renovations typically analysed improvements in operational energy efficiency (B6) [31–33]. In addition, there have been different analyses on the optimization of the cost of renovation [34,35]. To the knowledge of authors, there has been no study on how all three parameters are related to each other.

Analysis presented in this study aims to compare different options for renovation strategies at three levels: cost optimality, energy efficiency and carbon emissions produced throughout the life cycle of the building. The objective was to determine the following:

- How does the selection of renovation options criteria influence the renovation solution?

- To what extent does the cost-optimal renovation solution differ from the optimal CO_2e or total energy optimal?

Hypotheses:

- CO_2e and total energy optimal lead to better energy performance than a cost-optimal solution.

- The difference between the CO_2e optimal and total energy-optimal solutions is less than the difference from the cost-optimal solution.

- New optimal solutions change the building envelope structures and thus affect the architecture.

- Current study concludes, that choosing carbon optimal wall type solution for renovation leads to more valuable and diverse urban space.

2. Materials and methods

2.1. Case-study building

A typical Estonian apartment building (Fig. 1) was selected as a reference building (Table 1, Table 2). The building was constructed in 1986 and fully renovated in 2021. It is a three-story apartment building comprising of 24 apartments. After renovation, the thermal envelope was based on pre-fabricated timber elements [36]. The building is heated using district heating and one-pipe radiator heating system. The building studied is privately owned.

Before renovation all apartments had natural passive-stack ventilation and windows could be opened for airing. In some of them, kitchens were equipped with hoods. Before renovation, radiators were not equipped with special thermostats; therefore, individual control of room temperature was impossible. The room temperature of the entire building was regulated in the heat substations depending on the outdoor temperature.

After renovation, loggias in front of the buildings were closed, which increased apartment floor area. New balconies were added to the rear of the building. The building received new roof covering, heat & ventilation system, windows and doors.

2.2. Indoor climate and energy performance modelling

Indoor climate and energy performance of the reference building were simulated using the IDA Indoor Climate and Energy (IDA-ICE) programme [37,38]. The programme is well validated [39] and allows the modelling of a multi-zone building, dynamic simulation of heat transfer and air flows, HVAC systems, internal and solar loads, and outdoor climate, and has been used in many energy performance and indoor climate applications [40,41]. Energy renovation measures are made according to standard usage and using a unified calculation methodology [42]. Internal heat gains were as follows:

- Inhabitants: 15.8 kWh/(m^2a). Heat of the inhabitants is counted from 3.0 W/m^2 and 80 W/person using the ISO7730 standard [43] (1.2 met, 0.7 clo);
- Appliances and equipment: 15.8 kWh/(m^2a). Heat from appliances and equipment is counted using 3.0 W/m^2 and the usage rate is 0.6.
- Lighting: 7.0 kWh/(m^2a). Heat from the lighting was measured using 8 W/m^2 and the usage rate was 0.1.

Ventilation airflow was 0.42 l/(sm^2) for renovation packages representing indoor climate category II (normal level of expectation for indoor climate) [27] counted per heated area. The use of domestic hot water heating (DHW) requires 520 l/(m^2a) / 30 kWh/(m^2a), which makes approximately 35–45 l/(person, day) depending on the density of living.

An Estonian Test Reference Year [44] was used for the outdoor climate conditions (design temperature for heating measuring −21 °C, annual heating degree days at temperature 17 °C:4160 °C). Energy simulations were performed for different renovation measures (different thicknesses of additional thermal insulation, improvement of windows, and ventilation systems). The energy-optimal solution is based on primary energy and does not include embodied energy. The Energy Performance Indicator (EnPI) measuring the energy intensity which is used to gauge the effectiveness of energy management.

2.3. Building and renovation cost calculations

The costs of the building materials, components and construction works originate from a construction company named Timbeco. This company was the head contractor, who renovated the reference building. Used values are based on their private database and forwarded to the authors. All the cost data (Table 3) was obtained in 2019. Cost data was analysed using insulation options in the building envelope, where external walls, windows, and roofs are variable parameters.

The renovation strategies (Fig. 2) A-D were pre-fabricated timber elements such as a) stone wool + wooden cladding, b) stone wool + facade board, c) cellulose + wooden cladding, d) cellulose + facade board, and External Thermal Insulation Composite System (ETICS) facade systems such as e) ETICS stone wool + plaster, and f) ETICS EPS + plaster. The minimum width is 95 mm because below that it would not be possible to reach minimum energy efficiency requirements in the northern climate.

To analyse the heat and energy costs for a total building lifetime of 50 years, the average values were calculated. The basepoint for electricity and heating was 2020. District heating was 60 €/MWh and electricity was 120 €/MWh. This was calculated using linear growth rate of 3% per year.

Global cost calculations [45] (Equation (1) were used to assess the cost-effectiveness of the renovation measures and packages relative to the current state of the reference building. Based on current practise, the cost of renovation was calculated considering 85% loan financing and 15% self-financing. A discount period of 20 years was selected because the maximum period for renovation loans for apartment owner associations in Estonia is 20 years. The cost-optimal level is defined as "the energy performance level, which leads to the lowest cost during the estimated economic lifecycle"[46,47].

$$C_g(\tau) = \frac{C_i + \Sigma_{i=1}^{20}(C_{ai}(j) \times R_d(i))}{A_{floor}} - \frac{C_g^{ref}}{A_{floor}} \tag{1}$$

where $C_g(\tau)$ is the global cost (referred to the starting year), €/m^2; Ci is the initial investment cost (self-financing of a renovation loan), €; C_a,i(j) is the annual cost of year i for the component j (energy cost and loan payback cost), €; R_d(i) is the discount rate for year i; C_r^{efg} is the global cost of the reference building, €; A_{floor} is the net floor area, m^2.

2.4. Life-Cycle Assessment method

Life-cycle Assessment (LCA) calculations were used to provide objective information on the environmental impact during the building's 50-year service life. The LCA calculations are based on the Estonian methodology [48], and the material values used are listed in Table 4. The proposed calculation for the LCA method is based on ISO 14040 [49], European standards EN 15804 + A2:2019 [50] and EN15978 [51], and the European Level

Fig. 1. Case study building – before (above, built 1986) and after (below, renovated 2021) the renovation.

Table 1
Thermal transmittance U and area A of the building envelope before and after renovation. The area increased because the loggias merged with the living rooms.

		Wall Above the ground	Below the ground	Basement floor	Roof	Windows	Doors	Envelope area	Gross internal floor area	Heated area
Before renovation	U, W/(m^{2}K)	0.83	0.54	0.50	0.25	1.83	1.01	2638	2860	1766
	A, m^2	1461	152	618	673	310	38			
After renovation	U, W/(m^{2}K)	0.13	0.13	0.57	0.08	0.9	1.0	2856	3260	1866
	A, m^2	1415	152	618	723	400	38			

(s) framework [52], which provide system boundaries. The methodological approach considered the European Taxonomy Regulations [53], which came into force on July 12, 2020 (2020/852).

The Estonian methodology [48] contains the following LCA modules: materials production stage (A1-A3), transport to site (A4), construction stage (A5), replacement stage (B4), operational

Table 2
The average annual energy use before and after renovation.

	Room heating and ventilation		Domestic hot water		Electricity (lighting, appliances, fans, pumps)		EnPI
	MWh	kWh/(m^{2}a)	MWh	kWh/(m^{2}a)	MWh	kWh/(m^{2}a)	kWh/(m^{2}a)
Delivered energy (before)	269	151	28	16	56	32	178
Delivered energy (after)	136	72	56	22	69	37	123

Table 3
Description of renovation solutions and costs.

Renovation solution description	Indicator	Cost, €/m2
Additional insulation of external walls. Different insulation solutions:A: Ventilated facade (wooden cladding) , timber frame + stone wool B: Ventilated facade cement board), timber frame + stone wool)C: Ventilated facade (wooden cladding) , timber frame + cellulose insulation D: Ventilated facade cement board), timber frame + cellulose insulation)E: ETICS (EPS insulation)F: ETICS (stone wool insulation)	Additional insulation thickness 95 mm – 500 mm	Fig. 2
Windows	U = 0.8 W/m^{2}K, U = 0.6 0.8 W/m^{2}K	145 €, 200 €
Additional roof – blown cellulose insulation blown into the attic.	Width 600 mm, 800 mm, 1000 mm	13 €, 18€, 22€
Ventilation. centralised supply-exhaust ventilation with heat recovery	SFP 80%	The same solution to all cases, therefore the cost was not included in the comparison
Heating system. Two-pipe heating system, hydronic radiators with thermostats. District heating for heat source	Heat exchange efficiency 97%	
Renewable energy systems. building adapted photovoltaic panels on the roof	50 kW oriented to the southeast with 20-degree angle. Annual production ~ 40 MWh.	

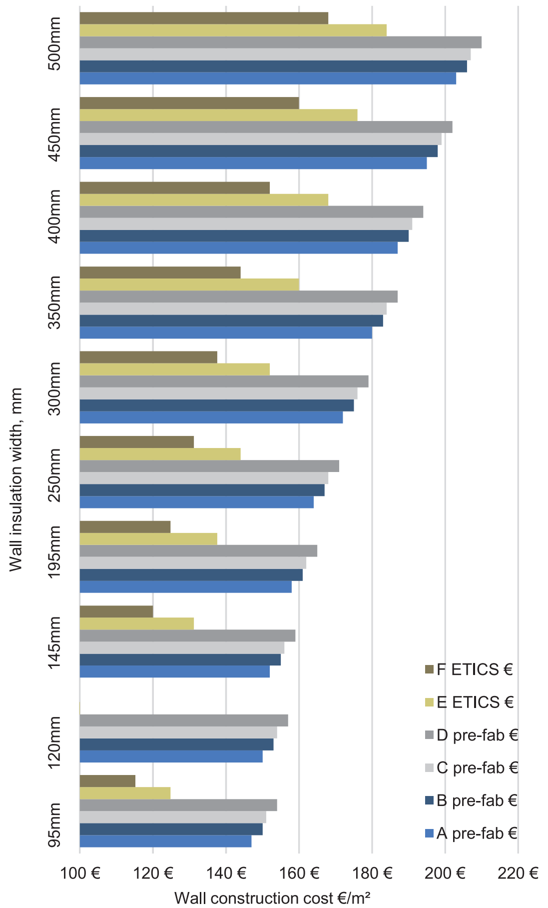

Fig. 2. Wall insulation construction costs for different thicknesses €/m^2. A-D represents pre-fabricated timber elements and E-F are ETICS systems. For ETICS facades, there were no insulation types with 120 mm width. Wall insulation system has linear growth depending on insulation width.

energy use stage (B6), end-of-life stage (C1-C4) and benefits and loads beyond the system boundaries (D) module.

A background analysis of the global warming potential (GWP) of each material was performed to determine the average values (Table 4). Five databases were used in this study – Estonian [48], Finnish [54], Ökobaudaut [55], IBU [56] and EPD Norge [57]. The sensitivity analysis included primary energy consumption of the element material throughout the life cycle, from cradle to the grave.

Three databases were used to determine the shelf lives of the material. Material life age is based on German sustainable building information portal – Service Life of Building Components [58], Goulouti *et al.* [30] in general, and Ximenes *et al.* [59] on the ETICS facade.

For the ETICS facade, different components affect the total CF, because it was assumed that after 30 years, a new layer of plaster, mechanical fixing, and reinforcement mesh will be added. These components constitute approximately 60% of the total CF value.

Sensitivity analyses included primary energy consumption of the element material throughout the component lifecycle, from cradle to grave. It is necessary to investigate this to evaluate the environmental sustainability of materials with greater precision.

Table 4
Materials used in different renovation options in this study.

Building part	Material	LCA modules used in calculations according to the Estonian method												Total primary energy demand	
layers		**A1-A3 GWP**		**A4**	**A5**	**B4, life-age, years**			**B6**	**C1**	**C2**	**C3**	**C4**	**cradle to grave (A1-C4)**	
		kg CO_2e/kg average$^{highest}_{lowest}$	w/o local comp	%	km	BNB	[30]	used	Energy according to Energy Performance Indicator (EnPI) calculations, kWh/m^2.	Demolition according to gross internal floor area, 3260 m^2.	Default value 50 km for materials to waste plant.	Materials divided: metal, mineral materials, wood-based materials. According to the Estonian waste management plan.	Materials divided: metal, mineral materials, wood-based materials. According to the Estonian waste management plan.	kwh	unit
Buffering layer	Glass wool	$1.49^{2.93}_{0.76}$	0.77	8	500	50	x	50						447	1 m^3
Air and vapor membrane	Water vapour membrane	$2.81^{2.87}_{0.64}$	5.95	10	500	50	x	50						6874	1 m^3
Installation	Mechanical fixing	*xx*	5.79	8	3000	x	30	30						3.3	1 m^2
	Glue	*xx*	1.09	10	3000	x	30	30						12	1 m^2
Insulation	Stone wool, timber frame	$1.27^{1.58}_{1.11}$	1.2	8	500	50	x	50						230	1 m^3
	Cellulose, timber frame	$0.94^{1.58}_{0.51}$	1.75	8	500	50	x	50						450	1 m^3
	Timber frame	$0.11^{0.21}_{0.05}$	0.1	18	500	40	x	50						591	1 m^3
	EPS, glued (part of ETICS)	$3.04^{3.71}_{2.64}$	3.54	4	500	50	30	30						501	1 m^3
	Stone wool, glued (part of ETICS)	$1.30^{1.58}_{1.06}$	1.35	8	500	50	30	30						282	1 m^3
Wind barrier	Fibre cement board, wind barrier	$0.78^{0.96}_{0.45}$	0.82	5	500	40	x	50						3250	1 m^3
Ventilated air gap	Sawn-timber vertical	$0.11^{0.21}_{0.05}$	0.1	18	500	40	40	50						591	1 m^3
Facade system	Facade board	$1.21^{1.79}_{0.94}$	0.97	5	500	40	40	50						4410	1 m^3
	Wooden cladding	$0.11^{0.21}_{0.05}$	0.1	18	500	50	40	50						591	1 m^3
	Facade paint	$2.59^{3.00}_{2.12}$	1.75	10	500	40	40	40						7	kg
	Reinforcement mesh	$2.20^{3.05}_{1.00}$	2.8	10	3000	4	x	15						2.6	kg
	Plastering mortar	$0.40^{0.94}_{0.21}$	0.25	13	500	50	30	30						30,764	1 m^3
Roof	Insulation, blown cellulose 600–1000 mm	$0.78^{1.58}_{0.09}$	0.95	8	500	30	30	25						168	1 m^3
	Battens, sawn-timber	$0.11^{0.21}_{0.05}$	0.1	18	500	50	40	50						591	1 m^3
	Steel sheets, cladding	$2.40^{3.32}_{1.85}$	2.52	3	3000	50	40	50						20,314	1 m^3
Window	Triple glazed, typical frame U = 0.8 W/(m^{2}K)	$2.27^{3.47}_{1.66}$	2.08	0	500	40	30	40						464	1 m^3
	Triple glazed, insulated frame, U = 0.6 W/(m^{2}K)		1.66	0	500	40	30	40						476	1 m^3

Table 4 (*continued*)

Building part	Material	LCA modules used in calculations according to the Estonian method							Total primary energy demand	
Door	Exterior door	$1.97^{4.74}_{1.50}$	1.51	0	500	50	x	50	1208	1 m^3
Basement wall	Bitumen waterproofing membrane	$1.63^{2.95}_{0.64}$	0.64	10	500	50	x	50	30,400	1 m^3
	EPS insulation	$3.04^{3.71}_{2.64}$	3.54	4	500	50	30	50	501	1 m^3
	Facade board	$1.21^{1.79}_{0.94}$	0.97	17	500	40	40	50	4410	1 m^3
Balcony	Structural steel	$2.20^{3.05}_{1.00}$	2.8	3	500	50	50	50	20,314	1 m^3
	Sawn timber	$0.11^{0.21}_{0.05}$	0.1	18	500	40	40	50	591	1 m^3
	Pre-cast concrete, hollow core slabs	$0.31^{0.84}_{0.16}$	0.19	0	500	50	50	50	604	1 m^3
Service systems	Building services	$19.10^{23.17}_{11.24}$	23	0	3000	25	20	25	x	1 m^2
	Solar panel	42^{42}_{42}	42	0	3000	xx	20	20	230	kg

The CO_2e optimal solution has the lowest carbon footprint value measured over the building's 50-year lifespan.

The values for transport (A4) origin from the Estonian methodology, where the default distance from the global source material is 3000 km, and locally sourced material distance is 500 km. Values for construction site (A5) originate from One-Click LCA database, which has been created using analyses from substantial amount of case-studies.

Average used electricity for operational energy stage (B6) global warming potential for 50-year service life in Estonia is 0.37 $kgCO_2e/kWh$ and for average district heating (B6) 0.11 $kgCO_2e/kWh$. Module C values were obtained from the National Waste Plan 2014–2020 [60].

The selected materials for the mineral wool systems were used in the real-life construction of the case study building. It appears that in ETICS, the products for the installation of the facade system, such as fixing and glue, do not have generic data in national systems; therefore, it was not possible to carry out a range of examples. In addition, little information is available on photovoltaic panels and building technology systems. However, both calculations were performed and used in default values, because these are important components in the future for energy-efficient and sustainable renovations.

2.5. Renovation strategies

A comparative analysis of the six facade alternatives (Fig. 3) was performed using three different parameters for a total of 643 solutions. Four of the facade alternatives can be produced as a prefabricated timber element in factory, and two others are ETIC-s facades systems, which are currently widely used in Nordic countries. For a more comprehensive analysis of building CF, the effect of individual parameters, such as replacing windows or installing extra insulation in the attics, needs to be considered.

All renovation strategies, which were analysed, included the following: insulating the foundation, replacing windows and exterior doors, adding balconies at the back of the building, and adding an extra layer of insulation to the attic with new roof cladding and exterior wall insulation. Exterior wall insulation solutions with windows and attics were comprehensive in this study. Doors, balconies, and foundations were included in each solution calculation. Assessments were carried out for 50 years as this is a common reference study period for LCA calculations based on standard EN 15978 [51], and it has been found that renovation could help extend the useful life of a building by 50 years [61].

The renovation options were combined using three parameters: wall insulation, window U-value, and attic insulation. The thickness of the wall insulation was between 95 and 500 mm, with a thickness step of 50 mm. Window values, which were compared are: 1.5 W/m^2K, (as existing), 0.8 W/m^2K and 0.6 W/m^2K. The attic insulation had three parameters: 400 mm (as existing), 800 mm, and 1000 mm.

2.6. LCA calculations

The Estonian methodology for CF construction works summarizes the results from modules of materials production (A1–A3), transport to construction site (A4), construction (A5), replacement (B4), operational energy (B6), and end-of-life (C1–C4) (Table 1). The load and benefits beyond the system boundaries (D) module was calculated and reported but was not included in the CF results. Important differences between the European standard and Estonia's national methodology are, that the latter has tenant electricity included in delivered electricity and the method applies the CO_2e emission options for energy carriers. [48].

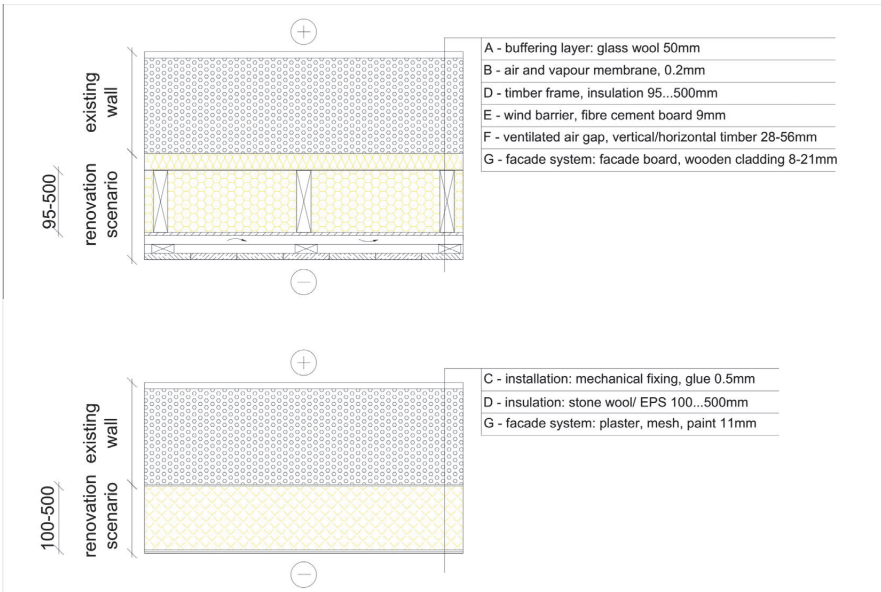

Fig. 3. Examples of external wall renovation solutions. Above pre-fabricated timber element and below ETICS system.

One Click LCA [51] calculation program was used to perform the analysis [62]. The starting point for the renovation calculation was the situation before renovation, with previous material replacements being excluded. The premise is that the past atmospheric emissions of greenhouse gases cannot be altered.

3. Results

3.1. Single renovation measures

The effects of the three different single renovation measure's (Fig. 4) total energy consumption and cost show different performance of different criteria. All the parameters included the total values of the material, energy used, and cost during the life-time (50 year for CF and energy, 20 years for total cost).

Fig. 4 show, that the best renovation option is to insulate external walls, because it significantly improves the energy performance and minimizes the CF, cost, and total energy use.

Replacing only windows or just adding insulation to the attic have an insignificant impact on the energy performance, therefore there is an increase in the building life cycle's environmental footprint. In Fig. 4, total energy demand and EnPI graphs show, that replacing windows or adding extra insulation to the attic reduces the total annual energy consumption of the building. Annual cost and energy performance calculations showed that wall insulation

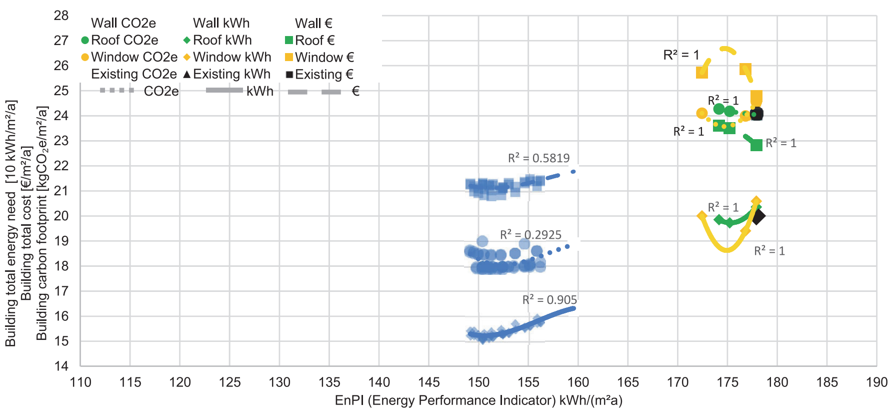

Fig. 4. It describes different single measure effects. All trendlines are polynomial of order 3. Figure shows that attic insulation and window replacement have minimal improvement impact on energy performance, but increases CF and cost value. Wall insulation lowers the energy need and thus has positive impact on CF and cost.

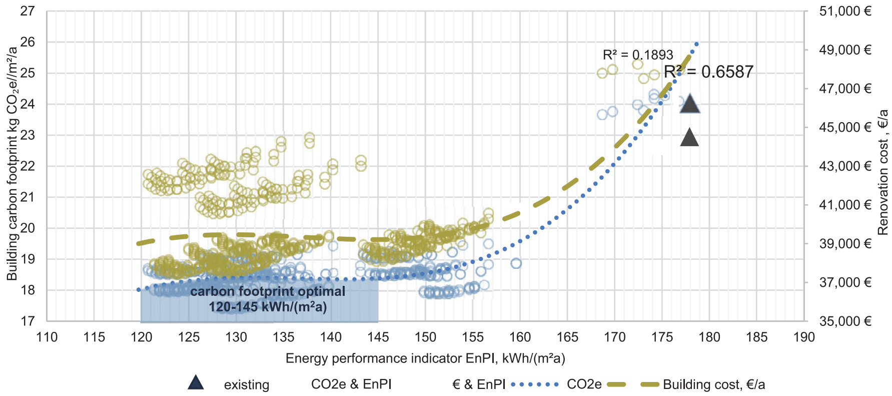

Fig. 5. Optimality of renovation measure combinations considering carbon footprint, cost, and EnPI. All trendlines are polynomial of order 3. Renovation cost trendline has low R^2 value because there are three clear clusters (pre-fabricated timber elements, below line and ETICS façade, above line). Figure shows, that optimal range from carbon footprint aspect matches with renovation cost optimal range. Optimal range is between 120 and 145 kWh/(m^{2}a).

and attic insulation can lead to the same annual cost; however, the difference in building energy efficiency was significantly different.

3.2. Renovation strategies

Different renovation packages (Fig. 5) were investigated in terms of CF, total cost, and total energy. The total cost parameter represents the total value of construction and energy use, with energy from producing the materials also included. The results show that a lower CF leads to better energy performance. In this case, the total extended lifetime from a 50-year perspective includes the cost of replacing building materials and the cost of heating and energy demand. It is shown that single parameters have little effect on the energy performance improvement, however, will increase CF and cost. The optimal range from the perspective of CF, energy performance and energy demand EnPI falls between values 120–145 kWh/(m^{2}a). Values below 120 kWh/(m^{2}a) lead to increased material requirement in terms of insulation thickness and values above 145 kWh/(m^{2}a) lead to higher energy demand and thus an increase in CF.

Fig. 6 shows that a lower CF leads to a better energy performance. A comparison of annual energy demand and CF showed that attic and window combinations without wall insulation led to a higher CF, but lower annual energy demand. This is because the number of input materials decreased, resulting in a minor gain in terms of energy efficiency.

It is shown that the optimal range for carbon footprint was not directly related to the optimal building energy range. In the Fig. 6, red dots refer to EnPI and the annual energy demand relations. This created two specific clouds in the graph. A higher cloud indicates replaced windows with higher U-value and lighter attic insulation. The lower cloud refers to solutions, which replaced the windows with lover U-value and thicker attic insulation. Most of the higher dots are from the ETICS facade. This means that the ETICS facade itself has a greater need for energy in all processes (from material production to demolition).

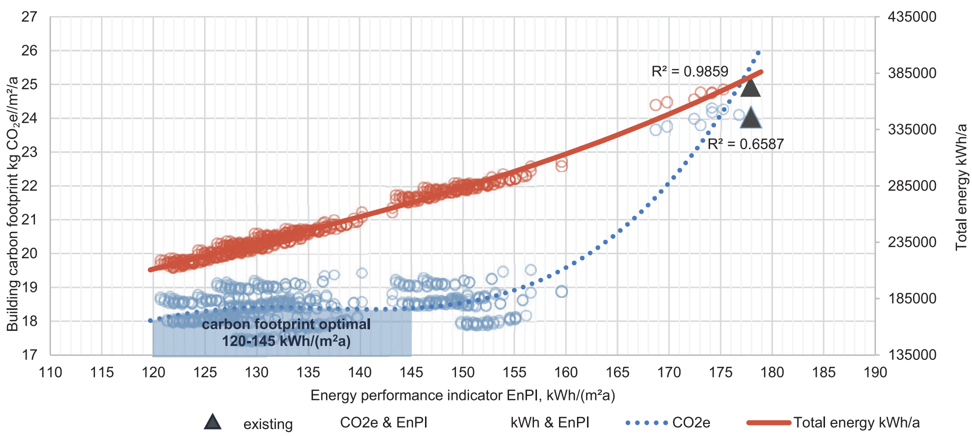

Fig. 6. Renovation options from carbon footprint, EnPI and total energy demand (material production included) perspective. All trendlines are polynomial of order 3. Figure shows, that optimal range for carbon footprint is not completely in correlation with total building energy. For building total energy demand, there is no clear optimal range. As operational energy demand (B6) significantly affects total energy demand, there is less operational energy needed during use stage (B6).

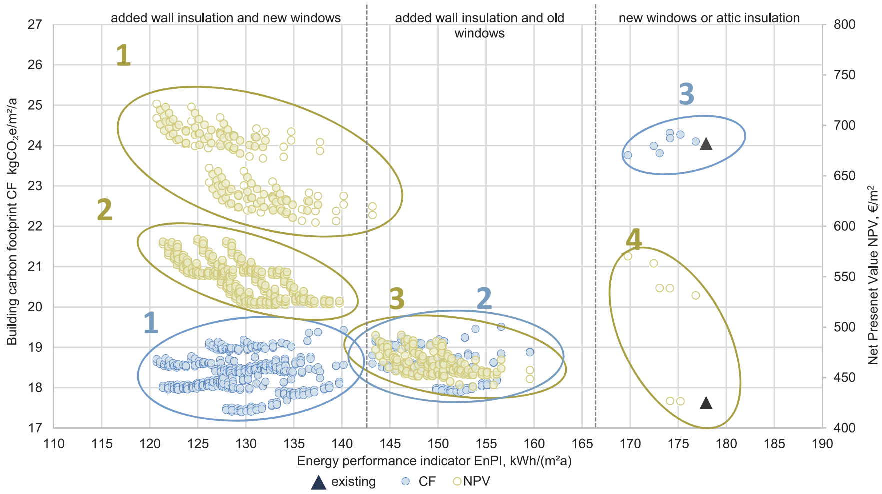

Fig. 7. Cost optimality and energy efficiency relations in a 30-year lifespan. Green circles refer to NPV. Circle number 1 refers to solutions with ETICS system and new windows, number 2 for pre-fabricated timber elements with new windows, number 3 for existing windows and number 4 for existing wall situations. This concludes that, if renovation is going to happen, then walls should be insulated and windows replaced [14]. Also, that pre-fabricated timber elements are more cost beneficial in current context, than ETICS façade. Blue circles refer to CF – number 1 for added wall insulation and new windows, number 2 for added wall insulation and number 3 for no added wall insulation, only attic insulation or window replacement. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3. Cost optimality compared with CO_2e optimality

Fig. 7 describes cost-optimality (green) and CF (blue) relationships with energy performance. From the perspective of cost optimality, the results yielded to four different clusters. The first one includes solutions with new windows and insulated walls using the ETICS system. The second cluster refers to the same parameters, but with pre-fabricated timber elements. The average CF was approximately 18.5 $kgCO_2e/m^2/a$. The third cluster set describes solutions with added wall insulation and existing windows of CF around 19.0 $kgCO_2e/m^2/a$. The fourth set describes solutions, where the common denominator is the absence of wall insulation, with an average CF of 24.3 $kgCO_2e/m^2/a$. Attic insulation was not clearly distinguishable in any of the sets. It can be concluded that lower CF indicates better energy efficiency (Fig. 7), because energy is the dominant factor in the CF calculations.

In the future, if low carbon footprint solutions are preferred, even more energy-efficient building thermal envelope solutions will be needed, leading to lower EnPI values to meet the carbon footprint and climate goals.

From the perspective of CF similar clusters formed. Therefore, lines can be drawn on the EnPI axis to split the results into three categories: added wall insulation and new windows; added wall insulation and old windows; and new windows or added attic insulation.

According to the study (Fig. 8), cost-optimal solutions do not result in carbon-optimal buildings. Therefore, carbon-optimal solutions result in more energy-efficient solutions, but higher renovation costs under the current financial system. In the future,

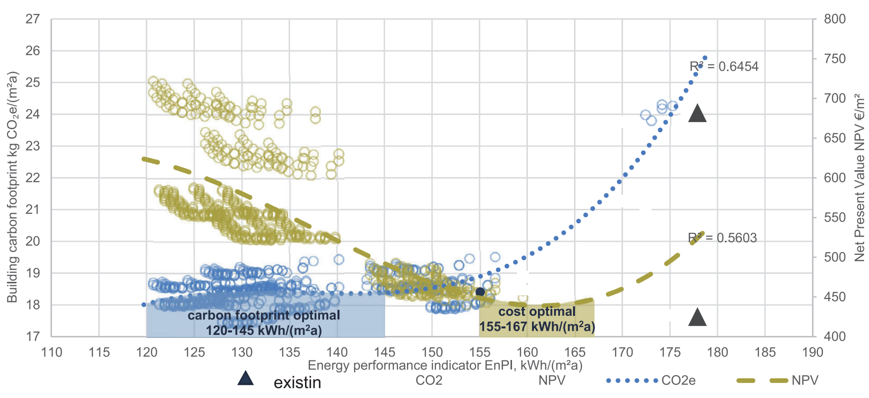

Fig. 8. Cost optimal and carbon optimal relations, when EnPI is the basis for comparison. All trendlines are polynomials of order 3. Figure shows, that cost optimal and carbon footprint optimal are not in the same place, therefore new aspect should be considered for cost-optimality to move closer to the CF optimality.

building CF calculations will be mandatory [10]. This leads to the realization that a revision in the principles for financial subsidies is required to favour low-carbon solutions.

3.4. Renovation strategies in the same perspective of energy performance indicator (EnPI)

It is important to examine the CF of materials separately; if operational energy (B6) decreases in the future, then material's embodied carbon share from total building life-cycle CO_2e will increase. In the current study, two renovation wall insulation systems were analysed (pre-fabricated timber elements and ETICS). Comparing the replacement stage (B4) between these two the difference was 22%, with ETICS being higher. This is because the expected service life of the ETICS is 25 years [59], whereas that of the pre-fabricated timber element system is 50 years (Table 4). In the LCA modules, when analysing deep renovation in the current context, 75% is operational energy stage (B6); 10% materials production stage (A1-A3); and 10% replacement stage (B4); and the other modules (A4, A5, C1-C4) are together 5%.

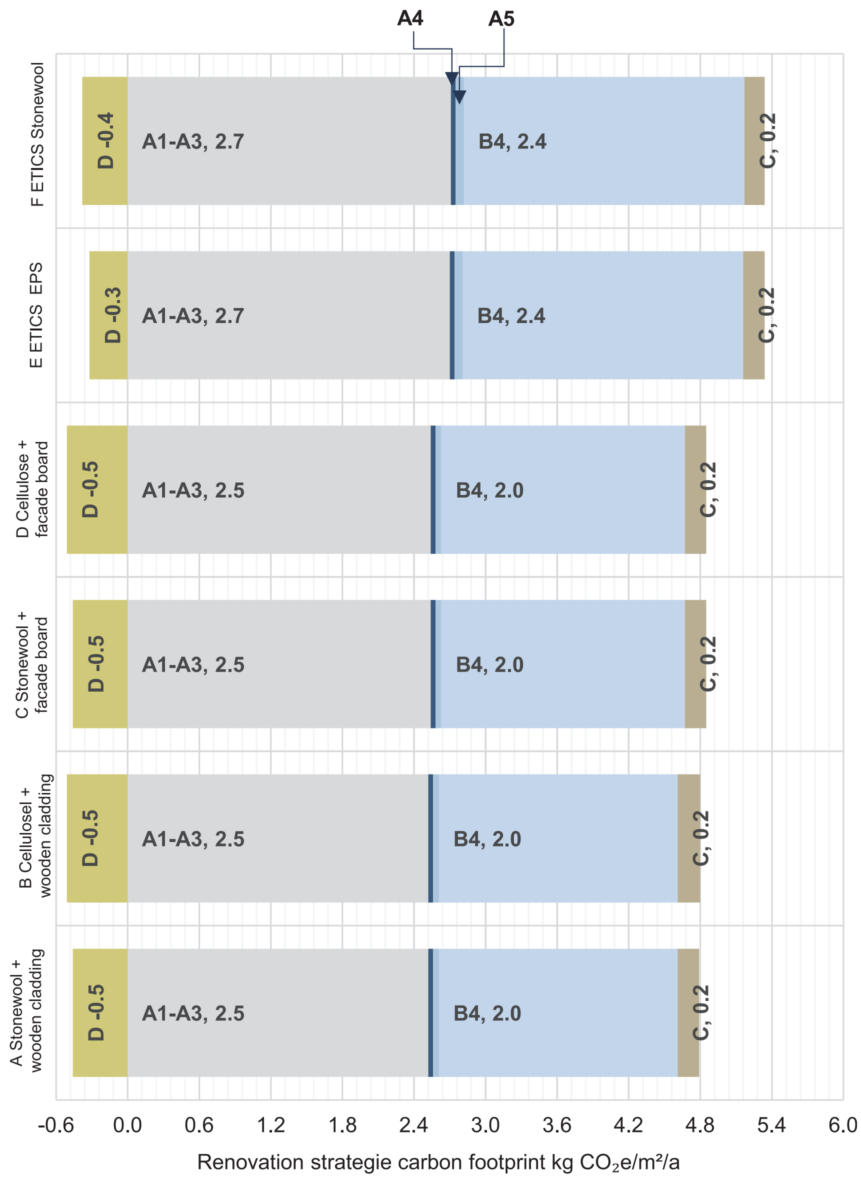

Fig. 9. Same thermal transmittance wall construction in different external wall renovation options. It shows that if operational energy module (B6) is left out, then there are differences in material production (A1-A3) and replacement (B4) modules. For pre-fabricated timber elements, replacement module (B4) is lower than ETICS, by around 15%. Modules transport (A4) and construction site (A5) have minimal impact in current context, if only materials without systems are considered.

The analyses showed, that when different renovation solutions had the same operational energy demand (B6) EnPI kWh/(m2a), they did not lead to the same CF values (Fig. 9). In the solutions, which were analysed, the EnPI was 123 kWh/(m2a). This had been selected as a design value for the case-study building (without PV) (Table 2). Therefore, both ETICS facade systems have wall insulation width of 200 mm, window U = 0.8 W/(m2K), and roof insulation width of 800 mm. The cellulose options have wall insulation of 145 mm, window U = 0.8 W/(m2K), and roof insulation width of 800 mm. The stone wool options have wall insulation of 195 mm, window U = 0.8 W/(m2K), and roof insulation width of 600 mm. Modules transport stage (A4) and construction stage (A5) had minimal impact in the current context as seen in the Fig. 9 (dark blue and green lines between A1-A3 and B4).

The pre-fabricated timber elements had lower CF values than the ETICS systems. This difference was approximately 1 $kgCO_2e/m^2/a$. The largest differences were observed in modules materials production stage (A1–A3) and replacement stage (B4). This is because the life span of the ETICS system is 25 years. The differences between material production stage (A1–A3) were 8% and in replacement stage (B4) 15%, respectively. As mentioned above, it is important to consider the choice of materials, because of the variation in total GWP difference in the modules.

Focusing on the benefits and loads beyond the system boundaries module (D), it was observed that mineral wool system with wooden cladding had the lowest CF values. The current results showed that, for the ETICS facade, it is not possible to reuse glued stone wool and EPS, which are covered with plaster, and the positive effect comes from blown cellulose in the attic and window reusability in these solutions.

The amount of energy required to produce different solutions was also examined. The results indicated that the ETICS facade has the highest energy demand from material production (A1-A3), which is almost 40% higher than that of the pre-fabricated timber elements. Therefore, it is necessary to investigate all building materials, expected life expectancy of the solution, and total building life-cycle costs.

For a detailed life-cycle analysis, comparison with three different life-ages was made – 25 years, 50 years and 100 years (Fig. 10). It resulted, that for every scenario, ETICS façade had the highest value in CF. For pre-fabricated timber elements, the unsuitable life-age is 25 years, because the materials life age is 50 years.

4. Discussion

To date, only the cost optimality (using Net Present Value calculations) has been considered, when renovation decisions have been made. To meet climate targets and evaluate real cost data, it is important to add carbon footprint (CF) as a third parameter to the evaluation process. The same notion, that energy reduction cannot be the only aspect, was found out by Almeida and Ferreira [16].

During this study, it was found that when comparing renovating solutions from a CF perspective, wall insulation should always be included, as this has the highest impact on reducing the annual energy demand and thereby total building CF. This is important value to the Kuusk, *et al.'s* [18] work with nearly zero energy renovation concepts. During the renovation process, if only windows were replaced or additional insulation was added to the attic, it resulted in higher cost and increased CF but insignificant gains in terms of energy efficiency.

When comparing energy efficiency with CF, it can be said that better energy efficiency leads to a lower CF. This is because more than half of the CF values of deep renovations originate from operational energy use stage (B6) in a cold climate context. When B6 was removed, and only embodied carbon was considered, the conclusions remained the same, confirming that materials CO_2e values from the production stage (A1-A3) had a significant impact on total building CF.

In this study the values for different renovation strategies were investigated. The ETICS facade had a higher CF than the pre-fabricated timber elements. When cost parameter was investigated, the main variable was whether windows were replaced. Finally, it appeared that ETICS facade system has a higher energy demand from cradle-to-crave than pre-fabricated timber elements. It was proven that materials choice is of high importance [25], in terms of building CF.

When analysing the total cost (including construction, maintenance and replacement) for a 50-year life cycle, it was recognised that a higher investment in the construction phase leads to lower CF and energy demand (Fig. 4). Therefore, in procurement phase, value-based procurements should be preferred over the lowest-price wins. It is suggested that there should be grants and subsidies to support such procurements to take effect. From a long-term perspective, this is a more economical and environmental option than

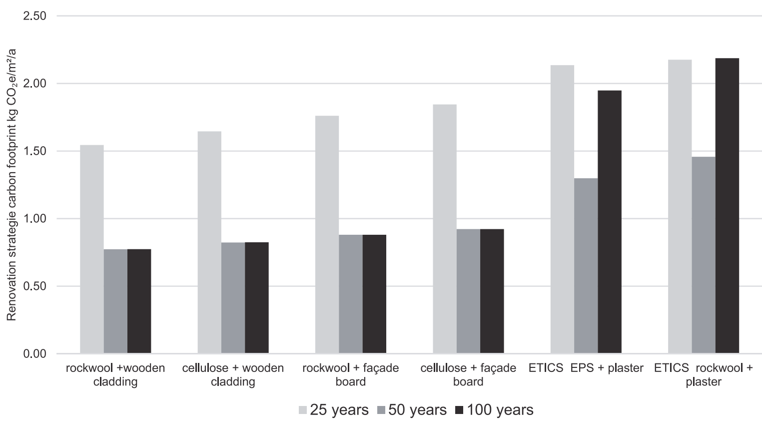

Fig. 10. Detailed life-cycle carbon footprint analysis for six different renovation strategies in the LCA modules A1-A3. Graph shows, that pre-fabricated timber elements are not profitable to make only for 25 years, because the material life-age is 50 years.

favouring minimal upgrades instead of deep renovation. If energy during the use of building (B6) decreases, it is more important to consider which renovation strategy is used, because the materials have different embodied carbon values. In the context of current case-study, highest CF is with the ETICS facade, and the lowest was with mineral wool and wooden cladding.

The current Estonian LCA methodology excludes materials and products, which were added before renovation. However, some studies have shown that these components should be added to measure the impact of renovation, because they may require repair, maintenance, or replacement during their extended lifetime [3 63]. In addition, these elements are currently left out during the C-module calculations however, to support the circular economy strategies and reuse elements and materials, it is important to investigate this module's impact if existing parts are considered (mostly considering load-bearing structure).

In future research, it is necessary to evaluate how the adoption of low-carbon renovation options can lead to better-quality urban spaces. New parameters for renovation solutions can support need of modern architecture; wooden cladding and facade boards can lead to an improvement in building facade appearance. Additionally, global renovation strategies to meet climate targets by 2050 are presently unknown.

Currently, there is no material carbon tax system in Estonia to support solutions with a lower carbon footprint. Therefore, there is a possibility to use the EPBD directive equations for national policy making to compare, how these aspects change the CF perspective. This can also lead to a better understanding on how to implement the EU Taxonomy Regulation [53] for renovation projects in other aspects, such as the circular economy and town-quarter-scale renovations.

5. Conclusions

The current study concludes that based on the case-study (apartment building renovation), cost-optimal, CO_2e optimal and total energy optimal parameters differ from each other. Carbon optimal solutions are between 120 and 145 kWh/(m^{2}a) and cost optimal 155–167 kWh/(m^{2}a). Calculations showed, that carbon footprint (CF) and total energy efficiency are more closely related, because lower energy demand leads to a lower CF value. Renovation improves building performance from both carbon and total energy use perspectives.

The optimisation of life-cycle carbon footprint, required by the new EPBD recast, leads to higher energy performance, than optimisation by delivered energy. This is an important knowledge to consider, when designing and selecting renovation projects. As the main objective of EPBD is to drive greenhouse gas reduction, then the steering mechanism should be based on CO_2e optimal, instead of operational energy (B6) optimal. It has been proven, that there is a strong incentive for renovating buildings more efficiently, as this leads to a lower energy demand and CF. This is because the operational energy module B6 is dominant in Estonia, where grid electricity has high carbon intensity.

This study showed, that when use stage operational energy (B6) component of the total CF decreases, it becomes necessary to focus on selection of the building materials for renovation. Calculations showed, that pre-fabricated timber elements have a lower material carbon footprint than ETICS, which is presently the commonly used strategy.

Hypotheses, that CO_2e optimal and total energy optimal lead to better energy performance than a cost-optimal solution was proven to be true. Hypothesis, that new optimal solutions change the building envelope structures and thus the architecture; carbon optimal solutions prefer durable façade materials, were also proven. Currently, non-ventilated plastered ETICS facade is widely used, however in CF aspect, pre-fabricated timber elements with wooden façade or board cladding have better environmental results.

Data availability

No data was used for the research described in the article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Authors Contribution

Kertsmik Kadri-Ann was responsible for all calculations, except the simulation for energy performance. Kuusk Kalle is responsible for calculating the energy performance of building components (walls, windows, and roofs) and total energy demand. Concept development and review of the article was carried out in cooperation with Lylykangas Kimmo and Kalamees Targo.

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Low carbon emission renovation of historical residential buildings

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ABSTRACT

The urgency of renovating residential buildings in heritage conservation areas while addressing carbon emission reduction and energy performance has become a concern in the context of climate change. European directives stress the importance of enhancing existing buildings to achieve climate neutrality by 2050. An approximately 100-year-old wooden apartment building in the heritage conservation area in Võru, Estonia, was designed as a nearly zero-energy building (nZEB). This study examined the impact of different renovation scenarios, considering both embodied and operational carbon emissions. During the study, the technical requirements of the National Heritage Board were developed in several aspects. The results of this study indicate that it is possible to renovate buildings in heritage conservation areas and achieve great energy performance. In addition to improving energy performance, it is possible to make the restoration of a significantly damaged exterior with intermediate repairs more cost-effective for the owner. Deep renovation of a historical wooden building decreases its carbon footprint as it leads to more energy-efficient renovation solutions. This is because operational emissions dominate over embodied emissions in a cold climate. From an environmental perspective, it is more feasible to renovate historically valuable buildings more deeply than it is to upgrade the external appearance of buildings. Renovation work to achieve an nZEB building should include insulating the thermal envelope while restoring the historical appearance and preserving the original building profile. In conclusion, this study offers a comprehensive analysis of various scenarios, including carbon footprint, energy performance, and cost optimality, related to different renovation strategies for buildings located in heritage conservation areas. There is a need to align heritage board technical requirements with the environmental perspective. Given that major renovation is more cost-effective and better at preserving the exterior appearance compared to staged renovation, the former should be preferred to ensure the owner's willingness to pay.

1. Introduction

1.1. Demand

With the introduction of the Energy Performance of Buildings Directive (EPBD recast, 2018) and the Energy Efficiency Directive (EED, 2012), the EU has long emphasized the crucial role of improving the energy performance of buildings in efforts to combat climate change. The Renovation Wave Initiative (EC COM 662, 2020) aims to increase the renovation rate of buildings to at least 3% per year, with an average energy demand reduction of 75%, to achieve climate neutrality by 2050. The results indicate that the main energy-saving potential lies in the improvement of the existing building stock (Tommerup and Svendsen, 2006; Uihlein and Eder, 2010; Lechtenböhmer and Schüring, 2011).

Approximately 20% of European residential buildings date to before the Second World War and today are often classified as holding historical value (Meijer et al., 2009). While these buildings, which have officially designated architectural or historical values (Besen and Boarin, 2018; EPBD recast, 2018), have the flexibility to modify energy performance requirements, the residents of these buildings may still have a desire to improve their homes' energy performance to lower energy expenses and mitigate the risk of energy poverty.

Renovation of existing buildings is a multi-criteria approach, in which, in addition to technical solutions, financial, social, and environmental aspects should be considered (Mjörnell et al., 2014; Pombo et al., 2016; Mjörnell et al., 2019; Galimshina et al., 2021). The EPBD requires that the energy performance requirements be cost-optimal. Kertsmik et al (2023) demonstrated that renovation solutions focused on minimising emission yield and reduced energy consumption, making them a more suitable benchmark for assessing energy performance in deep renovations than cost optimization. Careful renovation of historical buildings is crucial to decreasing carbon emissions in the building

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sector (Berg and Fuglseth, 2018; Wise et al. 2021).

The restoration of historical buildings is more environmentally feasible. Compared to renovation, it has similar environmental impacts but also preserves cultural heritage value (Serrano et al., 2022a). Using local materials and techniques is a more sustainable path than the alternatives, as it supports the preservation and restoration of historical buildings (Mileto et al. 2021). It has been found that the renovation of existing buildings of historical value has significant potential to reduce greenhouse gas emissions while preserving heritage outcomes and supporting the use of local materials, which in turn will lead to a reduction in carbon emissions (Fufa et al., 2021).

It has been shown that in cold climates (Alev et al. 2014; Arumägi and Kalamees, 2014; Nair et al. 2022) in order to deeply renovate historical wooden apartment buildings, the largest energy saving potential lies in the heat source. Building service systems and the insulation of the external wall have the greatest single energy-saving potential of the building envelope (Alev et al., 2015). The external insulation of walls and the ground floor and the improvement of windows, doors, and shutters predominantly result in high risks to the heritage value and character of historical buildings, even though they provide substantial energy savings (Ulu and Arsan, 2020). To minimize this risk (Arumägi and Kalamees, 2014), in different parts of the building and solving the joints of the façade elements results in a significant improvement in the energy performance of the historical building without deteriorating its architectural appearance. It was shown (Jerome et al., 2021) that the recreation of architectural values can be achieved without compromising on the environmental benefits of energy renovation. Gremmelspacher et al. (2021) demonstrated the feasibility of achieving Net Zero Energy Building (NetZEB) status for a historical structure in southern Sweden by implementing a deep retrofit strategy and photovoltaic panels (PV panels) system integration. Similar outcomes with a reduction in operational carbon have been proven in residential buildings (Amini Toosi et al. 2022). However, the solar panels were only located in the park around the building and a solution with integrated PV panels on the building was not offered in this study.

To realize the EPBD's goal of reducing emissions, Life-Cycle Assessment (LCA) should become part of the renovation of historical buildings. Lidelöw et al. (2019) conducted a literature review on the energy performance measures of heritage buildings and showed that there are relatively few studies that consider the energy consumed during the entire life cycle of a heritage building. Seduikyte et al. (2018) showed that renewing heritage buildings, even when renovation is performed, saves natural resources and energy that could be used to build a new building. Serrano et al. (2022) indicated that restoration is a potentially viable alternative to renovation as a means for maintaining the original appearance of historical buildings to retain cultural heritage while also keeping the environmental impact at a similar level to that o renovation. Gravagnuolo et al. (2020) evaluated the environmental impact of historical building conservation and showed that energy use (B6 module) has the largest impact on emissions. Therefore, in cold climates, deep renovations may result in lower life-cycle emissions. Nevertheless, few studies have been conducted to assess life-cycle emissions for deeply renovated historic apartment buildings.

The increasing need for the renovation of buildings has increased the attention paid to buildings in heritage conservation areas, which have been left out of scope when building carbon footprint calculations. The topic under investigation analyses and explores the possibilities for the low carbon footprint of historical apartment buildings on a renovation scale – from no renovation at all to deep renovation that achieves nZEB solutions for environmentally valuable building renovation work.

1.2. Purpose

Architects and engineers are expected to develop solutions to reduce buildings' environmental impacts and costs (Azari and Abbasabadi, 2018). These aspects can be analysed using the life-Cycle Assessment method with energy performance modelling. Embodied carbon emissions have an increasing influence in the construction sector when operational carbon emissions decrease, as buildings become more energy efficient (Asdrubali and Grazieschi, 2020; Goulouti et al. 2020; Marzouk and Elshaboury, 2022). This study presents a new perspective: it is possible to achieve nZEB status in historically valuable buildings.

The hypotheses of this study are as follows:

- The deep renovation of historical wooden buildings decreases their carbon footprint.
- Current technical requirements from heritage authorities prevent the achievement of low-emission buildings.
- The running cost of a renovated building can be lower than that before renovation.
- Preferring a low carbon footprint solution will lead to more energy-efficient renovation solutions for historical wooden apartment buildings in conservation areas.

The research questions were the following:

– Does additional insulation increase the carbon footprint due to the addition of new materials or decrease the carbon footprint as a result of minimizing energy use?
– How do renovation technical requirements from heritage authorities influence energy performance, cost efficiency, and environmental impact?
– To what extent do heritage authorities' requirements differ from the low carbon footprint renovation solution?
– Can renovation solutions be used to reduce a building's environmental impact and energy consumption and prevent the deterioration of the building's appearance?

The study analyses how deep renovation influences the energy performance, cost efficiency, carbon footprint, and external appearance of historical wooden apartment buildings. In previous studies, the focus on improving the energy performance of historical buildings has been relatively modest, with a limited goal of achieving an efficiency level of just a 10–20 percent. However, if the aim of energy performance is increased, it will inevitably reveal the inherent risks involved in preserving and maintaining the historical value of these buildings. Additionally, this study considers both the carbon footprint and cost efficiency aspects simultaneously. A 100-year-old apartment building located in the heritage conservation area in Võru, Estonia, was used as reference.

The analysis presented in this study aims to compare renovation strategies from the perspective of the Estonian National Heritage Board technical requirements. To the knowledge of the authors of this study, no recent work has been done from this perspective. It is first this kind of study in Estonia analysing residential buildings which has historical value and how different renovation measures affect building carbon footprint value. In this study, it is stated that it is possible to achieve a nearly zero-energy building while preserving its historical value.

2. Methods

2.1. Reference building

The reference apartment building used in this study is a two-story wooden building (12 apartments) located in the historical heritage conservation area of the city of Võru in Estonia. It was built in the first half or middle of the nineteenth century (Fig. 1 left). Thermal transmittance values (U, W/(m^2K), calculated according to EN ISO 6946 (ISO 6946:2017), and the corresponding energy performance values (calculated in this study according to chapter 2.4) of the building envelope are presented in The condition of the exterior façade and roof of the building was in such a state that they needed to be replaced both to protect the

Fig. 1. Building at Kreutzwaldi 2, Võru, before renovation (left) and after renovation (right, by Tõra, K and Kangro K., 2023).

underlying structure and to improve the exterior of the building. This is a typical situation where the service life of unmaintained wooden boarding is more than 40–50 years. Therefore, a complete comprehensive renovation needed to be done anyway to extend the service life of the building.

Table 1. The heated area of the case study building is 617 m^2, the door area 14 m^2, the gross internal floor area 642 m^2, and the envelope area 1218 m^2. The reference case is a building with its original structure, stove heating, and natural passive stack ventilation. The building's technical condition, moisture damage, indoor hygrothermal loads before renovation and the need for renovation were determined by an onsite survey.

The condition of the exterior façade and roof of the building was in such a state that they needed to be replaced both to protect the underlying structure and to improve the exterior of the building. This is a typical situation where the service life of unmaintained wooden boarding is more than 40–50 years. Therefore, a complete comprehensive renovation needed to be done anyway to extend the service life of the building.

2.2. Life-cycle assessment methodology

Life-cycle assessment (LCA) was used to provide objective information about the environmental impact of the building during its 50 years of service life. The LCA calculations are based on the Estonian methodology (MKM, 2022), and the material values used are listed in Fig. 2. The proposed calculation for the LCA method is based on the European standards EN 14040, 2006 and EN 15978, 2011, in addition to the European Level(s) framework (European Commission, 2018), which provided system boundaries. The methodological approach considered the European Taxonomy Regulations (European Parliament and the Concil, 2020).

The Estonian methodology contains the following LCA modules: material production stage (A1-A3), transport to site (A4), construction stage (A5), replacement stage (B4), operational energy use stage (B6), end-of-life stage (C1-C4), and benefits and loads beyond the system boundaries (D).

The change in carbon emissions (ΔCO_2e) (Eq. 1) of the additional carbon emissions related to the renovation solutions and renewable energy solutions needed to meet the requirements of the energy performance level building was assessed as follows:

$$\Delta CO_2e = \frac{\left(C_G^{target} - C_G^{oringinal}\right)}{A_{floor}} \tag{1}$$

where: C_G^{target} means the total carbon emissions of the targeted energy performance level according to the renovation solution, $C_G^{oringinal}$ means the total carbon emissions of the original situation before renovation, and A_{floor} means the areas of the rooms with energy use for indoor climate.

A background analysis of the global warming potential (GWP) of each material (A1-A3) was performed to determine the average values from several databases – Estonian, Finnish (Finnish Environment Institute SYKE, 2022), Ökobaudaut (Federal Ministry for Housing, 2022), IBU (Institut,) and EPD Norge (2022). The values for transport (A4) depended on distance: globally sourced material at a distance of 3000 km and locally sourced material at a distance of 500 km. Values for the construction site (A5) originate in the One-Click LCA database, which has been created using analyses from a substantial number of case studies (Bionova, 2022).

The lifetime of PV panels is 20 years according to common practice. The photovoltaic panels will be replaced twice during the building's lifespan. The emission factor is 1.75 kgCO_2e/(m^{2}y), which includes the replacement, transport, and end-of-life scenarios. The factors used were based on the regional average value.

To represent the relationship between carbon footprint and thermal transmittance, which were used in the study, graphs were created (Fig. 2). The figures indicate that the highest carbon footprint value was associated with the windows, while the lowest was associated with the basement floor insulation component.

Table 1
Parameters of heat loss of building envelope before and after renovation, compared in Energy Performance Certificate (EPC) classes.

EPC category	Building envelope properties						Energy performance	
	Struc-ture A, m^2	External wall 489	Ground floor 318	Roof 564	Windows 77	Air leakage rate q_{50}, m^3/(h·m^2)	EffDH kWh/(m^{2}y)	GSHP, kWh/(m^{2}y)
G Before renovation		0.59	0.57	0.61	1.88	9	(Stove) 331	-
D BAU	U, W/(m^{2}K)	0.30	0.57	0.24	1.10	6	176	160
C		0.13	0.57	0.10	1.10	4	149	140
B		0.10	0.08	0.09	0.85	2.5	124	123
A Final design		0.10	0.08	0.09	0.85	2.5	84*	81*

*with 33 kWp PV installed on the roof.

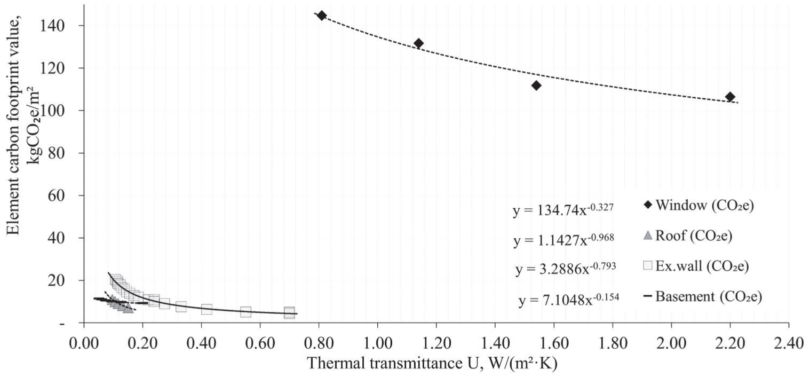

Fig. 2. The dependence of the carbon footprint of the additional insulation of the roof, external wall, and basement and the change of windows on thermal transmittance.

For the windows, an EPD from Norwegian window producer NorDan was used, which represents the value for wood-framed windows (NEPD-3458–2057, 2022). To analyse the thermal transmittance value for different window types, it was calculated that if the window had low emissivity glass, then the carbon footprint value would increase by 10% (NorDan, 2017, Babaizadeh and Hassan, 2013; Souviron et al.2019).

For HVAC services, the same value was used in all renovation strategies, as it is common practice to add heating and ventilation systems to buildings to provide a healthy indoor climate. For this study, the final design projects (both heating and ventilation) were used to calculate the carbon emissions of the HVAC system in the building, with total emissions of 0.83 $kgCO_2e/(m^2y)$.

2.3. Renovation cost calculations

The building envelope solutions were derived by increasing the insulation thickness of the external walls, roof, and ground floor in successive steps. The costs of the structural solutions for buildings based on bids were obtained from a construction company. The budget officers provided unit costs per square metre for various structural solutions and openings, including the costs of materials and installation. An example of price deviation depending on thermal transmittance (*U*) is shown in Fig. 3.

The renovation of the heating system (from stove heating to hydronic radiator with thermostats) and domestic hot water (new insulated pipes, circulation, etc.), respectively 55 euros/m^2 and 20 euros/m^2, were included in the cost-optimality analysis. The costs of changing the heat source from stove to efficient district heating (EffDH) or ground-source heat pump with boreholes (GSHP) were considered to be 305 euros/kW (EffDH) and 2150 euros/kW (GSHP), respectively. Improvement of the ventilation (from natural passive stack ventilation to mechanical ventilation, with heat recovery) was added to all renovation measures (49 euros/m^2).

Global cost calculations (EN 15459-1:2017, 2017) (Eq. 2) were used to assess the cost-effectiveness of the renovation measures and packages relative to the current state of the reference building. The cost-optimal level is defined as "the energy performance level that leads to the lowest cost during the estimated economic lifecycle" (Buildings, 2012; European Commission, 2012).

$$C_g(\tau) = \frac{C_i + \Sigma_{i=1}^{30}(C_{ai}(j) \times R_d(i))}{A_{floor}} - \frac{C_g^{ref}}{A_{floor}} \tag{2}$$

where $C_g(\tau)$ is the global cost (referred to the starting year), €euros/m^2; C_i is the initial investment cost, €euros; C_a,i(j) is the annual cost of year i for the component j (energy cost), €euros; R_d(i) is the discount rate for year i; C_r^{efg} is the global cost of the reference building, €euros; and A_{floor} is the net floor area, m^2.

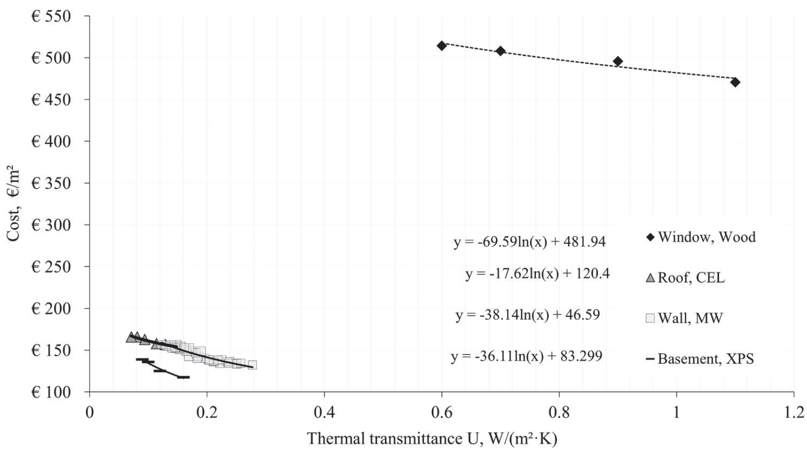

Fig. 3. The dependence of the cost of additional insulation of the building envelope and the change of windows on their thermal transmittance.

The change in the net present value (ΔNPV) (Eq. 3) of the additional costs related to the renovation solutions and renewable energy solutions needed to meet the requirements of the energy performance level building was assessed as follows:

$$\Delta NPV = \frac{(C_G^{target} - C_G^{oringinal})}{A_{floor}} \quad (3)$$

where: C_G^{target} means the total cost of the targeted energy performance level according to the renovation solution, $C_G^{oringinal}$ means the total cost of the original situation before renovation, and A_{floor} means the areas of the rooms with energy use for indoor climate.

The discount rate was calculated using the calculated interest rate and the relative price increase during the calculation period. Depending on the uses of the buildings, the cost-effectiveness calculation period was chosen as 30 years (residential buildings). The discount was based on the real interest rate of 2.0%, which corresponds to the rate of return of 4% when inflation is 2%. The real escalation of energy prices for the calculation period was taken at 1% per annum.

The parameter values used for the discount were heat cost (EffDH), 0.0972 euros/kWh; electricity cost from the grid, 0.170 euros/kWh; and electricity cost when sold to the grid, 0.160 euros/kWh. The cost of building components was calculated by totalling the types of expenses and applying a discount rate of 2% using the discount factor.

The financial calculations were based on the investments needed to improve the energy performance of the building to achieve a different EPC category. In the financial calculations of the additional cost of the measure/package, the prices payable by the customer, including all applicable taxes (VAT 20%), were considered. The calculations did not take into account the potential support that may apply to the improvement of energy performance or the introduction of various technologies related to the production of renewable energy.

2.4. Indoor climate and energy performance modelling

The indoor climate and energy performance of the reference building were modelled using the IDA Indoor Climate and Energy (IDA-ICE) program (Sahlin et al., 2003), (Björsell et al., 1999). The program is well validated (Achermann and Borbély, 2003) and allows the modelling of a multi-zone building and dynamic simulation of heat transfer and air flows, HVAC systems, internal and solar loads, and outdoor climate and has been used in many energy performance and indoor climate applications (Jokisalo et al., 2008), (Alev et al. 2015). Energy renovation measures are made according to standard usage and using a unified calculation methodology (MKM, 2020). Internal heat gains were as follows:

- Inhabitants: 15.8 kWh/(m^2·a). The heat of the inhabitants is counted from 3.0 W/m^2 and 80 W/person using 1.2 met, 0.7 clo (ISO, 7730, 2005);
- Appliances and equipment: 15.8 kWh/(m^2·a). The heat from appliances and equipment is counted using 3.0 W/m^2 and the usage rate is 0.6.
- Lighting: 7.0 kWh/(m^2·a). The heat from the lighting was measured using 8 W/m^2 and the usage rate was 0.1.

Ventilation airflow was 0.42 l/(sm^2) for renovation packages representing indoor climate category II (normal level of expectation for indoor climate) (Hirvonen et al., 2021) counted per heated area. The use of domestic hot water heating (DHW) requires 520 L/(m^{2}a) and 30 kWh/(m^{2}a), which takes approximately 35–45 L/(person, day) depending on the density of living.

An Estonian Test Reference Year (Kalamees and Kurnitski, 2006) was used for the outdoor climate conditions (design temperature for heating measuring −21 °C, annual heating degree days at temperature 17 °C: 4160). Energy simulations were performed for different renovation measures (different thicknesses of additional thermal insulation, improvement of windows, and ventilation systems). The energy-optimal solution is based on primary energy and does not include embodied energy. The Energy Performance Value (EPC) measures the energy intensity, which is used to gauge the effectiveness of energy management.

The used efficient district heating emissions factor of 0.039 kgCO₂e/kWh (Kurnitski and Latõsov, 2017) is substantially better than that for electricity at 0.37 kgCO₂e/kWh (MKM, 2022), which is needed to operate a ground source heat pump system. The existing building uses wood logs for heating, with an emission factor of 0.00028 kgCO₂e/kWh (GHG Footprint of Organizations, 2022). This study also analysed the carbon emission factors if the existing building were to use a local gas boiler: emission factor 0.221 kgCO₂e/kWh (GHG Footprint of Organizations, 2022). For the same amount of energy, burning wood emits 1.5 times more carbon dioxide than coal and 3 times more than gas (Searchinger et al. 2018).

2.5. Renovation strategies, designed renovation solution

The solutions developed and analysed covered the entire building, from step-by-step single renovations to the deep renovation of the entire building. External walls were insulated with mineral wool and a cellulose layer was added to the attic. These material combinations were selected to get results for the most common and leading solutions in the field (Arumägi and Kalamees, 2014). To guarantee hygrothermal performance, XPS and EPS insulation was used for the slab on the ground.

The heating systems analysed in the calculations were the ground source heat pump (GSHP) and efficient district heating (EffDH). Certain heating systems were excluded, such as the pellet boiler, as there is no space for this system in the current case-study building. Additionally, the air-water heat pump was not considered due to the Estonian heritage authorities' disapproval of technical system devices on the façades of conservation area buildings (Heritage Board, 2023).

For an A-class energy performance certificate (EPC), it is necessary to install an on-site renewable energy production system, which was included in the analysis. As a result of the design phase, the completed architectural project (Fig. 1 right) was compiled by architects Karmo Tõra and Kaupo Kangro, 2023.

Several meetings were conducted with the National Heritage Board to discuss and obtain consent for the technical requirements of the building design (Table 2). These meetings and developments are necessary to explore the possibilities of renovating a residential building located within a heritage conservation area.

3. Results

3.1. Life-cycle assessment

Heat source is an important parameter to take into account for LCA and energy performance while designing the renovation of the existing stove-heated residential building. Fig. 4 shows how the change of heat source (from stove to efficient district heating (EffDH) and ground

Table 2
Formation of heritage building technical requirements.

Stage	Additional insulation: External wall	Roof	Floor of ground floor	Window	Total carbon footprint value kgCO2e/(m2y)
Existing	-	-	-	-	23
BAU	Up to 5–7 cm	Only attic insulation			21–30
Outcome	Enough to achieve the A-class	Can be lifted to insulate roof also	No limitation	Must be moved out	17–19

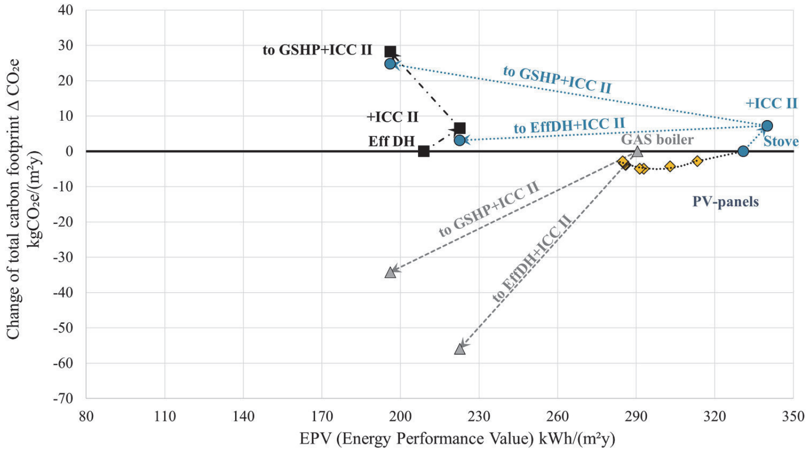

Fig. 4. The influence of change from the perspective of heat source and ventilation system carbon emission values and the addition of onsite electricity generation by PV panels without changing the existing heating source system (without other renovation measures).

source heat pump (GSHP); from gas boiler to GSHP and EffDH; and from EffDH to GSHP) affect the building's carbon emissions. Due to the high emission factors of electricity (0.37 $kgCO_2e/kWh$) and gas (0.221 $kgCO_2e/kWh$), installing GSHP increases carbon emissions and changing the heat source from a gas boiler decreases emissions.

When EffDH is the currently used system, the building should be renovated to C class EPC to achieve climate benefits better than the existing ones. This building uses stove heating with wood logs. It cannot reach to change of carbon footprint level below zero with the current system, which means that the heating system should be replaced by GSHP or the environmentally more beneficial EffDH.

Adding PV panels for onsite electricity generation decreases carbon emissions by up to 64 kWp (104 Wp/m^2). By adding more PV, these panels are no longer in their optimal orientation. Less self-use of locally generated electricity also reduces efficiency, which is why emissions increase.

Fig. 5 depicts a combination of renovation measures for the building envelope, such as additional insulation and window replacement (The condition of the exterior façade and roof of the building was in such a state that they needed to be replaced both to protect the underlying structure and to improve the exterior of the building. This is a typical situation where the service life of unmaintained wooden boarding is more than 40–50 years. Therefore, a complete comprehensive renovation needed to be done anyway to extend the service life of the building. Fig. 6

(Table 1).These measures effectively reduce carbon emissions.

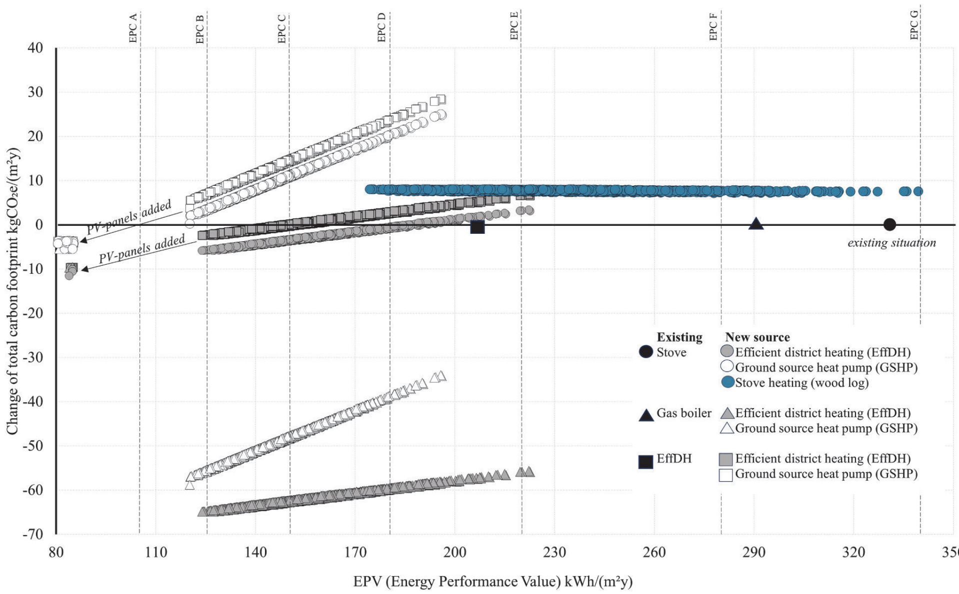

Fig. 5. The influence of renovating the building envelope on carbon emissions in combination with different heat sources. If the vertical axis is negative, then carbon emissions are saved compared with the existing situation. The marker shape refers to the base case heating system (existing in legend).

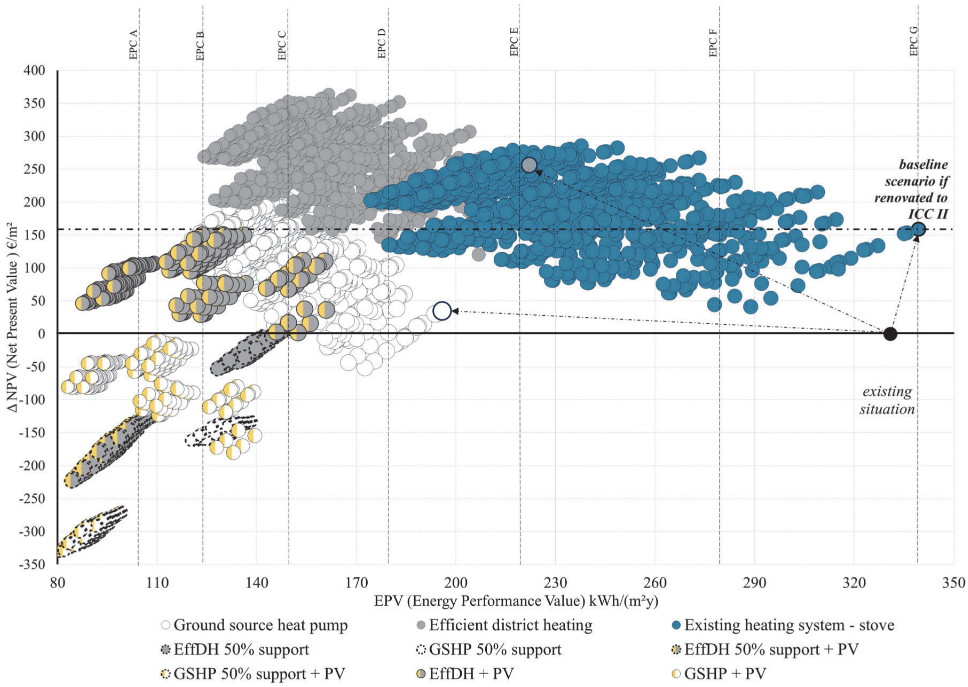

Fig. 6. The dependence of net present value on the energy performance of the building with three heat sources for heating rooms, ventilation aid, and DHW. The black marker refers to the current situation. Scenarios are looked at as if the base case is a stove heating system and compared with a change to GSHP and EffDH solutions. The lowest value with EffDH and GSHP is gained with a 50% grant to support the renovation. The size of the bubble refers to a renovation solution's embodied carbon footprint value, yellow colour indicates PV panels affect in the solution.

However, when it comes to stove heating, the impact of these measures on emission reduction is minimal due to the low emission factor of wood. Nonetheless, the building's energy performance improves and heating costs decrease significantly. To achieve a carbon-neutral renovation, it is necessary to enhance the energy performance of the building to achieve an Energy Performance Certificate (EPC) rating of D when transitioning from stove heating to efficient district heating. In the case of an original heat source of efficient district heating prior to renovation, achieving an EPC rating of C (the current requirement for major renovations) is necessary for a carbon-neutral renovation. If a ground source heat pump (GSHP) is installed in a stove-heated building, the building envelope should be insulated to an EPC rating of B, and the addition of PV panels will result in an EPC rating of A, thus achieving a carbon-neutral renovation.

3.2. *Cost optimality of renovation*

illustrates the relationship between the net present value and the energy performance of a building using three heat sources for room heating, ventilation support, and domestic hot water. Insulating the external walls with mineral wool and the attic with cellulose proves cost-effective (as shown in Fig. 6) when the energy performance value (EPV) is between 150 and 200 kWh/(m^{2}y) over a 30-year period, even without any grants or subsidies. The results of the analysis suggest that these solutions offer a favourable balance between costs and energy savings, particularly when considering the long-term perspective without external financial assistance. In current national renovation practices, a 50% subsidy is provided for complete renovations that are carried out away from central areas of attraction. This further enhances the cost-effectiveness of the renovation project.

Solutions that describe cost-effective situations include improving air leakages and adding ventilation with attic and/or external wall insulation. However, ventilation alone is not enough during renovation work, as it does not improve the air leakage value on its own. If grants or subsidies are available, it is possible to achieve EPC class A, B or C in reasonable terms. This requires the walls and attic to be insulated, along with the installation of a mechanical ventilation system with heat recovery. With 50% grant and PV panels (in the figure, left side from bubble is yellow), cost optimality is beneficial with both systems – EffDh and GSHP.

On the other hand, currently supported solutions by the National Heritage Board are not cost-effective because they involve adding new materials (such as paint and/or wooden cladding) without visible energy savings.

Another aspect that emerged from the cost optimality study is the relationship between carbon emissions, cost optimality, and energy performance. The size of the bubbles in the figure represents carbon emissions, indicating the presence of two different clouds: one with higher costs but lower emissions (above) and the opposite (below). The difference between these clouds lies in the heating system used. The upper cloud refers to district heating, while the lower cloud represents a ground source heat pump. This result suggests that a more efficient district heating system with a lower emission factor leads to lower carbon footprint values, as shown Fig. 6.

The insights from this study provide a critical understanding of the cost implications of various energy improvement strategies. They also shed light on the importance of financial incentives in achieving optimal energy performance standards.

3.3. Current heritage conservation technical requirements

Several meetings with the Estonian Heritage Board were held (Table 2) over four months. The first feedback ("business as usual" – BAU situation) from the Heritage Board commission was that the exterior walls of the building can be insulated by a 50–70 mm insulation layer, therefore including the wind barrier and the wooden façade board to preserve the original (Fig. 7) wall-to-roof profile. However, the windows should be moved outside in this scenario. For the attic, it is possible to add as much insulation as wanted; what is important is that the existing roof profile and building height are not changed.

The final decision from the Estonian Heritage Board after four months was that the current building could be renovated up to EPC A class if the original façade profiles were preserved. This means that the external walls will be insulated, the windows and doors moved outwards, and the roof lifted, thereby preserving the original historical façade profiles.

The first and last meetings included the possibility of insulating the ground floor; however, it should be mentioned that meant that residents would have had to move out of the building for the duration of this work. This improvement solution was therefore considered carefully. Detailed works can be seen in where it can be seen that insulating the ground floor is used for EPC class A and B combinations. The same material combinations were used based on the final design project. For external walls, glass wool, for the attic, cellulose, and for floor insulation, XPS and EPS insulations were used. The difference between an efficient district heating system (EffDH) and a ground source heat pump (GSHP) was analysed. BAU scenarios indicate for the first scenario what was offered by the National Heritage Board for the current case-study building and are compared with different heating sources.

If the case-study building is renovated according to the BAU heritage recommendations from the first meeting (Table 2), the best solution would be to achieve a D-class rating of 176 kWh/(m^2y) with district heating and 160 kWh/(m^2y) with a ground source heat pump (Fig. 8). However, it is important to note that there is not enough space on the plot to accommodate sufficient vertical pumps. The heritage committee has stated the technical requirements for both scenarios (first and final meetings), which state that the building should be connected to the district system in order to avoid heat pumps or any other technical systems being placed on the building façade.(Fig. 9)

If the building is renovated to meet the technical requirements first, the carbon footprint of the building will range between 21 and 30 kgCO2e/(m^2y) depending on the heating systems used. Operational energy (module B6) accounts for approximately 95% of the total emissions, while embodied carbon (cellulose in the attic, glass wool in the external wall, new windows, etc.) accounts for 5% of the total value.

During the study, an analysis was conducted to determine whether the existing heating systems, such as local gas or efficient district heating, could replace the current wood log stove. The results show that the carbon footprint would decrease significantly if the existing gas system was replaced with EffDH or GSHP (Fig. 8).

Once the renovation works are carried out according to the findings, there will be a saving of 5–7 kgCO2e/(m^2y) compared to the existing wood log heating system. The difference in carbon footprint between EPC class A and EPC class B is not significant, as class A requires photovoltaic panels, which would increase the overall value. However, the energy savings are notable.

When comparing the initial heritage requirements to the outcome, the carbon emissions decrease by 30% over the lifetime of the building for EPC class B and there is no change for EPC class C. However, there is a 10% increase in carbon emissions with GSHP and a 10% increase with EffDH. This emphasizes the importance of deeply renovating heritage buildings from a carbon footprint perspective. In conclusion, this finding is significant as it allows for the preservation of the historical outcome, while also saving a significant amount of energy and reducing carbon emissions. These results are mainly due to the use of wood logs for heating in the existing building, which has a significantly low emission factor.

When analysing the formation of embodied carbon footprint (Fig. 9), it was observed that windows have the most significant impact in each scenario. One contributing factor is that wood-framed windows have a lifespan of 40 years, meaning they need to be replaced once during the 50-year calculation period, after 40 years. Another substantial impact is caused by PV panels in the EPC A class scenario, as their lifespan is only 20 years. However, considering the high emissions factor of Estonian grid electricity, the addition of PV panels proves beneficial. Improved energy performance results in a higher embodied carbon footprint, with the windows and PV panels in the EPC A class version playing a major role.

4. Discussion

The results of this study from the carbon footprint perspective of the building found that if the building is renovated as per the business-as-usual practice from the National Heritage Board technical requirements scenario, then it will be environmentally unfavourable. This

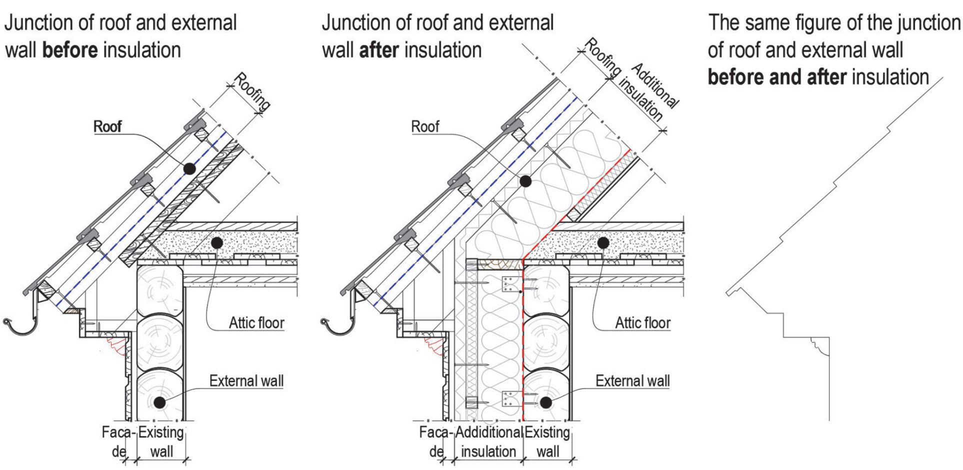

Fig. 7. Historical building preserves its original profile during renovation works while achieving nZEB requirements.

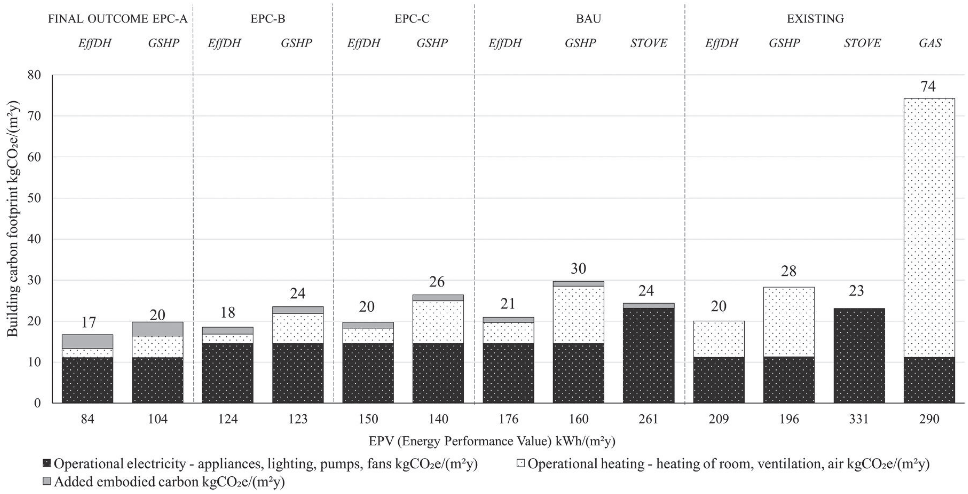

Fig. 8. The influence of carbon footprint at different energy performance. Same material combinations were used - based on final design project. Difference between efficient district heating system (EffDH) and ground source heat pump (GSHP) were analysed. BAU scenarios are indicating for first scenario what was offered by National Heritage Board for current case-study building and compared with different heating sources.

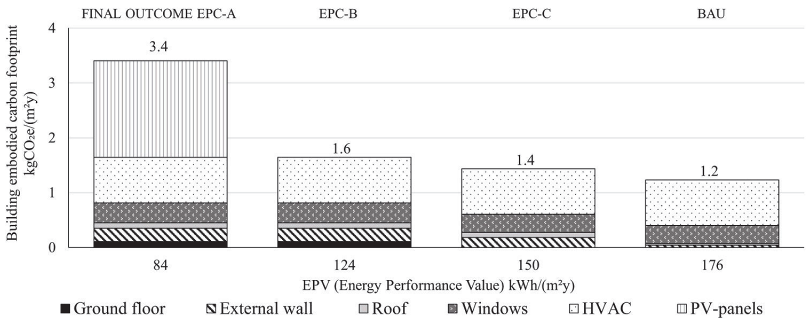

Fig. 9. The influence of embodied carbon footprint at different energy performance values with efficient district heating system.

is because producing and using materials will be more burdensome for the environment than the benefit received from minimal insulation in the form of reduced energy consumption.

Furthermore, the studies underscore the importance of cost optimality and energy savings to guarantee owners' willingness to pay. Solutions that will lead to the minimum energy performance requirement for renovation (EPC C class, 150 kWh/(m2y)) can be achieved without any supporting grant or subsidies when a new heat source is provided. If the entire building envelope is insulated according to the grant requirements, this makes renovation more cost-effective than staged renovation due to the possibility of receiving a renovation grant.

It means that the renovated building's running costs (payback on renovation investments and energy costs) will be lower than the running costs before renovation.

As the building's original situation before renovation lacked proper indoor climate systems and did not offer a healthy indoor climate (Arumägi et al. 2015), all renovation measures were calculated by adding mechanical balanced ventilation with heat recovery. Since the impact of electricity on emissions is greater than that on energy performance, this measure increases emissions despite significant improvements in energy performance and indoor climate. Therefore, the remaining renovation steps must cover the emission increase of this essential renovation step.

From the carbon footprint perspective, choosing the heating system for the building has a large impact, especially in urban areas where the connection to an efficient district heating system has notably advantageous results compared with a ground source heat pump. Emission factor differences between a ground source heat pump (GSHP) and efficient district heating (EffDH) are great – district heating has a value ten times smaller than that of the ground source heat pump, which needs electricity to work.

Based on current practice, heritage authorities accept rather minimal changes to the building envelope to keep the external appearance of historical buildings. These works include repainting existing wooden cladding. Adding new cladding and a thick wind barrier has been accepted as a renovation measure. This approach has a minimal impact on the improvement of energy performance and at the same time increases carbon emissions. In the present study, the wooden boarding of the external wall of the building was in such bad technical condition that it had to be replaced anyway. Additionally, the board was not original from the time of the construction of the building. Therefore, it was possible to replace the external boarding, which, upon replacing it with a replica of the original, improves the appearance of the building (Arumägi et al. 2015).

In the study, PV panel systems were analysed for solutions that can achieve EPC class A as is the current practice. For the existing building scenario, the building can achieve EPC A class with both energy systems – EffDH and GSHP. However, it should be mentioned that if the national energy emission factor is decreased due to more renewable energy sources in the grid, then there will come a point in the results when PV panels will not save on carbon emissions as they will be replacing energy that already has a low emissions factor.

5. Conclusions

This research investigates the relationships between energy performance, the preservation of historical architecture, and the reduction of carbon footprint values in the context of renovating heritage buildings in conservation areas. This research highlights the critical roles of suitable energy sources and renovation strategies and provides essential guidance for environmentally sensitive urban development within a historical context.

The deep renovation of the historical wooden building reduces its carbon footprint. Since the transition from low-emission stove heating and the installation of indoor climate systems increase emissions, these emissions must be reduced by the renovation of the entire building envelope. In order to achieve the same level of emissions as before the renovation, EPC class D must be achieved when changing from stove heating to EffDH, and EPC class B in the case of GSHP. If the original heat source is EffDH, EPC class C must be achieved for district heating and class A for GSHP to avoid an increase in emissions. It can be concluded that if the building is situated in an urban area and it is possible to connect it to the district heating system, it should be done, as this has remarkable benefits from the carbon emissions perspective.

Current technical requirements from heritage authorities prevent the achievement of a low-emission building and an optimal cost-renovation solution. In the long run, an unrenovated building has a larger carbon footprint compared to a deeply renovated building. The gap between the requirements of the heritage authorities and a low-emission building is large. If the carbon footprint of monuments or buildings in the heritage area is calculated, there is a need to change current restoration practices. Conserving the monuments in their existing condition, lowering emissions, energy, and cost savings must be achieved with other measures. Homeowners should be compensated for the higher costs of the unrenovated building. The current study showed that it is possible to renovate a historical building to a great extent without losing its exterior appearance and façade profile. The evaluation of technical requirements by the Estonian Heritage Board emphasises the need for more flexible and environmentally considerate approaches to renovation in order to minimize carbon footprint while preserving the profiles of historical buildings.

The running cost of a renovated building can be lower than that before renovation only in the case of deep renovation. Staged/step-by-step renovation (which does not correspond to the renovation grant requirement) is not cost-effective; therefore, we should be careful in supporting or recommending these solutions. Since the building's renovation debt is large and it is necessary to do a lot of renovation work not related to improving energy performance, renovation is not always cost-effective. The costs incurred to preserve the historical building must be paid from sources other than energy savings. If these works are done together with improving energy performance, the end result is more cost-effective and the owners' willingness to pay is higher.

The preference for a low carbon footprint solution will lead to a more energy-efficient renovation solution because operational emissions dominate over embodied emissions. Additional insulation does not increase the carbon footprint due to the addition of new material but reduces the carbon footprint due to the minimisation of energy consumption.

In conclusion, this study offers a comprehensive analysis of various scenarios, including carbon footprint, energy performance, and cost optimality, related to several renovation strategies for buildings located in heritage conservation areas.

Authors statement

The authors declare no conflict of interest and they share equally the contribution in this paper.

CRediT authorship contribution statement

Endrik Arumägi: Writing – original draft, Visualization, Methodology, Formal analysis. **Kadri-Ann Kertsmik:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jaanus Hallik:** Methodology, Formal analysis. **Targo Kalamees:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in his paper.

Data Availability

Data will be made available on request.

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Appendix

Materials used in the renovation options in this study:

Building components	LCA modules used in calculations according to the Estonian method											
	Material	A1-A3 GWP kg CO_2e/kg		A4	A5	B4, life-age, years			C2	C3	C4	D GWP kg CO_2e/kg
		$average^{highest}_{lowest}$	w/o local comp	km	%	BNB	G*	used	Default value 50 km for	Materials divided: metal, mineral materials, wood-	Materials divided: metal, mineral materials, wood-	

(*continued on next page*)

(*continued*)

Air and vapor membrane	Water vapour membrane	$2.81_{0.64}^{2.87}$	5.95	500	10	50	-	50	materials to waste plant.	based materials. According to the Estonian waste management plan.	based materials. According to the Estonian waste management plan.	-1.15
Frame, insulation for roof and external wall	Glass wool, 0.035 W/(mK) 18 kg/m^3	$1.32_{1.13}^{1.80}$	1.8	500	8	50	-	50				0
	Stone wool, 0.035 W/(mK) 35 kg/m^3	$1.27_{1.11}^{1.58}$	1.5	500	8	50	-	50				0
	Cellulose, 0.039 W/(mK) 50 kg/m^3	$0.94_{0.51}^{1.58}$	0.2	500	8	50	-	50				-0.27
	Timber frame	$0.11_{0.05}^{0.21}$	0.1	500	18	40	-	50				-0.89
Wind barrier and external wall finish	Glass wool 0.031 W/(mK) 63 kg/m^3	$1.85_{1.20}^{2.20}$	1.0	500	10	50	-	50				0
	Wood fiberboard 0.049 W/(mK) 230 kg/m^3	-	0.7	500	10	50	-	50				-0.42
	Wooden cladding	$0.11_{0.05}^{0.21}$	0.1	500	18	50	40	50				-0.89
	Façade paint	$1.21_{0.94}^{1.79}$	1.75	500	10	10	10	10				0
Roof finish	Stone tiles for roofing	-	0.4	3000	5	50	x	50				-0.01
	Steel sheets, cladding	$2.40_{1.85}^{3.32}$	2.80	3000	3	50	40	50				-1.53
Basement floor insulation	XPS 0.031 W/(mK)	$3.04_{2.64}^{3.71}$	2.70	500	17.9	50	-	50				-1.62
	EPS 0.035 W/(mK)	$3.04_{2.64}^{3.71}$	3.09	500	10	50	-	50				-1.62
Windows	Triple glazed, U=0.8 W/(m^{2}K)	$2.27_{1.66}^{3.47}$	2.08	500	0	40	30	40				-1.68
	Triple glazed, U=0.6 W/(m^{2}K)		1.66	500	0	40	30	40				
	Double glazed, U=1.1 W/(m^{2}K)	$1.65_{0.97}^{2.14}$	1.15	500	0	40	30	40				-1.51
PV-panels	Monocrystalline, 19 kg	42	42	3000	0	xx	20	50*				0

G* Goulouti et al. 2020

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The feasibility of zero-emission neighbourhood renovation of apartment buildings in a cold climate

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ABSTRACT

The role of cities is instrumental in achieving the climate neutrality of building stock by 2050. This study evaluates the renovation potential of a group of 22 apartment buildings in Tartu, Estonia, and particularly feasibility of a transformation to a Positive Energy Neighbourhood (PEN). The challenges of urban density and cold climate are emphasised, representing a vital case for the European Union's "Zero Emission Districts and Neighbourhoods for Sustainable Urban Development" initiative.

To assess the feasibility and implications of achieving PEN standards, an analysis was conducted in a densely populated urban area enhancing energy efficiency, evaluating land use implications, and achieving carbon neutrality. This study applies Life-Cycle Assessment to discuss four renovation scenarios: (1) baseline, (2) the minimum requirement set by the Estonian long-term renovation strategy, (3) the performance of nearly zero-energy buildings (nZEB), and (4) PEN.

The findings show that while PEN is achievable, the extensive land area required for renewable energy production or nature-based carbon sinks challenges its feasibility in dense urban environment. The results reveal that the minimum energy efficiency level required by the long-term renovation strategy does not reduce the whole-life emissions, therefore it is crucial for renovation grants to also require investments in on-site renewable energy production.

Transitioning urban neighbourhoods into zero-emission districts requires integrated strategies that combine energy-efficient renovations, renewable energy deployment, and innovative urban planning. The results of this study imply that decarbonisation policies should not be driven merely by the net-zero emissions balance due to the disproportionate land-use impact of offset measures.

Abbreviations

BAU	Business-As-Usual
CO_2eq	Carbon Dioxide Equivalent, $kgCO_2eq$
CF	Carbon Footprint
DHW	Domestic Hot Water
EffDH	Efficient District Heating
EN	European Standard
EPBD	Energy Performance of Building Directive
EPC	Energy Performance Certificate
EPV	Energy Performance Value, $kWh/(m^2y)$
ETICS	External Thermal Insulated Composite System
GHG	Greenhouse Gas
GSHP	Ground Source Heat Pump
GWP	Global Warming Potential
HA	Hectare
HVAC	Heating Ventilation and Air Conditioning
LCA	Life-Cycle Assessment
nZEB	Nearly zero-energy building
NZE	Net Zero Energy
PEN	Positive Energy Neighbourhood
Pre-Fab	Previously Fabricated element
PV-panel	Photovoltaic panel
RES	Renewable Energy System
SPEN	Sustainable Plus Energy Neighbourhood

1. Introduction

1.1. Demand

Cities play a significant role in achieving climate neutrality by 2050,

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as they consume up to 65 % of the total global energy and cause over 70 % of the total global CO_2eq2 emissions [1]. In 2022 one hundred European Union cities were selected for an experiment of "Zero emission Districts and Neighbourhoods for Sustainable Urban Development" to become climate-neutral and smart cities by 2030 [2], paving the way for all other cities' journey towards climate-neutrality by 2050. One of these cities is Tartu, Estonia, where the case study area is located.

The steps towards climate neutrality are recommended to start with minimising the emissions, for which the most important aspect is the reduction of operational energy use through energy efficiency, followed by the supply of renewable energy, and carbon offsets [3]. Agendas for net-zero greenhouse gases (GHG) are extensively used as the basis for the European Union policies to achieve a more sustainable built environment [4,5], emphasising the urgent need for building renovation as a primary approach to reduce construction sector environmental impacts which highlights the importance of developing energy and emission performance in the building sector [6].

Recently, the focus has shifted from new buildings to renovations with the European Union Renovation Wave Strategy which is emphasised in the 2022 recast of the EPBD [7] and aims to double the annual renovation rate. From the greenhouse gas mitigation perspective, renovating buildings should be prioritised over new construction [8].

Given the limited availability of public funding, priority should be given to vulnerable groups at risk of energy poverty—often defined as the inability to maintain a building adequately [9]. To reduce energy poverty, public support should prioritise renovating housing, improving living conditions while boosting renewables, jobs, savings, and environmental benefits [10]. Low-income households in rented apartments gain the most from mandatory renovation initiatives [11]. Building renovations benefit low-income families the most, as they often face the greatest barriers to retrofitting due to administrative complexity, while also playing a crucial role in supporting urban development [12], in Tartu, this is particularly relevant for the Annelinn suburb, where most low-income families currently reside.

To achieve carbon neutrality, renewable energy sources with low carbon intensity are needed [13,14]. In the Estonian context, efficient district heating is one of the most suitable solutions [15,16]. To further reduce built-environment emissions and to reach climate targets, the focus should be shifted from operational energy consumption to a decrease in environmental footprint. Therefore, different building envelope renovation solutions are important for the analysis [17,18]. For holistic estimates of environmental impacts, life-cycle assessment (LCA) is applied to quantify embodied and operational carbon throughout a building's lifetime [19].

1.2. Review of previous studies

Clean energy transition of urban areas is urgently needed to pursue the Paris Agreement climate goal [20]. Therefore, different concepts have been developed to measure a climate-neutral city. The European Commission Horizon 2020 program suggests a respective strategy for neighbourhoods that actively manage their energy flow and consumption of several buildings in one group [21]. This concept is commonly used in many European Union (EU) research projects, and it is defined as "a district with annual net zero energy import" and net zero CO_2eq emissions [22]. These districts have smart energy grids and demand responses, which also decrease energy needs, and are designed to be part of the district energy system. Another concept is the Sustainable Plus Energy Neighbourhood (SPEN), which aims to achieve a renewable energy source with more than 90 % and 10 % life-cycle cost reduction [23]. The SPEN concept is defined as a group of buildings within the same geographical boundary. The aim of SPEN is to reduce carbon emissions, both indirect and direct, through energy use measures.

Furthermore, Positive Energy Neighbourhoods (PEN) [24] are considered to have more potential to reduce emissions, than one individual building separately [25]. This type of district is considered to consist of several buildings that actively manage the emissions flow between consumption and production, building materials, and operational energy. PEN definitions are included in the European Strategy Energy Technology Plan [26], EERA Join Programme Smart Cities [27], and COST Action Positive Energy Districts European Network [28]. As the operational energy used from electricity in buildings increases faster than the carbon intensity decreases in the power sector, on-site renewable energy is seen as a key factor in achieving targets [28]. Moving from a building perspective to a district scale is suggested to maximise the advantages of resources and minimise environmental loads [29,30].

In Dijon, similar climatic condition [31] as Tartu, it was found that most important aspect in LCA is building heating [31]. Analysis of Dutch residential building stock renovation scenarios shows that insulation building envelope is high-impact measure, which helps with operational emission reduction, requiring addressing both heating and electricity systems [32]. Case study analysis shows that total emissions are lower for deep renovation than new construction, highlighting the importance of retrofitting the buildings to reach net-zero goals [33]. Göswein et al. [34] underlined the need for transition to bio-based materials in renovation systems and renewable energy to reduce urban carbon emissions. With Switzerland building stock, it was demonstrated [35], that in cold climates bio-based insulation and low-emission heating sources reduce both embodied and operational energy, making them optional for deep renovation. Kertsmik et al. [17] found that renovation solution insulation material impact vary, therefore preferring material with lower emissions could help to decrease total carbon footprint. Drouilles et al. [36] examined the Swiss building stock's transition potential, highlighting that, despite economic and feasibility concerns, deep renovation of residential buildings to the highest energy efficiency standards can significantly reduce global warming indicators and non-renewable primary energy use by 74 % to 85 %, depending on the building type. Similarly, UK study [37] (over 160 different buildings) demonstrated that refurbishment projects are showing consistently lower emissions than new-build. Lifecycle analysis of 23 renovation projects in Denmark showed that while operational emissions dropped by nearly 50 % after renovation, embodied emissions amounted to approximately 40 % of the post-renovation operational emissions [38]. Renovation carbon footprint may vary by local energy grid [39] - in fossil-based systems, shifting to electric heating reduces emissions, while in cleaner grids, added embodied emissions can outweigh operational savings, underscoring the need for region-specific renovation strategies on cold climate.

Many current studies highlight the critical role of energy systems in achieving emissions reductions, as Georges et al. [40] demonstrated that zero operational emissions can be attained for nZEB concepts regardless of the CO_2e factor, while Koezjakov et al. [41] found a potential 36 % reduction in total energy use by 2050, driven by a 46 % decrease in operational energy but offset by a 35 % increase in embodied energy. Conversely, Passer et al. [42] saw that in Austria, where energy performance optimisation is already advanced, the potential for further improvement is relatively low.

Currently, there are limited studies on embodied and operational carbon in buildings; however, these are important components for achieving climate targets, especially in cold climates where it is necessary to heat over half a year. The concept Net Zero Energy (NZE) is closest [43], focusing on retrofitting buildings, whereas installing integrated energy system, however, no building envelope analysis has been performed. In addition, as renovation needs increase, there is a lack of knowledge on how to develop whole districts with zero emissions. On the one hand Caruso et al. [44] verified that A1-A3 module has significant impact at city scale, however operational energy dominates, which will lead to spatial planning strategies. Moisio et al. [45] studied the environmental impacts of retaining or replacing buildings in Finland and showed that refurbishing and extending existing buildings is worthwhile in terms of GHG emissions. Modelling of a zero-emission neighbourhood in cold climate [33] revealed that nearly half of embodied emissions arise from long-term material replacements, highlighting the importance of material efficiency strategies across the entire building life cycle. García-López et al. [46] assessed carbon footprint at district-scale and showed that retrofitting buildings is better for decarbonisation than building new ones.

Leichter et al. [47] found that regardless of scenario, operational emissions are the largest contribution regardless the energy carrier or renovation strategies, especially at the urban scale perspective. On the other hand, Alaux et al. [33] found that both embodied and operational emissions must me reduced over all EU member states to achieve GHG reduction. Nevertheless, evaluating whole neighbourhood [48] renovation strategies, building has the greatest impact and obligation on balancing emissions - both embodied and operational.

At 2019 Atelier [49] in Amsterdam new neighbourhood was finished, which is producing more renewable energy on-site than the need for district energy for consumption on an annual basis. In this example, emissions from zero direct non-biogenic CO_2eq are also considered which means that different several types of activities which produce CO_2eq are included. Other examples from projects +CityxChange [50], Sparcs [51] and Pocitfy [52], it is also defined that sites under analysis can produce more energy than it is needed to consume, over an annual basis definition. Situation was created through on-site renewable energy production. None of the projects focused on which kind of new paradigm for land-use change is needed to achieve such results from the energy production perspective, and only grid flexibility was created.

Numerous studies demonstrate that buildings have the highest impact (over 50 %) in urban life-cycle assessments (Fig. 1). Trigaux et al. [53] highlighted significant environmental differences between neighbourhood design alternatives, underscoring the importance of optimising building layout and density. Stephan et al. [54] showed that replacing suburban built areas with higher-density apartment buildings reduces per capita energy consumption by 19.6 %. Similarly, Wiik et al. [55] found that developing interconnected buildings into a Zero Emission Neighbourhood entails higher first capital costs but significantly lowers operational energy use, reinforcing the pivotal role of buildings in urban sustainability. Road maintenance carbon footprint is according to Biswas study [56] is 181 $kgCO_2eq/m^2$, highest impact lays in maintenance phase.

1.3. Objective

The aim of this study is to analyse the challenges in achieving energy-efficient and energy-flexible groups of connected buildings, which produce net zero greenhouse gas emissions - one part of PEN definition [24]. What sets this study apart and novel is its examination of a densely populated area forming high-rise buildings within a cold-climate region. To achieve a net zero greenhouse gas emissions in PEN context, the size of the urban area to sink emissions was considered, and which are produced with buildings and cannot be fully balanced with onsite energy generation from renewable sources as a vital parameter.

The hypotheses of this study were as follows:

- H1. Renovated urban neighbourhood requires more land for emission offsets than building areas.
- H2. Current building renovation policies do not mandate on-site renewable energy integration and external compensation measures to balance carbon emissions effectively.
- H3. Deep renovations significantly reduce the land needed for emission offsets compared to the existing situation.

2. Materials and methods

2.1. Description of analysed area and buildings

The study was conducted in the Estonian (Northeast Europe) cold climate (design outdoor temperature for heating −23 °C, annual average temperature. +5.7 °C, annual heating degree days at temperature 17 °C: 4160 °Cd [57] in highly occupied urban area (person/ha). The methodology used is universal, with local climate conditions accounted for through the test year. To determine the study area, different living densities of neighbourhoods were compared (Fig. 2). Left, red colour in Fig. 2 refers to single-family detached house area, middle, yellow marks mid-rise apartment buildings with 4–5 stories and right, blue marks high-rise apartment buildings with 9 stories. For the current study area, the highest density area (right, blue) was selected, as this is the most challenging district to achieve PEN requirements.

The study area consisted of a group of apartment buildings in Tartu, southern Estonia. The total area of the case study land is 13.3 ha, including 22 apartment buildings. All buildings were built between 1970–1980 and built by using standardized concrete large panels to optimise space and accommodate a large number of residents. These kinds of structural solutions often raise multiple stories high and are a showcase of rational design, efficient floor plans, and uniform facades. The existing façade is a coloured concrete element. According to Estonia Land and Spatial Development Board the case area is consisted of three different intended use – 11 % transport land, 14 % public land and 75 % residential land. Thereby the focus of this study is closely related improving building energy efficiency and on-site renewable energy creation. Also focusing on energy poverty reduction, which can be achieve with renovating existing apartment buildings [31].

Apartments originally had a one-pipe hydronic radiator system,

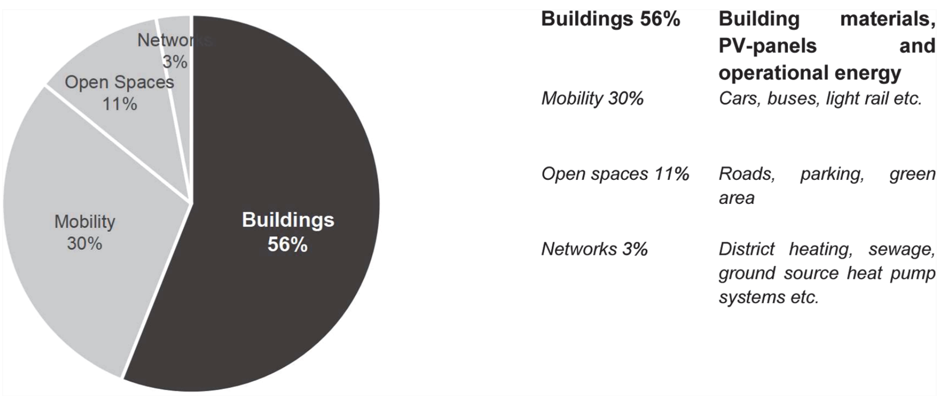
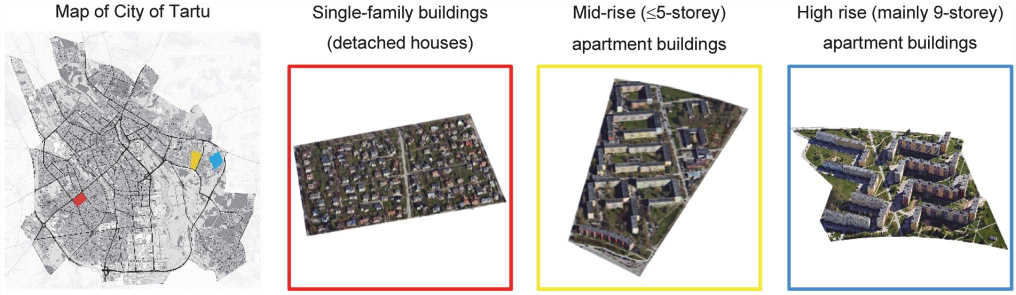


Fig. 1. District LCA components are shared in several studies [33,44,45].



	Single-family buildings (detached houses)	Mid-rise (≤5-storey) apartment buildings	High rise (mainly 9-storey) apartment buildings
The total area of the neighbourhood, ha	10.7	13.8	13.3
Heated floor area of buildings, m²	23 219	98 564	121 155
Living density, total area of the neighbourhood and heated floor area of the buildings, m²/m²	0.22	0.71	0.91
Limit value to achieve nZEB = EPC-A, kWh/a	120	105	105
Annual energy needs for energy performance of nZEB, MWh/a/m² per ha	260	750	1 165

Fig. 2. Tartu City, the most densely populated area, was chosen for the case study, with high-rise buildings (right, blue).

natural passive-stack ventilation and 2-panel windows could be opened for airing. The buildings are heated and equipped with hydronic radiators using Tartu city efficient district heating network. With renovation of buildings, the introduction of modern technologies and the use of local and renewable fuels in heat production, Tartu's CO_2eq emissions have been reduced over 30 % over last years [58], but there is still long way to go to achieve full carbon neutrality. Future renovations should decrease embodied and operational emissions from the heat loss of the building envelope by insulating external walls, roofs, slabs between the first floor and basement, replacing windows, and improving HVAC systems to provide a healthy indoor climate.

The key operational energy parameters of the thermal transmittance (*U*-value) for the different scenarios were from heat reduction. Socio-economic factors, such as renovation subsidies, have been considered, where EPC—C represents for the business-as-usual (BAU) scenario, and EPC-A is the minimum requirement for new buildings based on cost-effectiveness. The areas measured included the total envelope area (roofs, basements, external walls, and windows) (103 047 m^2), net internal floor area (125 944 m^2), and heated area (121 155 m^2).

Table 1outlines the improvements in building performance across renovation scenarios, focusing on insulation, airtightness, heating, ventilation, and energy sources. Building renovations significantly reduce carbon emissions by improving thermal envelope insulation and airtightness, which minimises heat loss, and by replacing outdated one-pipe heating systems with efficient two-pipe setups equipped with thermostatic control. Advanced ventilation systems, evolving from none in the existing state to balanced mechanical systems with heat recovery, can further reduce emissions.

However, achieving higher performance levels, such as EPC-A and PEN, increases the demand for materials, such as PV-panels (solar panels) [15], which contribute to embodied carbon emissions. Currently PV-panels for rooftops and south face façades were included [59]. Among these strategies, PEN dynamic renovation is the most impactful, combining advanced technologies and renewables to achieve substantial reductions in both the operational and embodied carbon footprints.

Table 1
Summary of renovation measures.

Renovation parameter	Existing	Minimum requirement for major renovation EPC—C	Nearly zero-energy buildings (nZEB) renovation to EPC-A	PEN dynamic renovation
Scenario number	1	2	3	4
	Building envelope			
$U_{external\ walls}$, W/(m^2·K)	0.8	0.20	0.16	
U_{roof}, W/(m^2·K)	0.42	0.20	0.20	
$U_{windows}$, W/(m^2·K)	1.8	1.10	0.90	
q_{E50}, m^2/(h·m^2)	6	4	2.5	
	Building service systems for indoor climate			
Efficient District Heating (EffDH)	One-pipe	Two-pipe system with hydronic radiators and room thermostats		
Ventilation	Natural passive stack ventilation	Mechanical balanced ventilation with heat recovery		
	Energy source			
Heat for room heating, heating of ventilation air and DHW	Efficient district heating, mainly based on biomass fuel, Ground source heat pump (GSHP)			
Electricity	Grid	Grid	Grid	Grid
Renewable energy systems (RES): PV panels	No	No	to achieve EPC A	to achieve PEN

2.2. Carbon footprint of renovation measures

The scope of Life-Cycle Assessment (LCA) approaches and energy balance are set by four different renovation scenarios which will be analysed: baseline (existing situation before renovation), business-as-usual - major renovation (EPC C-class), nearly zero-energy building (nZEB, EPC A-class), zero-emission building (EPC 10 % lower than nZEB) [60], PEN no emissions from operational energy and compensated emissions from embodied carbon.

LCA calculations were performed to provide objective information about the emission balance during the buildings 50-years' service life. The LCA calculations are based on the Estonian first LCA methodology [61].The LCA application in this study aligns with the framework outlined by Lützkendorf et al. [62]., providing a comprehensive perspective on life cycle assessment methodologies and their relevance to built environment sustainability. The embodied emission factors of used materials are listed in the Appendix of the current article. The proposed calculation for the LCA method is based on ISO 14,040 [63], European standards EN 15,804+A2:2019 [64] and EN15978 [19,65] and the European Level(s) framework [65], which provide system boundaries. The methodological approach considered the European Taxonomy Regulations [66],which came into force on July 12, 2020 (2020/852).

Emissions from operational energy use (module B6) were calculated using the delivered energy (for space heating, heating of ventilation air and domestic hot water (DHW), and electricity for building service systems, lighting, and appliances) and emission factors for electricity of 0.374 $kgCO_2e/kWh$ and for district heating (B6) 0.110 $kgCO_2e/kWh$. Before renovation, the average heat use for room heating, heating of ventilation air, and DHW was 145 $kWh/(m^2y)$, and electricity use was 24 $kWh/(m^2{\cdot}y)$. Renovation measures are based on the current best practice in Estonia and include insulation of the building envelope using pre-fabricated (pre-fab) insulation elements with mineral wool with a façade of cement fibre board and triple glazing windows in the external wall [17,66]. The pre-fab system has a low carbon footprint value [17] and because these are 9-story buildings, mineral wool helps achieve fire regulation requirements. A ventilated cement fibre board façade has a longer service life and smaller maintenance needs [67].

Embodied energy for building materials and on-site renewable energy carriers which are attached to building façades and roofs (PV-panels) included A1-A5, B4, C2-C4 modules. The installation of replaced materials for retrofitted components are not included. The Finnish method justifies [68] this simplification by assuming that replaced materials (B4) will have the same carbon intensity as today. Future materials are expected to be less carbon-intensive, with this reduction offsetting the omitted installation emissions.

In the Consequential Replacement Framework (CRF), Huuhka et al. [69] assume an open-ended study period post-renovation, excluding final C-module emissions, unlike this study. Their approach, ideal for comparing renovation to new construction, includes C-module emissions from demolished materials, though their impact is minimal and negligible under the 2 % rule. Lund et al. [70], seem to suggest that two separate LCA's should be conducted: one for the building before the renovation and another for the building after the renovation. The difference is that the B- and C-modules for the old components are included in the latter LCA.

The methodological application of LCA depends on the study's purpose, with typical cases including guidance on choosing between refurbishment and maintenance, refurbishment versus demolition and reconstruction, optimisation of refurbished building design, sustainability assessment for certification, and research to improve modelling of changes in the building stock [71]. This study focuses on a net emissions approach, where both embodied and operational emissions are averaged over the reference study period and offset through sequestration measures. Methodologically, it aligns with approach "zero" [71], excluding the embodied emissions of existing building materials after renovation.

The change in carbon emissions ΔCO_2eq (Eq (1)) of the additional carbon emissions related to the renovation solutions and renewable energy solutions needed to meet the requirements of the energy performance level building was assessed as follows:

$$\Delta CO_2eq = \frac{\left(C_G^{target} - C_G^{original}\right)}{A_{floor}} \quad (1)$$

Eq (1). The change in carbon emissions

C_G^{target} means the total carbon emissions of the targeted energy performance level according to the renovation solution, $C_G^{original}$ means the total carbon emissions of the original situation before renovation, and A_{floor} means the net area of the rooms.

Emission balance was calculated as PEN dynamic [72] boundary condition. This means that all produced and grounded emissions are considered in the same geographical area on an annual balance, considering dynamic exchanges with the hinterland to compensate for momentary surpluses and deficits. This is a middle boundary condition solution as PEN autonomous means emission balance at any moment in time (no imports from the hinterland) or even helping to balance the wider grid outside, and PEN virtual means emission balance within virtual boundaries.

Calculating land-use changes to provide local renewable source energy production calculations for PV-panels and the required area of biomass for efficient district heating to compensate for the emissions generated in the study area. It has been proved that commonly trees are not carbon sinks as within their total life span emitted and sink emissions will be zero for the total LCA [73]. Based on this knowledge, trees from the case study area were not included in the calculations. In this study, to visualise results it is assumed that the new energy bush will capture 4.0 tonnes CO_2 per one hectare [74] and for biomass energy creation is 7 ha to cover 500 MWh [75].

The compensation measures focus on three key areas:

- Ground-mounted PV-panels to produce electricity where rooftop and façade installations are already covered to meet the area's net annual energy demand
- Biomass cultivation for efficient district heating systems
- Forest regeneration supplies renewable materials and serves as a carbon sink to offset the emissions generated by fossil fuels used in the production of building materials and PV-panels.

3. Results and discussion

3.1. Energy performance and carbon footprint for renovation measures

Using the renovation strategy tool, renovation measures were selected from thousands of renovation combinations [76]. Fig. 3 illustrates the cumulative carbon footprint of a high-rise building (nine floors, four hallways, and 144 apartments) over a 50-year service life period. The graph compares two scenarios: an existing building and a deeply renovated building, to meet the EPC-A requirements. The x-axis represents the service life in years, while the y-axis shows the building's carbon footprint in $kgCO_2eq/(m^2y)$, which includes façade maintenance of existing buildings and thermal envelope upgrades, changes in HVAC systems, and the addition of PV panels at specific intervals.

The change in the total carbon footprint ΔCO_2eq represents the difference in cumulative carbon emissions between the existing and renovated building scenarios. Renovation activities, including changes in HVAC systems, PV-panels, and facade maintenance, are clearly marked on the graph, showing their impact on the carbon footprint over time. The renovated scenario demonstrates lower carbon emissions than the existing building, highlighting the benefits of energy efficiency measures implemented during the building's lifecycle. Based on Fig. 3 GHG payback is 10 years, after which deeply renovated building will

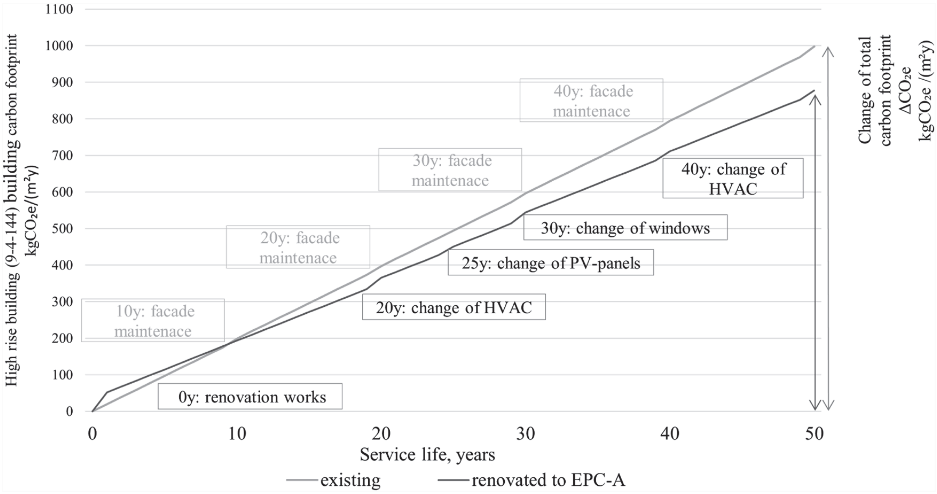


Fig. 3. Building carbon footprint change using high-rise buildings 9–4–144 from the case study area as an example, scenario (3) EPC-A.

have lower emissions in 50-year lifespan than not renovated building.

Fig. 4 provides a more detailed analysis of the relationship between ΔCO_2eq and EPV for the various renovation scenarios. The x-axis represents for the EPV in kWh/(m^{2}y), which measures the building's energy efficiency, whereas the y-axis shows the change in the carbon footprint in kgCO_2eq/(m^{2}y). Each cluster of data points represents different renovation measures, such as heating source, insulated external walls, and single measures.

The Fig. 4 illustrates the impact of various renovation measures on EPV and ΔCO_2eq across four groups of different building types, highlighting the relationship between renovation strategies, energy efficiency, heating systems, and the resulting carbon emissions. The results emphasize the importance of comprehensive renovations in achieving emission reductions and energy savings while showing the limitations of less extensive measures. The analysis covers different renovation approaches, including improvements to the building envelope, heating systems, and insulation strategies, providing a detailed overview of their effectiveness.

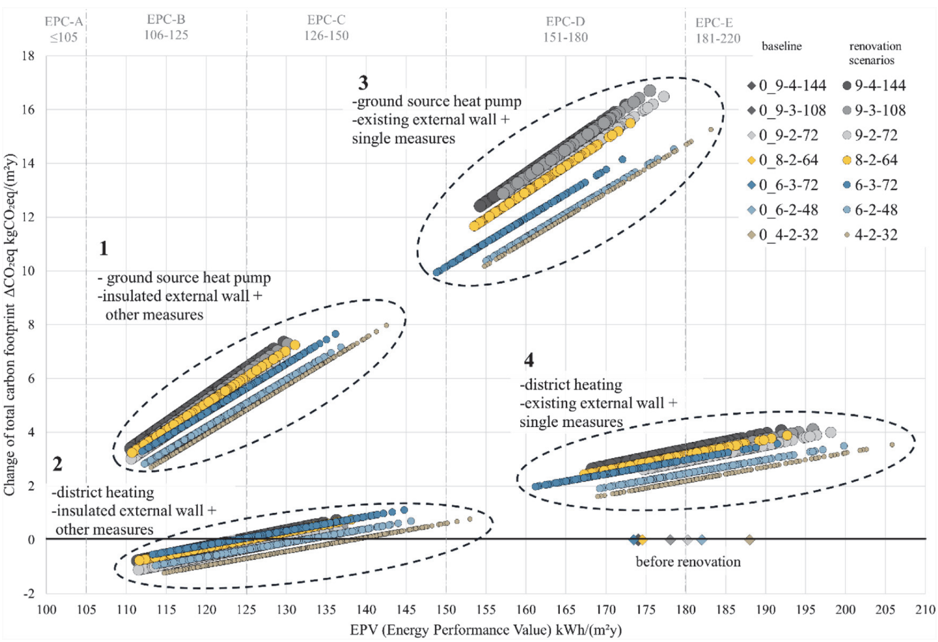


Fig. 4. Carbon footprint of renovation measures without RES. The circle stands for different renovation measures, while rhomb indicates the existing scenario before renovation. Building is described, as "0″ in front of describes before the renovation situation and then "9″ means floors, "3″ means hallways and "108" means apartments, legend shows floor hallway apartments. For all scenarios improvement of HVAC systems is included.

The key findings for each group are as follows:

- Group 1: Renovations that include a ground source heat pump, insulated external walls and other building envelope measures demonstrated substantial emission reductions.
- Group 2: Buildings connected to district heating, with insulated external walls and insulated building envelope, achieved the most significant reductions in carbon footprint.
- Group 3: Renovation strategies that kept existing external walls while using ground source heat pumps as heating source and implementing only single envelope measures demonstrated the least reduction in emissions
- Group 4: Buildings using district heating but keeping existing external walls with only isolated renovation measures showed more moderate reductions in carbon emissions.

Net-negative carbon emissions are achievable with efficient district heating and highly insulated walls ($U = 0.11$ W/(m^{2}K)), roofs ($U = 0.12$–0.14 W/(m^{2}K)), and floors ($U = 0.14$ W/(m^2·K)), airtight windows ($U = 0.7$ W/m^{2}K), and minimal air leakage (q50 = 2.5 m^3/(hm^2)). Renovation investments significantly reduce heating energy demand and, so the carbon footprint, as module B6 stays the most dominant factor in the cold climate residential building carbon footprint. The CO_2eq impact of technical systems correlates directly with electricity use, showing proportional contributions across building sizes.

Renovations become emission-effective when the EPV reaches 130 kWh/(m^{2}y) or better, aligning at least with EPC—C. For larger buildings (8–9 stories) it takes longer to become financially viable compared to smaller buildings (4–6 stories). The graph illustrates the impact of various renovation measures on EPV and ΔCO_2eq across four groups of seven different building types, highlighting the relationship between renovation activities, energy efficiency, and the resulting carbon emissions.

These results emphasise the critical role of targeted renovations in reducing emissions, thereby achieving energy savings while identifying the limitations of isolated measures. The analysis covers different renovation strategies, including improvements to the building envelope, window replacements, and combinations of insulation measures, and provides a comprehensive overview of their effectiveness.

Finally, while targeted renovations focusing on improving whole building envelopes (as shown in groups 1 and 2) deliver substantial energy savings and justify their carbon investments, isolated measures such as window replacement or partial roof/floor insulation (groups 3 and 4) often increase the carbon footprint of renovated building. These single activities do not significantly reduce operational energy demands, making them less cost-effective and environmentally beneficial in the current context.

To examine the impact of individual renovation measures on changes in a building's carbon footprint, an analysis (Fig. 5) was conducted. Each measure was evaluated separately to understand its contribution to reducing carbon emissions. Notably, an added heat-recovery ventilation system, which is currently absent in existing buildings, was incorporated into the analysis to assess its influence on operational carbon emissions.

When PV-panels are included, best results are obtained by covering both the roof and façade, as this maximises electricity generation and offsets emissions. However, adding only PV panels to the roof is insufficient to compensate for building electricity-related operational emissions. Upgrading windows or insulating the roof alone does not provide notable carbon benefits, as these measures do not achieve the necessary improvements in energy efficiency and instead lead to increased embodied carbon emissions. Fig. 5 illustrates that the most significant impact on reducing a building's carbon footprint was achieved through external wall insulation. To explore this in greater detail, a comparative analysis was conducted (Fig. 6)to examine the individual building performance along with the average values across all 22 buildings in the study area.

The results showed that improving the indoor climate through the addition of HVAC systems increases the carbon footprint owing to the embodied emissions of the new systems. However, when only an added external wall insulation layer is applied, the reduced energy demand results in a noticeable decrease in the carbon footprint, demonstrating the effectiveness of the targeted thermal envelope upgrades in achieving emission reductions.

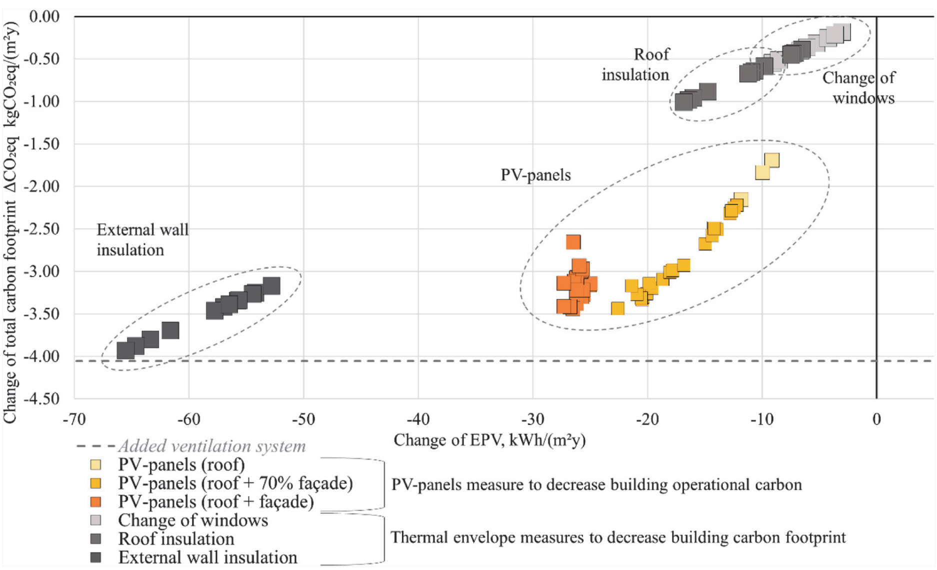


Fig. 5. Single-measure impact on carbon footprint and energy efficiency improvement. Yellow tones represent PV-panels impact and grey colours represent the thermal envelope, such as windows, roof, and external wall measures. The various points stand for the distinct types of buildings within the case study area.

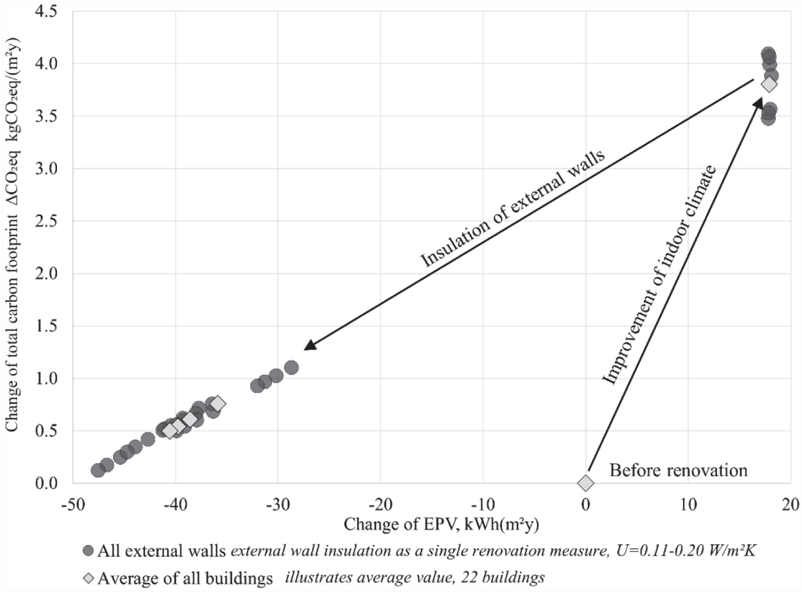


Fig. 6. Insulating the external wall as a single renovation measure and its impact on the building carbon footprint.

3.2. Neighbourhood buildings total emissions and compensation methods

Understanding the sources and proportions of carbon (embodied and operational) emissions in buildings is crucial for developing effective strategies to reduce their environmental impact. Fig. 7 was created to analyse the individual contributions of electricity, heating, and building materials to the total carbon footprint. By separating these components, the analysis offers valuable insights into how varied factors influence emissions and allows for the evaluation of energy sources and compensation methods to achieve more sustainable building performance.

The results (Fig. 7) indicate that the (4) PEN renovation scenario provides a comprehensive framework for mitigating emissions through the integration of renewable energy systems, such as PV-panels, energy bush, and newly planted forests. However, the PEN concept requires precise planning to account for all the emerging emissions associated with these systems to ensure that net carbon reductions are achieved.

The minimum requirement for a major renovation (2) EPC—C significantly reduces heat loss and decreases the energy demand for heating by more than half. This outcome is primarily due to the improved building envelope (insulating external wall). Moreover, in older apartment buildings, where ventilation systems are typically inadequate, the installation of mechanical ventilation with heat recovery is not only a necessity but also a requirement under renovation grants [77]. Emissions according to the current minimum requirement for major renovations are the same as in the no-renovation case because improving the indoor climate requires mechanical renovation. Therefore, renovation grants should be enhanced by requiring onsite renewable energy generation to cover at least the increased electricity use during the building's improvement. In cold climates, achieving nearly

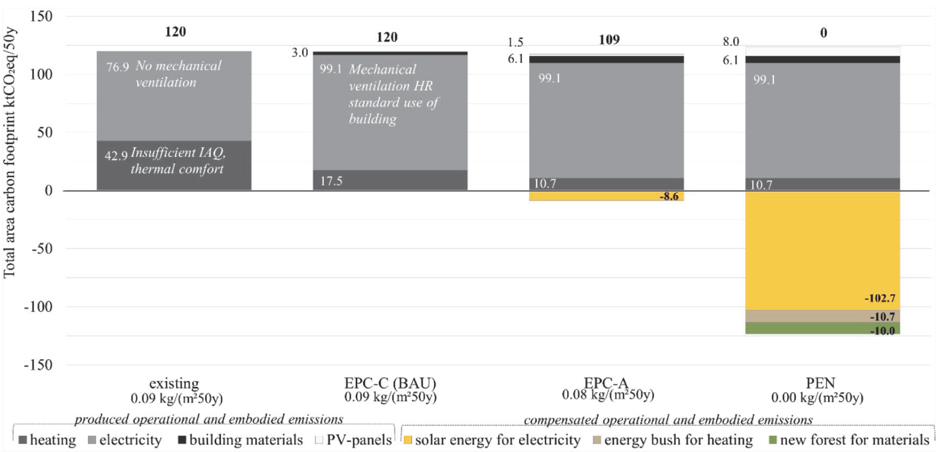


Fig. 7. Total area of 50-year emissions and compensation methods to achieve the target scenario.

zero-energy building (nZEB) standards necessitates a highly insulated building envelopes, which can decrease heat use by nearly threefold and significantly lower emissions from space heating.

A comparative analysis with prior studies [78,79] revealed that heating remains the dominant contributor to emissions at the urban scale, making it the primary focus of reduction measures in this case study. The findings underscore that while all renovation strategies effectively reduce energy consumption and carbon emissions, PEN dynamic renovation appears as the most impactful. This approach not only integrates highly efficient building envelope upgrades, but also incorporates renewable energy systems, offering a holistic solution that substantially lowers the overall carbon footprint.

The PEN scenario highlights the critical need to address heating-related emissions that dominate the urban building sector. This demonstrates the potential of leveraging renewable energy technologies such as PV-panels and energy bush to mitigate emissions while maintaining energy efficiency. Additionally, mechanical ventilation with heat recovery is essential for improving indoor air quality and thermal comfort in older buildings. Given the electricity demand associated with such systems, it may be prudent to recommend policy changes that mandate the installation of photovoltaic PV-panels to offset this energy use. These findings suggest that legislative adjustments could further support the transition to low-carbon renovations, making such measures environmentally and economically viable.

3.3. The need for land to achieve PEN

The subsequent analysis calculated the urban land area required to achieve net-zero greenhouse gas emissions across different scenarios: (1) Existing (before renovation), (2) EPC—C, (3) EPC-A, and (4) PEN (Table 2). This calculation was based on a case study area standing for a typical group of buildings, incorporating multiple compensation measures tailored to the local context. This methodology uses an energy bush as a biomass source for heating production, PV-panels for electricity generation, and newly plant forest to offset emissions from new construction materials and PV-panel production.

These compensation strategies were selected based on their geographical compatibility, integration with the national energy grid, and practical feasibility. Furthermore, the approach adheres to the PEN dynamic concept, which mandates a balance of emissions within a defined city boundary. For this study, the land required for compensation was located at the outskirts of the City of Tartu (Fig. 8), reflecting the spatial constraints and urban planning considerations of the region.

The findings prove that achieving net-zero emissions for buildings in the case study area is feasible under all scenarios, ultimately transforming the area into PEN. However, the existing pre-renovation stage requires the largest land area to compensate for current emissions, underscoring the inefficiency of this baseline. Notably, the required land areas across all scenarios (Table 1) are large, raising concerns regarding the practicality of such approaches on a city or even national scale.

The results indicate that to minimise land use for emission compensation, buildings should be renovated to at least the EPC—C standards, with EPC-A offering even greater benefits. Renovating these into higher energy performance levels significantly reduces the required compensation area. Moreover, district energy systems for heating and electricity, particularly those powered by renewable sources, are essential for optimising land use and ensuring sustainable energy management. For example, district heating systems powered by heat pumps and supplemented by small biomass boilers for peak demand present viable alternatives to fossil fuels, reducing reliance on large-scale biomass cultivation.

Table 2
The need for an area in hectares to compensate for emissions to achieve the target level.

Category	Existing	EPC—C (BAU)	EPC-A (nZEB)	PEN
Energy bush (ha) for heating emissions	959	392	240	240
PV-panels (ha)for electricity emissions	0	0	1	7
New forest (ha) for building materials emissions	0	15	38	70
Total emissions to cover to achieve climate neutrality (ha)	*959*	*407*	*279*	*317*

This study emphasises that heating-related emissions remain the largest contributor to land use needs, particularly for growing biomass (e.g. energy bush for biomass). While biomass offers a renewable alternative for heat production, its future role is uncertain owing to environmental constraints, competition with other energy sources, and limited scalability. Emerging technologies such as power-to-X, BECCS (Bioenergy with Carbon Capture and Storage), and advanced biomaterials suggest alternative roles for biomass [80], focusing on carbon sequestration and sustainable fuel production rather than large-scale energy generation [81].

These findings underline the significant land requirements associated with energy bush cultivation for emission compensation and highlight the limitations of relying solely on land-based strategies to achieve PEN. This analysis revealed the trade-offs and challenges inherent in balancing energy efficiency improvements and compensation measures, emphasising the need for a diversified approach that integrates renewable energy systems, energy-efficient technologies, and material strategies.

It is also important to note that this study focused exclusively on emissions from buildings, including electricity, heating, and construction materials, while excluding other significant sources such as mobility, open spaces, and infrastructure networks (Fig. 1). Future research should explore these sectors to provide a more comprehensive framework for achieving sustainability goals.

3.4. Different energy sources to achieve net-zero emission goals in built environment

In the context of a cold climate with limited access to fully renewable district grid energy, the operational energy stage (module B6) remained the most significant contributor to building emissions. To address this, this study explores alternative energy production strategies with a focus on maximising land use efficiency. Earlier research from Italy underscores the importance of transitioning from fossil fuels to renewable energy sources to achieve net-zero targets in residential buildings, demonstrating that this can be achieved without relying on innovative technologies [74]. Similarly, findings from a study in Islington highlighted the critical role of replacing gas systems with ground source heat pumps (GSHP) [66]. However, the space requirements for GSHP systems pose challenges in urban contexts, where the limited available land between buildings necessitates the use of vertical pumps and specific soil conditions. The Islington study further emphasised the significance of district heating systems and supportive national energy policies, which often have a greater impact on emission reductions than individual building envelope improvements.

Achieving net-zero emissions and ensuring energy security require sustainable solutions that balance benefits and trade-offs at the city and district scales. A comparative analysis (Table 3) of various energy sources reveals unique strengths and limitations:

Renewable energy sources (Table 3) vary significantly in land use, site suitability, and life cycle limitations, affecting their role in building stock decarbonisation. Wind and hydropower are land-efficient but constrained by geography. Solar panels suit decentralised use but underperform during wintertime in cold climates. Bioenergy and forest sources involve high land use and environmental risks. These findings align with earlier studies, but current studies add nuance by linking energy source limitations to renovation strategies. This study integrates

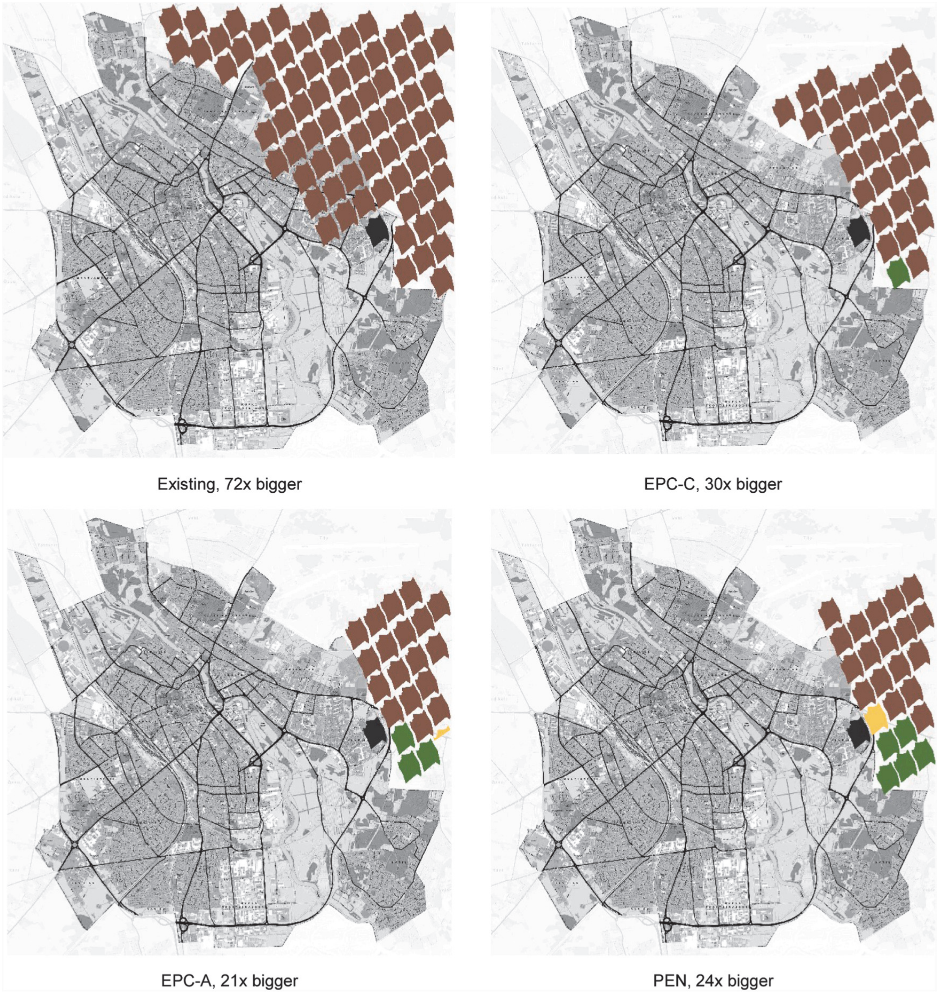


Fig. 8. Different area needs to achieve target level at the case area, unit is one case-area. Brown colour stands for energy bush to produce heat, yellow PV-panels to produce electricity and green forest, to compensate emissions from building materials and PV-panels.

energy into building-specific decisions, such as heating system selection and thermal envelope insulation. The choice of energy sources must also consider the embodied emissions of the building materials. This highlights the importance of using materials produced with zero greenhouse gas (GHG) emissions and maximizing the reuse potential of construction materials [94]. For example, bio-based insulation materials offer the dual benefit of enhancing building energy performance while absorbing CO_2 from the air. A case study from Lisbon demonstrated that deep renovations paired with biobased insulation materials yielded the most significant reduction in emissions from the built environment [95]. Furthermore, end-of-life scenarios for construction materials must be incorporated into planning processes to ensure sustainability throughout the lifecycle of a building, from construction to decommissioning and disposal [96].

The findings from this analysis emphasise that transitioning to renewable energy sources is not merely a technical necessity, but also a strategic imperative for achieving net-zero targets in urban environments. While renewable energy systems, such as PV-panels, heat pumps, and biomass, can significantly reduce emissions, their land requirements, scalability, and integration with existing urban infrastructure must be carefully considered. In this context, district energy systems, particularly those leveraging renewable energy, play a pivotal role in reducing emissions at scale, as evidenced by case studies in Sweden [97] where district heating systems have successfully halved CO_2 emissions over several decades. The results emphasise that successful building stock decarbonisation requires aligning energy supply with renovation goals and considering whole life cycle emissions. Further region-specific LCA analyses are needed to guide policy and design choices.

3.5. Changes in urban planning to achieve carbon neutral neighbourhoods

Achieving zero-emission building districts, such as the Annelinn Living Lab in Tartu, requires significant shifts in urban planning strategies. While 50 % of the study area consists of green spaces, these are primarily grassed areas that do not function as carbon sinks. To meet climate targets, urban planning must prioritise increasing forested areas and integrating energy-bush cultivation. Although specific land

Table 3
Energy sources to balance emissions.

ENERGY SOURCE	HA LAND NEEDED TO PRODUCE 1 MWH	LOCATION	LIMITATIONS
BIOENERGY [82]	200	Farmland	- Highly land-intensive, competes with agriculture [82] - Whole life-cycle emissions (harvesting, transport, combustion) are high [83]
PV-PANELS [84]	10	Building roofs and facades, flat land area	- Needs storage system, colder climates are productive only between March and October [76]; - Unstable behaviour, varying rapidly between January and April [85] - More beneficial if produced energy can be used on daytime (non-residential) [86]
WIND POWER [87]	0.0152	(near) the sea, windy farmland	- Needs windy area within a reasonable radius [87] - Operational costs challenging to predict (failures, aging) [88] - Lower cost leads to lower efficiency and vice versa [89] - National grid system security [90]
FORESTS [74]	0.014	Farmland	- Vital for ecological preservation[78] - Overexploitation of forest – soil erosion [91]
HYDROPOWER [92]	0.0038	Near fast-flowing river	- Need for specific natural aspects, such as moving water and suitable topography [92] - Ecological and environmental impacts, disrupt of aquatic ecosystems [93]

requirements require further study, it is evident that achieving these goals within current district boundaries may be unrealistic, necessitating expanded compensation areas [98,99].

Urban planning must also address transportation emissions to avoid unintended increases owing to expanded forests and energy bush cultivation. The 15-minute city concept—ensuring that vital services are accessible within walking or cycling distances—offers a solution to balance urban liveability and carbon sequestration efforts [100]. This highlights the complexity of achieving climate goals and requires integrated and multidimensional approaches.

The PEN concept relies on-site renewable energy generation and compensatory measures to balance the emissions [27]. However, if the land requirements exceed urban boundaries, cities must explore virtual PEN boundaries or establish external compensation areas. This raises critical questions about urban land availability and the integration of compensation mechanisms into long-term planning [97].

Climate factors, such as solar radiation, wind, and precipitation, are equally vital in determining urban energy use and renovation strategies. Tailoring solutions to local climatic conditions ensures optimal energy performance and material durability [101]. Additionally, repurposing vacant spaces and buildings reduces energy demand while preventing unnecessary emissions from heating unused areas [95].

This study highlights the importance of district-wide renovations for individual building upgrades. By addressing all districts, urban planners can reduce redundancies, improve energy efficiency, and maximise synergies across multiple structures [102]. Moreover, replacing parks with forests in specific areas provides more effective carbon sequestration to offset emissions from renovation activities (Fig. 6).

Ultimately, transitioning from compensating to reducing emissions remains a central goal [96]. Urban planning must adopt a holistic perspective that considers the interconnectedness between buildings, mobility, open spaces, and infrastructure. District-wide renovation strategies, supported by sustainable energy systems and thoughtful land-use planning, are critical to achieving carbon-neutral neighbourhoods and addressing the broader complexities of urban sustainability.

3.6. Implications of results

Achieving net-zero carbon emissions at the urban scale is a complex challenge because of its dependence on numerous external factors, including national and regional policies. Coordinating stakeholders, regulatory frameworks and diverse urban elements further complicates this goal. Therefore, a multifaceted and adaptive approach is essential to achieve sustainable urban development.

The results of this study prove that achieving regional climate targets require the extensive energy-efficient renovation of buildings. Renovations help to reduce the land area which is needed to sink emissions and decrease the emissions created by buildings. Like earlier research, this study confirmed that emissions related to building heating have the most significant impact. Consequently, it is crucial to reduce the heating demand of buildings and ensure that the energy sources used have minimal emissions and are derived from renewable sources.

In the context of Estonia, a significant new finding is that to minimise the carbon footprint, renovations should achieve an EPC A-class rather than the previously targeted EPC—C class. This enhancement is vital for substantial reduction in carbon emissions. Policies should mandate EPC-B or higher energy rating for deep renovations to achieve meaningful emission reductions and align with climate goals.

Regulations should require mechanical ventilation with heat recovery systems in renovations to improve indoor air quality and energy efficiency. It reduces heat loss, ensures occupant comfort, and supports energy conservation in airtight buildings.

Furthermore, it is essential to create opportunities for on-site electricity generation by installing PV-panels. This approach not only reduces the dependency on external energy sources but also supports the integration of renewable energy into a building's energy system.

Policies must mandate or incentivise renewable energy systems, for example like PV-panels to offset increased electricity use. This ensures carbon reduction, aligns with climate goals, and delivers cost savings.

These findings emphasise the importance of adopting stringent energy efficiency standards and integrating renewable energy solutions to meet climate goals. The transition to high-efficiency buildings and on-site energy generation stands for a critical step towards sustainable development and climate resilience. This study suggests the need for a balanced approach that includes energy efficiency improvements and renewable energy integration to effectively develop sustainable energy solutions. Current greenhouse gas accounting includes passive carbon sequestration, such as forest carbon sinks, in net-zero targets. However, Allen et al. [103]argue that this is misleading, as passive sinks result from natural processes rather than active climate action. Relying on them allows residual emissions to continue warming the climate, potentially delaying effective mitigation efforts. Brunner et al. [104] argue that only permanent carbon removals, lasting at least 1000 years, can offset fossil emissions. Natural sinks, like forests, do not meet this criterion, making geological storage essential for credible carbon sequestration.

The transition to net-zero emissions in urban environments requires a comprehensive strategy that addresses both the reduction in energy demand and the integration of renewable energy sources. By adopting a holistic view and considering the entire lifecycle of construction materials, urban planners and policymakers can create sustainable, resilient, and energy-efficient cities.

This study focused on the analysis of only one specific city area. To understand the broader picture, it is important to conduct further research on a national scale to understand the set climate goals and the potential for their fulfilment.

4. Conclusion

This study highlights the significant challenges of achieving Positive Energy Neighbourhoods (PEN) in cold climates, where operational energy demand (module B6) from buildings is the dominant factor in urban life-cycle assessments (LCA). Even with deep renovations, the land needed for emission compensation far exceeds the city boundary, raising concerns about the feasibility of PEN in dense urban environments. However, improving building performance to achieve at least EPC-A standards will reduce land requirements, reinforcing the necessity of deep renovation strategies compared with current national regulations to achieve EPC—C.

Despite these benefits, integrating renewable energy sources, such as PV-panels increases embodied carbon emissions, needing a balanced approach that optimises both energy efficiency and building material sustainability. Current renovation policies, lack mandatory requirements for on-site renewable energy integration and external compensation measures. Since the EPC—C standard does not significantly reduce emissions, stricter policies are needed to drive deeper energy efficiency improvements.

Additionally, the weak electricity grid presents a barrier to large-scale solar energy development. Appearing technologies, including energy storage systems and smart grids, could enhance grid stability and enable more efficient use of locally generated renewable energy. While buildings stay the primary source of emissions in cold climates, whole-city LCA approaches may be necessary in warmer regions where other urban factors contribute more significantly to emissions. Further research is needed to expand LCA studies across different climates and urban typologies, where building-related emissions may not be the most dominant component. Understanding how emissions distribute in warmer climates will provide a more comprehensive perspective on effective urban decarbonisation strategies.

Furthermore, achieving city and national climate targets requires a better understanding of the impact and feasibility of policy measures. Future studies should explore the effectiveness of stricter renovation standards, financial incentives, and regulatory mechanisms in accelerating energy performance improvements beyond EPC—C levels. Comparative analyses between cities with different policy frameworks could offer valuable insights into best practices for urban carbon reduction.

Finally, given the spatial constraints and high land demand associated with the PEN concept, its feasibility across various urban contexts needs further investigation. Expanding PEN studies beyond cold climates and assessing their adaptability to different regulatory and spatial conditions will be crucial for defining its role in future urban sustainability strategies.

The time has come for a critical assessment of the feasibility of decarbonisation policies to ensure their effectiveness in achieving long-term climate goals. If a 1-hectare forest sequesters carbon in 2022 but emits it in 2023, its reliability as a carbon sink for supporting city and national climate targets is questionable. This highlights the need for critical validation to figure out whether such fluctuating carbon storage can be realistically included in climate mitigation strategies. By addressing these research gaps, a more comprehensive approach can be developed to balance emission reduction, urban energy transition, and land-use planning, ultimately supporting more effective climate-neutrality strategies at both city and national levels.

CRediT authorship contribution statement

Kadri-Ann Kertsmik: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Targo Kalamees:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition. **Jaanus Hallik:** Software, Formal analysis, Data curation, Conceptualization. **Endrik Arumägi:** Software, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Kadri-Ann Kertsmik reports financial support was provided by Tallinn University of Technology. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Appendix

Table 4
Materials used in different renovation options in this study.

Building part	LCA modules used in calculations according to the Estonian method											
	Material	A1-A3 GWP $kgCO_2eq/kg$		A4	A5	B4, life-age, years			C2	C3	C4	D GWP $kgCO_2eq/kg$
layers		$average^{highest}_{lowest}$	w/o local comp	km	%	BNB	(82)	used				
Air and vapor membrane	Water vapour membrane	$2.81^{2.87}_{0.64}$	5.95	500	10	50	x	50	Default value 50 km for materials to waste plant.	Materials divided: metal, mineral materials, wood-based materials. According to the	Materials divided: metal, mineral materials, wood-based materials. According to the	−1.15
Installation (ETICS)	Mechanical fixing	xx	5.79	3000	8	x	30	30				0
	Glue	xx	1.09	3000	10	x	30	30				0

(*continued on next page*)

Table 4 (*continued*)

Building part layers	LCA modules used in calculations according to the Estonian method: Material	A1-A3 GWP kgCO₂eq/kg: average$^{highest}_{lowest}$	A1-A3 GWP kgCO₂eq/kg: w/o local comp	A4: km	A5: %	B4, life-age, years: BNB	B4, life-age, years: (82)	B4, life-age, years: used	C2	C3	C4	D GWP kgCO₂eq/kg
Frame, insulation for roof and external wall	Glass wool, 18 kg/m^3	1.32$^{1.80}_{1.13}$	1.8	500	8	50	x	50		Estonian waste management plan.	Estonian waste management plan.	0
	Stone wool, 35 kg/m^3	1.27$^{1.58}_{1.11}$	1.5	500	8	50	x	50				0
	Cellulose, 50 kg/m^3	0.94$^{1.58}_{0.51}$	0.2	500	8	50	x	50				−0.27
	Timber frame	0.11$^{0.21}_{0.05}$	0.1	500	18	40	x	50				−0.89
	EPS (ETICS) 24 kg/m^3	3.04$^{3.71}_{2.64}$	3.09	500	4	50	30	30				−1.62
	Stone wool, (ETICS) 60 kg/m^3	1.30$^{1.58}_{1.06}$	1.58	500	8	50	30	30				0
Wind barrier	Glass wool 63 kg/m^3	1.85$^{2.20}_{1.20}$	1.0	500	10	50	X	50				0
	Wood fiberboard	x	0.7	500	10	50	x	50				−0.42
External wall finish	Facade board	1.21$^{1.79}_{0.94}$	0.97	500	5	40	40	50				0
	Facade paint	2.59$^{3.00}_{2.12}$	1.75	500	10	10	10	10				0
	Reinforcement mesh	2.20$^{3.05}_{1.00}$	2.80	3000	10	4	x	30				−1.53
	Plastering mortar	0.40$^{0.94}_{0.21}$	0.25	500	13	50	30	30				0
Roof finish	Stone tiles for roofing	x	0.4	3000	5	50	x	50				−0.01
	Steel sheets, cladding	2.40$^{3.32}_{1.85}$	2.80	3000	3	50	40	50				−1.53
Basement floor insulation	XPS	3.04$^{3.71}_{2.64}$	2.70	500	17.9	50	X	50				−1.62
	EPS	3.04$^{3.71}_{2.64}$	3.09	500	10	50	X	50				−1.62
Windows	Triple glazed, $U = 0.8$ W/(m^{2}K)	2.27$^{3.47}_{1.66}$	2.08	500	0	40	30	40				−1.68
	Triple glazed, $U = 0.6$ W/(m^{2}K)		1.66	500	0	40	30	40				
	Double glazed, $U = 1.1$ W/(m^{2}K)	1.65$^{2.14}_{0.97}$	1.15	500	0	40	30	40				−1.51
	Double glazed, $U = 1.4$ W/(m^{2}K)			500	0	40	30	40				
Services	PV-panel	38.5$^{42}_{35}$	42	3000	0	xx	20	20				0

Data availability

Data will be made available on request.

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IV

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Decarbonisation of Estonia's residential building stock☆

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ABSTRACT

This study analyses the climate implications of deep renovation and energy supply decarbonisation in Estonia. Employing life cycle assessment and building stock modelling through an archetype-based approach, it estimates the greenhouse gas mitigation potential of renovating the entire Estonian residential building stock by 2050, as outlined in the national long-term renovation strategy. The analysis incorporates alternative future scenarios to depict potential emissions trajectories contingent upon the effectiveness of policy implementation. The study utilises comprehensive data from the Estonian Building Registry—one of the earliest examples of a national digital twin—encompassing the whole residential building stock. The findings indicate that the complete implementation of decarbonisation strategies could reduce annual greenhouse gas emissions from the existing residential stock by up to 95 % compared to 2020. The embodied emissions from the renovation measures are minor compared to the energy savings gained. In the Estonian context, the overall success of building decarbonisation is closely tied to the carbon intensity of grid electricity. If the current fuel mix in electricity and district heating production persists, comprehensive renovation may paradoxically result in higher emissions than the baseline. While seemingly counterintuitive, this outcome is primarily attributable to the low carbon intensity of wood-based heating, which is prevalent in detached houses. Electrification of heating and installing mechanical ventilation systems increase the electricity demand. The construction of on-site photovoltaic electricity capacity can significantly contribute to the decarbonisation of the building stock in Estonia.

1. Introduction

1.1. European policies driving the decarbonisation of the building stock

The European Union (EU) is addressing the escalating threat of climate change through the European Green Deal [1], a comprehensive strategy aimed at achieving climate neutrality across the EU by 2050. Key milestones along this trajectory include a reduction in total greenhouse gas (GHG) emissions by at least 55 % by 2030 and, in accordance with the recent proposal to amend the EU Climate Law, a 90 % reduction by 2040, relative to 1990 levels.

At the heart of these strategies lies the decarbonisation of energy and buildings. Under the umbrella of the European Green Deal, a suite of mutually reinforcing policy instruments has been introduced, guided by

Abbreviations: CO_2eq, Carbon dioxide equivalent; EED, Directive (EU) 2023/1791 on energy efficiency; EEIO, Environmentally extended input–output method; EHR, Estonian Building Registry; EKUK, Estonian Environmental Research Centre, *Eesti Keskkonnauuringute Keskus OÜ*; ENMAK 2030, [Estonian] Energy Sector Development Plan until 2030; EPC, Energy performance certificate; EPBD, Directive (EU) 2024/1275 on the energy performance of buildings; EU, European Union; GHG, Greenhouse gas; GWP, Global warming potential; IMF, International Monetary Fund; KredEx, [Estonian] Credit and Export Guarantee Fund; LCA, Life cycle assessment; LIDAR, Light detection and ranging; LOD, Level of detail; LTRS, Long-term renovation strategy, in this article the Estonian renovation strategy 2020; nZEB, Nearly Zero Energy Buildings; NECP, National Energy and Climate Plan; OECD, Organisation for Economic Co-operation and Development; RED, Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources; SEI, Stockholm Environment Institute; WEM, With existing measures (scenario); ZEB, Zero-emission building.

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the Energy Efficiency First principle, the Renovation Wave initiative [2], and a range of financial and social mechanisms.

The obligations of the Member States are delineated in directives. The revised Energy Performance of Buildings Directive (EPBD) [3] stipulates that all new buildings must be zero-emission by 2030 instead of nearly zero-energy buildings (nZEB). It defines zero-emission buildings (ZEBs) as highly energy-efficient structures with minimal operational energy demand, entirely covered by renewable energy sources (either on-site, nearby, or through district systems). The directive further mandates national renovation plans to upgrade the worst-performing buildings toward the ZEB standard. Concurrently, the Renewable Energy Directive (RED) [4] promotes the integration of renewable technologies (such as solar photovoltaics and heat pumps) in buildings and sets minimum renewable energy shares for heating and cooling. The Energy Efficiency Directive (EED) [5] establishes a binding EU-wide energy efficiency target.

With regard to the decarbonisation of the existing building stock, the EPBD outlines a roadmap supporting the Renovation Wave. This includes measures such as national renovation targets and binding objectives for Member States to improve the average energy performance of their residential building stock by 16 % by 2030 and by 20–22 % by 2035, relative to 2020 levels. From 2030 onwards, deep renovations are expected to transform existing buildings into nearly zero-energy buildings (nZEBs), and subsequently into zero-emission buildings (ZEBs). To support this transition, the EPBD introduces a requirement for renovation passports—building-specific renovation roadmaps detailing the steps needed to achieve zero-emission performance [3]. Although integrated district- or neighbourhood-based approaches can improve the cost-effectiveness of spatially coordinated renovations [3], most EU Member States have not addressed mass renovations in their long-term renovation strategies [6].

Since 2014, EU Member States have been required to submit national long-term renovation strategies, with the most recent round of submissions completed in 2020. In accordance with Article 3 of the recast EPBD, Member States are currently preparing the next round—National Building Renovation Plans—which must be developed by the end of 2025 and finalised by the end of 2026. These plans must include a comprehensive overview of the national building stock, a roadmap with specific targets for 2030, 2040, and 2050, as well as a summary of policy measures and associated investment requirements [3].

The success of the EU's climate objectives is contingent upon effective implementation by the Member States. Flooded by the multitude of requirements imposed by various European policy instruments, alongside their own national commitments, EU Member States grapple with implementation challenges that are shaped by their distinct historical trajectories, climatic conditions, political contexts, and socio-economic dynamics.

1.2. *Estonia's decarbonisation policies*

In 2019, Estonia was the most carbon intensive and third most energy-intensive economy in the OECD [7], burdened by the high share of oil shale in the electricity production and relatively low energy efficiency of the existing building stock. Since then, Estonia has implemented a range of effective decarbonisation policies, evidenced, among other indicators, by the rapid decline in the carbon intensity of grid electricity and by national energy scenarios that anticipate the continued pursuit of decarbonisation. Estonia's energy performance requirements for new apartment buildings are recognised as the most ambitious in Europe [8]. According to Eurostat statistics from 2022, Estonia emerged as a European frontrunner in decarbonisation relative to 1990 baseline emissions, having already achieved the EU's 55 % net emission reduction target for 2030 by 2022 (Fig. 1). Furthermore, in 2023, Estonia ranked among the top ten developed economies for effective energy transition, as measured by the Energy Transition Index published by the World Economic Forum [9].

The considerable progress has not made Estonia a low-carbon economy yet. The Organisation for Economic Co-operation and Development (OECD) [11] notes that Estonia continues to face challenges in further reducing carbon emissions and mitigating the impacts of climate change, necessitating a comprehensive approach that integrates policy instruments such as carbon pricing, public investment, and incentives for private investment. The OECD concludes that electricity generation must continue to transition away from fossil fuels towards a more diversified mix of renewable energy sources.

The International Monetary Fund (IMF) [12] similarly highlights Estonia's carbon-intensive energy mix as a significant barrier to decarbonisation. Furthermore, the IMF identifies improved energy efficiency in the residential sector as a key measure for meeting energy savings targets. It estimates that a comprehensive upgrade of Estonia's housing stock to the highest energy performance standard would reduce per capita emissions by 42 % compared to 2024 levels. The IMF also projects that the resulting energy cost savings would fully offset the investment costs within a shorter timeframe than the EU average, thereby justifying

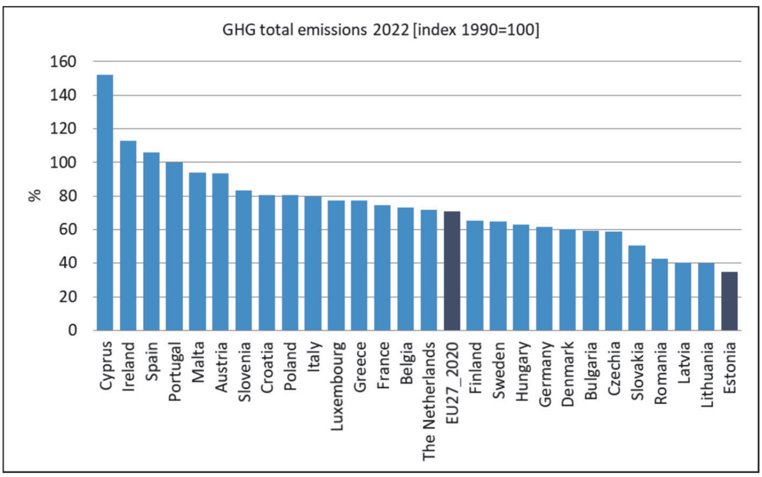

Fig. 1. The relative total GHG emissions reduction in the EU27 countries by 2022 compared to the base year 1990 [10].

prioritisation of such investments from an EU-wide perspective.

1.2.1. National Energy and Climate Plan

Estonia's National Energy and Climate Plan 2030 (NECP) [13], initially submitted to the European Commission in 2019, sets out a target to achieve climate neutrality by 2050, in alignment with EU objectives. It also establishes an interim target to reduce GHG emissions by 80 % by 2035. The most recent revision, dated June 2025, strengthens strategies for clean energy development, grid modernisation, energy efficiency, and gas security. While the NECP commits to increasing renewable electricity generation to match total national electricity consumption by 2030, it does not outline a clear exit strategy for phasing out fossil fuels in energy production.

1.2.2. Long-term Strategy for Building Renovation

The Estonian Long-term Strategy for Building Renovation (LTRS) [14] sets out the objective of fully renovating all buildings constructed before 2000 by 2050. According to the LTRS, a total of 14 million m^2 of detached houses (approximately 105,000 dwellings) and 18 million m^2 of apartment buildings (around 14,000 buildings) are to be retrofitted by 2050. The ambition for major renovation is reflected in the minimum energy performance requirement for buildings undergoing renovation, which, under current Estonian regulations, is an energy performance certificate (EPC) class C.

The LTRS incorporates subnational dynamics by projecting future changes in the building stock across five territorial categories: regional centres, second-tier centres, immediate hinterlands, transitional zones, and peripheral areas (Fig. 2). While the slightly declining population is becoming increasingly concentrated in and around two major cities (Tallinn and Tartu), the LTRS anticipates that approximately 40,000 private houses and 5,300 apartment buildings [15] will fall out of use by 2050, primarily in peripheral areas.

The LTRS has faced criticism for lacking sufficient detail on policies and measures targeting the worst-performing buildings, the split-incentive dilemma, energy poverty, and national initiatives promoting smart technologies, skills development, and education. The Buildings Performance Institute Europe [16] considers the Estonian LTRS non-compliant with the EPBD, citing the absence of concrete governmental commitments to deliver on the goal of a decarbonised building stock. In its assessment report, the Joint Research Centre of the European Commission [17] noted the absence of quantified energy savings for any of the policy measures described.

New obligations arising from the recast EPBD require Estonia to reduce primary energy use across the residential building sector by 16 % by 2030, with 55 % of this reduction to come from the worst-performing 43 % of the stock [3]. These targets are expected to be addressed in the forthcoming National Building Renovation Plan, to be developed in 2025, which will include detailed renovation pathways.

1.2.3. Decarbonisation of electricity supply

The Estonian electricity grid was only disconnected from the Russian grid in February 2025. According to Eurostat statistics, GHG energy intensity in Estonia decreased by 23 % between 1990 and 2022; however, it remains slightly above the EU27 average. While Ireland had the most carbon-intensive energy mix among EU27 countries in 2022, Finland recorded the most significant reduction in GHG energy intensity over the period 1990–2022, with a decline of 42 % [10]. As illustrated in Fig. 3, although the GHG intensity of Estonia's energy supply remains relatively high, it does not constitute an outlier within the EU.

The carbon intensity of Estonian electricity production remains burdened by the continued reliance on oil shale, which has been the primary raw material used in the energy sector. Its extraction and processing are highly energy-intensive and result in significant carbon dioxide emissions. Under its Recovery and Resilience Plan [18], Estonia has committed to phasing out oil shale in electricity production by 2035, and in all energy uses by 2040.

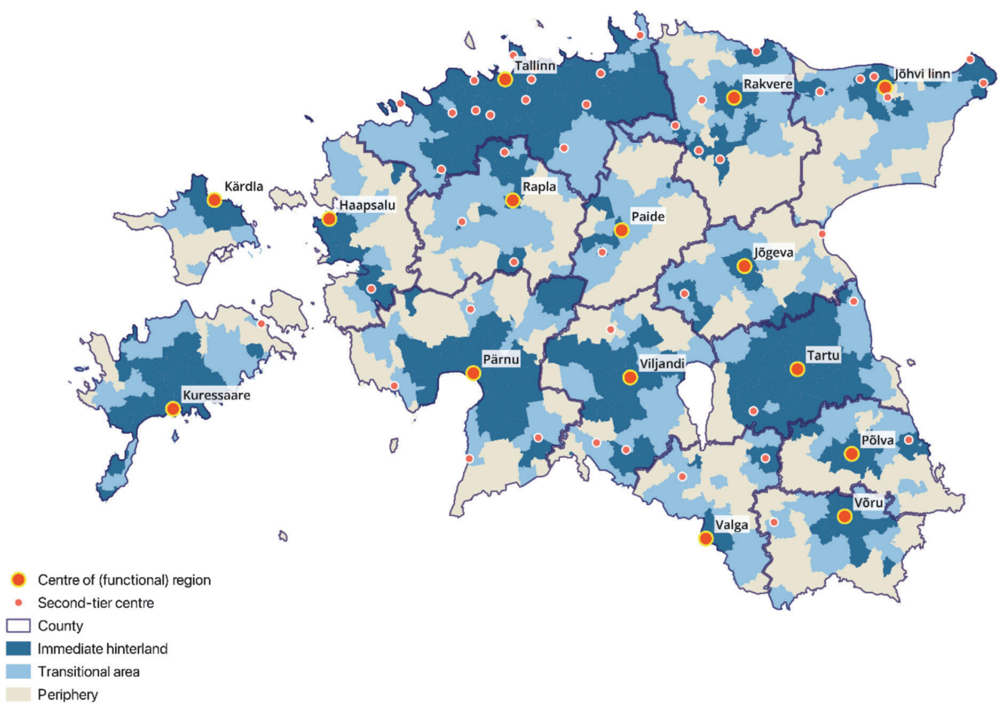

Fig. 2. The categorisation of regions in LTRS, first published in 2020 [14].

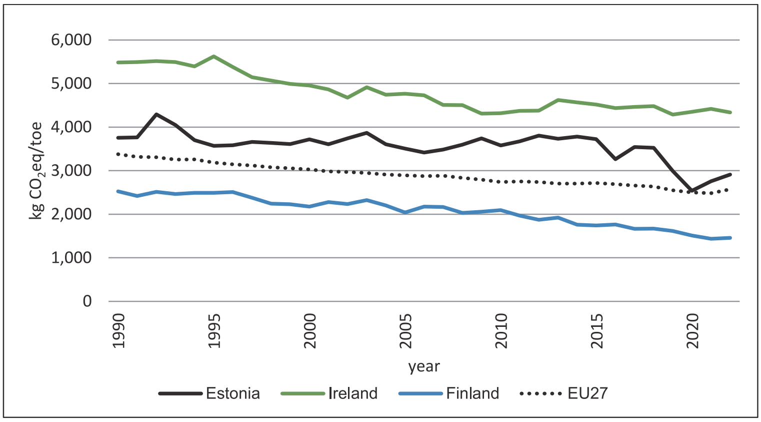

Fig. 3. The GHG intensity of energy in Estonia and the EU27 countries in 1990–2022. While Ireland had the highest GHG intensity of energy in 2022, the relative decrease between 1990 and 2022 was highest in Finland [10].

The report "Transitioning to a Climate-Neutral Electricity Generation" [19], compiled in 2022, evaluates seven pathways to a climate-neutral electricity supply. It concludes by recommending three scenarios: "All Technologies", "Renewable Gas", and "RES + Storage". The first pathway allows for the deployment of all low-carbon technologies; the second emphasises substantial investment in biogas capacity by 2030; and the third prioritises offshore wind energy combined with storage capacity.

As no major onshore wind farms have been constructed in Estonia over the past decade, the National Audit Office [20] has publicly expressed concern regarding the country's ability to meet its NECP target, which stipulates that renewable electricity generation should equal total electricity consumption by 2030. The National Audit Office observed that, in 2022, only 32 % of electricity consumed in Estonia originated from renewable sources, indicating the need to triple renewable electricity generation by 2030 to meet the 100 % target. Nonetheless, a steady increase can be observed, as in 2024, renewable electricity accounted for 39 % of total annual consumption [21]. Part of the growth comes from solar energy that has rapidly scaled to become a cornerstone of Estonia's renewable electricity mix [22]. Estonia exceeded its 2030 target for photovoltaic electricity generation as early as 2021 [23].

In 2025, Estonia initiated a national planning process and environmental impact assessment for the development of a 600 MW small modular reactor nuclear power plant. Two potential sites, both located in north-eastern Estonia, are currently under consideration. According to the existing plans, electricity generation could commence by 2035 [24].

Holmgren et al. [25] identified two dominant storylines within the Estonian energy sector, reflecting differing interpretations of the EU energy objectives of decarbonisation, energy security, and market integration. The pro–oil shale discourse coalition emphasises the role of oil shale in ensuring national energy security and supporting socio-economic development, particularly in the Ida-Virumaa region. In contrast, the anti–oil shale discourse coalition advocates for a transition away from oil shale towards renewable energy sources. Holmgren et al. regarded the pro–oil shale narrative as dominant in the Estonian energy sector as of 2019. Although investments and policy developments since then suggest a pathway towards phasing out oil shale, evolving geopolitical uncertainties may reinforce concerns related to energy security.

1.2.4. Decarbonisation of district heating and cooling

According to the Estonian Competition Authority [26], there were 170 district heating regions in 2020, of which 137 are smaller networks with annual sales below 10,000 MWh. Among Estonia's larger district heating networks, Tartu and Pärnu primarily rely on wood pellets, while Narva and the Kohtla-Järve–Jõhvi region are predominantly fuelled by oil shale and shale gas. In Tallinn, the new wastewater and seawater heat pump plant will cover up to a fifth of the annual heat consumption of Tallinn's district heating network from the winter of 2026 on, reducing the share of imported fossil fuel to less than 10 % [27]. As of recent data, only 5 % of networks operate exclusively on gas or shale oil. In 2024, heating and cooling accounted for 83 % of Estonia's residential final energy consumption, with renewable sources providing 61 % of the total energy used for heating and cooling across all sectors [28].

The Energy Sector Development Plan until 2030 (ENMAK 2030) [29] targets 80 % renewable heat production, with an emphasis on sustainable district heating systems and the use of locally available energy sources. Complementing this, the 2022 summary report "Transitioning to a carbon neutral heating and cooling in Estonia by 2050" [30], with Stockholm Environment Institute (SEI) Tallinn Centre as a lead consultant, presents four scenarios for decarbonising heating and cooling, recommending a hybrid strategy combining energy-efficient electrification with the expansion of district heating and the use of regional waste heat. The report highlights lagging renovation rates and growing cooling demand, underscoring the need for building renovation to reduce system-wide energy demand. For detached houses outside district heating networks, heat pumps supplemented by bioenergy are identified as the most appropriate low-carbon solution.

The future projections for grid electricity and district heating provided by EKUK [31] indicate a steep decline in carbon intensities toward 2050 (Fig. 4). Although labelled as a WEM (With Existing Measures) scenario, the trajectory more closely reflects a vision of desired future developments rather than a quantified outcome of current policy measures. Given the significant variability in carbon intensities among local district heating systems, the scenario represents a national average.

1.3. The residential building stock in Estonia

There are 264,000 dwellings in Estonia, with a total net area of 66,691,103 m^2 [33]. Apartment buildings account for 51 % (34,282,103 m^2) of the total net residential area. The second largest dwelling type is detached houses, comprising 41 % (26,447,103 m^2) of the total. Brick and prefabricated concrete large-panel construction are the predominant structural types for apartment buildings, while wood and brick are the most common for detached houses, Fig. 5. The median occupancy rate for all the apartment buildings, regardless of type and location, is 86 % [34].

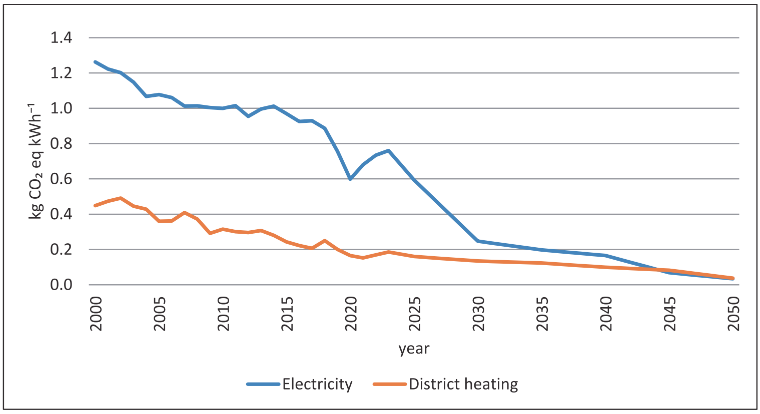

Fig. 4. Future projections for the carbon intensities of grid electricity and district heating. The trajectories are scenario-based from 2024 onward [32].

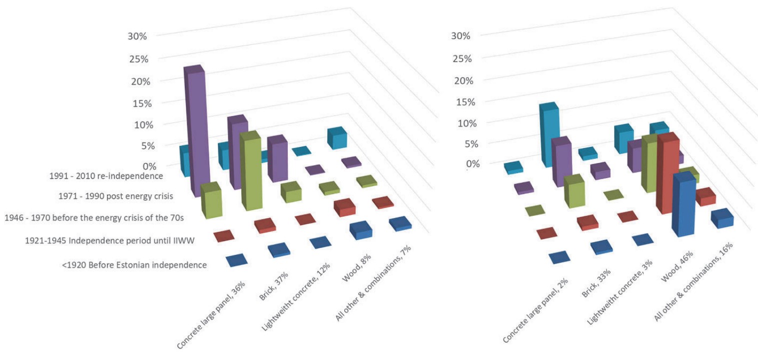

Fig. 5. Distribution of apartment buildings (left), and detached houses (right) by the net area and the construction types in Estonia.

Typically, non-renovated dwellings constructed before the 1990s are equipped with natural passive stack ventilation, while buildings constructed between 1991 and 2010 generally have mechanical exhaust ventilation systems. Kitchens are typically fitted with extractor hoods. In most dwellings, windows can be opened for additional ventilation. Technical inspections of Estonian dwellings have revealed that natural ventilation systems are often in poor condition [35]. The main issues include inadequate installation quality of ventilation ducts and exhaust devices, as well as a lack of compensatory airflow due to uncontrolled air leakage in the building envelope.

Apartment buildings are primarily heated via district heating networks and one-pipe hydronic radiator systems. Detached houses generally rely on building-specific heat sources, such as wood-burning stoves or central heating systems with boilers. Radiators are typically not fitted with thermostatic valves, making individual room temperature control impossible. Instead, room temperatures are regulated centrally via heat substations, which respond to outdoor temperature variations. Energy use in the existing residential building stock remains high [36,37], largely due to significant heat losses [32] and critical thermal bridging [38] and critical thermal bridges [39,40] in the building envelope. Indoor climate conditions also require improvement [41].

According to Census 2021 [42], approximately 72 % of Estonians reside in owner-occupied housing. A significant share of multi-family residential stock—approximately 70 % of apartment buildings—is managed by apartment associations [43]. Current policies aimed at improving energy efficiency have primarily relied on subsidies. Since 2009, apartment associations may apply to the Credit and Export Guarantee Fund (KredEx) for expert advice, grant funding, and loan guarantees [44], but renovation subsidies are not equally distributed among the regions of Estonia [45].

1.4. Previous studies on the building stock decarbonisation

1.4.1. LCA in the building stock modelling and renovation analyses

While European directives continue to define ZEBs and renovation targets primarily in terms of operational energy use, the scientific literature has increasingly broadened this perspective through the application of whole life-cycle carbon footprint assessments. This shift in metrics is reflected in recent literature reviews estimating the GHG mitigation potential of the Renovation Wave.

Röck et al. [46] assessed 104 scientific papers and shortlisted 22 environmental building stock modelling approaches, highlighting the importance of adopting a long-term perspective across the entire building stock and of aligning research with EU policy objectives. Dong et al. [47] reviewed eight LCA studies employing archetype-based building stock models, concluding that using archetype-based models in LCA supports a more holistic evaluation of policy measures and helps avoid overestimating their actual environmental contributions. However, the study acknowledges persistent challenges related to data availability and methodological standardisation. Vilches et al. [48] analysed 13 LCA-based refurbishment studies and found that most were limited to Modules A1–A3 and B6, while other modules remained underrepresented. Fahlstedt et al. [49] analysed 54 scientific articles published between 2005 and 2022, observing that the majority of studies focused on single buildings and primarily assessed Module B6, with limited attention to other use-stage modules and Module D. Only a few studies accounted for future dynamics, such as the decarbonisation of grid electricity. Echoing the concerns of Vilches et al., Fahlstedt et al. called for the adoption of national LCA standards that include more precise methodological descriptions for modelling building renovations. Amini Toosi et al. [50] examined the use of LCA, life cycle costing, and social life cycle assessment in building energy retrofitting, concluding that insufficient attention is given to factors such as future electricity mixes.

1.4.2. Previous studies on the decarbonisation of building stocks

The effectiveness of building decarbonisation policies varies significantly across regions [51].

Arbulu et al. [52] evaluated decarbonisation strategies for residential buildings in the Basque Country (northern Spain), finding that active interventions were the most cost-effective—achieving over a 60 % reduction in global warming potential (GWP) across all building types while yielding a substantial internal rate of return. To meet EU decarbonisation targets, a minimum level of deep renovation, primarily through active strategies, is deemed necessary.

In the context of decarbonising German residential buildings, Czock et al. [53] find that the replacement of fossil fuel systems with electric heat pumps is essential. According to Dworatzek et al. [54], this transition must be supported by renewable energy requirements, subsidies, pricing strategies, moderate increases in gas and electricity prices and local renewable energy production with storage solutions—depending on the depth of retrofit measures.

Müller et al. [55] analysed decarbonisation pathways for the Austrian housing sector and concluded that mandatory long-term targets for building renovation are crucial. Without such obligations, achieving comparable levels of decarbonisation would require a much greater reliance on limited renewable energy sources such as biomass, electricity, and biogas, significantly increasing costs. Given rising global demand, there is a growing necessity to add value to bioresources, thereby limiting their availability for the energy sector [56].

Wang et al. [57] compared electrification and deep retrofit strategies for decarbonising the United Kingdom's residential building stock. Their findings suggest that replacing fossil fuel-based systems with high-efficiency electric systems, upgrading inefficient electric systems, integrating and managing stand-alone renewable energy sources, and implementing a range of thermal insulation measures could reduce lifetime carbon emissions by up to 99 %.

Karlsson et al. [58] assessed the potential for reducing greenhouse gas emissions from multi-family housing in Sweden. They indicated that GHG emissions could be reduced by up to 40 % using currently available technologies and practices, with even greater potential reductions of 80 % by 2030 and 93 % by 2045.

1.5. Knowledge gap and research questions

In addition to the LTRS, no prior studies have systematically addressed the decarbonisation of Estonia's residential building stock. This study addresses this knowledge gap, providing novel perspectives on the decarbonisation of Estonia's residential building stock in accordance with the LTRS, using LCA and detailed archetype renovation data to improve accuracy and enable an integrated evaluation of policy impacts through 2050. No earlier studies have compared operational energy savings with the embodied emissions of projected renovation activities. In the broader European context, this analysis offers insight into the implementation of the Renovation Wave in a Member State facing the dual challenge of delivering effective decarbonisation policies while contending with a carbon-intensive energy mix and a poorly performing residential building stock.

The study focuses on the following research question:

- RQ1: What is the combined climate impact of the decarbonisation of the energy supply and the deep renovation of Estonia's entire residential building stock by 2050?

  The primary research question is further elaborated through two sub-questions:
  - o RQ2: What are the impacts of (a) the energy performance level after a deep renovation, (b) the annual renovation rate, and (c) the carbon intensity of grid electricity on the decarbonisation of Estonia's residential building stock?
  - o RQ3: What is the role of material-related (embodied) GHG emissions in the decarbonisation of Estonia's residential building stock?

2. Theory and calculation

2.1. Residential building stock constructed before 2000

The data on the Estonian residential building stock constructed before 2000 originates from the Estonian Building Registry (EHR) [59], one of the world's first 3D national digital twins. The EHR compiles data from various sources, providing open-access information on building functions, construction materials, and other attributes for the entire Estonian building stock, georeferenced to LOD2 building models. While the EHR incorporates data from multiple inputs, including the Estonian Land Board's digital twin [60], which is based on regular LIDAR surveys and ensures comprehensive coverage of existing buildings, notable data gaps remain—particularly concerning the heating systems of older buildings. Pre-processing of the data involved grouping diverse building types into two main categories: detached houses and apartment buildings, in line with the LTRS, which provides future projections up to 2050. Although these broad categories are used for long-term forecasts, the aggregation of building stock data employs a more detailed classification based on building type, location, and decade of construction, enabling more nuanced assumptions in the scenario analyses.

Demolition and renovation rates of the residential building stock from 2023 onwards were modelled according to the LTRS (Table 1), which outlines a pathway towards a fully renovated building stock by 2050. The LTRS estimates that 4.8 million m^2 of detached houses and 5.0 million m^2 of apartment buildings will be decommissioned by 2050, predominantly in peripheral and transitional zones. In this study, the demolition of abandoned residential buildings is assumed to follow a non-linear trajectory [61]. Fig. 6 illustrates the resulting development of the residential building stock constructed before 2000.

2.2. The assumptions on energy performance

The assumption regarding delivered energy prior to renovation was based on the measured energy consumption of the residential building stock in 2020 [62]. Assumptions concerning average delivered energy after renovation were derived from case study results targeting either EPC B (nZEB without PV) or EPC C (major renovation) energy rating (Fig. 7).

The combustion of fossil fuels and wood for heating is expected to be phased out during renovations, replaced primarily by efficient district heating systems in urban areas and by heat pumps in rural areas. These assumptions are informed, on one hand, by the extent of district heating network coverage and, on the other hand, by the findings of the SEI study [30], which presents alternative scenarios for decarbonising heating energy supply and ultimately recommends a combination of strategies that enhance effective district heating alongside heat-pump-based solutions.

2.3. Emission factors for energy carriers

The emission factors for the energy carriers are presented in Table 2. In this study, the decarbonisation strategies for electricity and district

Table 1
The expected renovation and demolition rates in the Estonian residential building stock constructed before the year 2000, according to LTRS [14].

	Building stock in 2000		Renovated by 2020		Disuse by 2050		In need of renovation	
	Quantity	Area, m^2	Quantity	Area, m^2	Quantity	Area, m^2	Quantity	Area, m^2
Detached houses	155,000	19,998,000	10,000	1,500,000	40,000	4,800,000	105,000	14,000,000
Apartment buildings	22,600	28,378,000	3000	5,000,000	5300	5,000,000	14,000	18,000,000

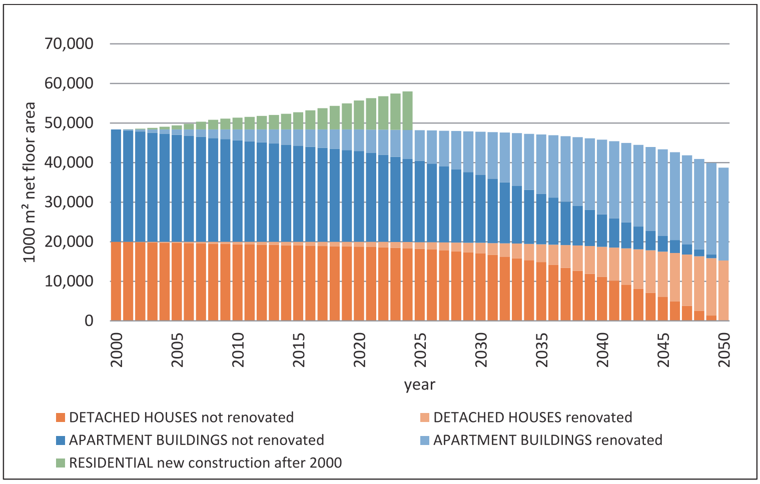

Fig. 6. Future projection of the residential building stock according to LTRS (2020), thousand m^2 of net floor area.

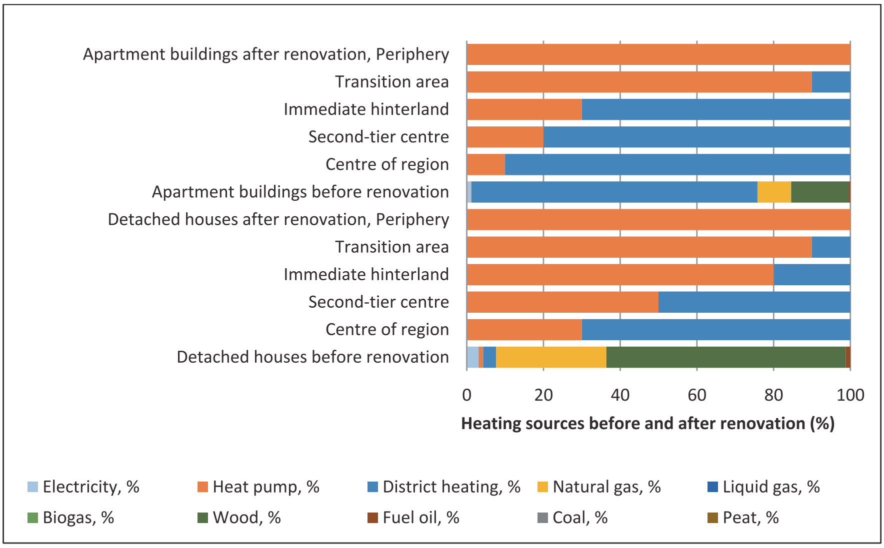

Fig. 7. Shares of heating sources in detached houses and apartment buildings constructed before 2000 [62]. Heat pumps and efficient district heating are assumed to replace fuel combustion in buildings, in line with the national studies for the decarbonisation of heating energy.

heating are represented by the EKUK scenario, which projects a 99.7 % reduction in the carbon intensity of electricity and a 90.4 % reduction in district heating by 2050, relative to the levels in 2000.

The upstream emission factors with future projections were calculated for this study using the environmentally extended input–output (EEIO) method and Exiobase version 3.9.5 [63]. This was done by setting the components of the emission factors directly related to electricity production to zero (representing the first tier of emissions), while leaving all other components unchanged. Production shares were determined using energy balances from Eurostat (NRG_BAL_PEH). The same procedure was applied for district heating. Emission factors for all other energy carriers were determined directly from Exiobase, as this is a

Table 2
Emission factors for energy carriers.

Energy carrier	Direct emissions 2025 kg CO_2 eq kWh^{-1}	Upstream emissions 2025 kg CO_2 eq kWh^{-1}	Sources
Electricity	0.550	0.011	Ministry of Environment, EKUK, Exiobase, Estonian statistical office
District heating	0.132	0.023	Ministry of Environment, EKUK, Exiobase, Estonian statistical office
Natural gas	0.199	0.001	Ministry of Environment, Exiobase, Estonian statistical office
Liquid gas	0.266	0.005	Ministry of Environment, Exiobase, Estonian statistical office
Biogas	0.000	0.007	Ministry of Environment, Exiobase, Estonian statistical office
Wood pellet	0.000	0.002	Ministry of Environment, Exiobase, Estonian statistical office
Wood, miscellaneous	0.000	0.001	Ministry of Environment, Exiobase, Estonian statistical office
Fuel oil	0.266	0.070	Ministry of Environment, Climatique
Coal	0.341	0.027	Ministry of Environment, Exiobase, Estonian statistical office
Peat	0.352	0.036	Ministry of Environment, Exiobase, Estonian statistical office

cradle-to-gate model. Values were converted from monetary units to energy units using price statistics from the Estonian Statistical Agency [64]. Calculations were performed for all years between 2000 and 2022, with the 2022 value taken to represent all earlier years back to 1990 (due to the limited availability of Estonian price statistics prior to 1990).

For future projections until 2050, the average annual percentage change over the preceding ten years was successively applied, based on the average emission factors for 2021 and 2022 (as the 2022 values were anomalously high). This approach implies that no assumptions were made regarding future changes in the electricity production mix, which could introduce some inaccuracy given Estonia's stated ambition to achieve renewable electricity production equivalent to 100 % of consumption by 2050. However, as the upstream component accounts for only 3–18 % of the total emission factor for grid electricity up to 2022, the resulting inaccuracy is considered minimal. The future energy consumption projections (Fig. 7) are based on national decarbonisation scenarios for electricity and district heating [32].

2.4. Building categorisation and the application of LCA

This study employs a sample archetype approach, i.e., representative renovation case studies for which the global warming potential GWP_{fossil} is assessed through LCA. Detached houses were categorised into two principal construction periods: pre–1940 and 1941–2000. The pre-1940 buildings often possess heritage value, necessitating careful consideration of technical interventions to preserve their architectural integrity. Apartment buildings were classified based on construction typologies from the periods pre-1940, 1941–1960, 1961–1980, and 1981–2000, each exhibiting distinct structural and energy performance characteristics. Renovations of these buildings are expected to address both energy efficiency and indoor environmental quality, particularly through improvements in heating and ventilation systems. Buildings constructed between 1941 and 1960 typically consist of small brick structures, generally two to four storeys in height. Between 1961 and 1980, larger Soviet-era prefabricated concrete panel buildings became common, usually ranging from four to nine storeys. Structures built between 1981 and 2000 represent later Soviet design principles, predominantly comprising large-panel concrete buildings with five or more storeys. The six archetypes represent 65 % of detached houses and 75 % of apartment buildings of Estonia's housing stock constructed before 2000.

The climate impact of typical renovation measures achieving EPC class C were calculated as a whole-life carbon footprint over a 50-year reference study period, applying the Estonian carbon footprint assessment method [65], Fig. 8. LCA covered cradle-to-grave GWP_{fossil} emissions for the retrofitted components, excluding operational energy use (module B6), which was assessed for the building as a whole. The

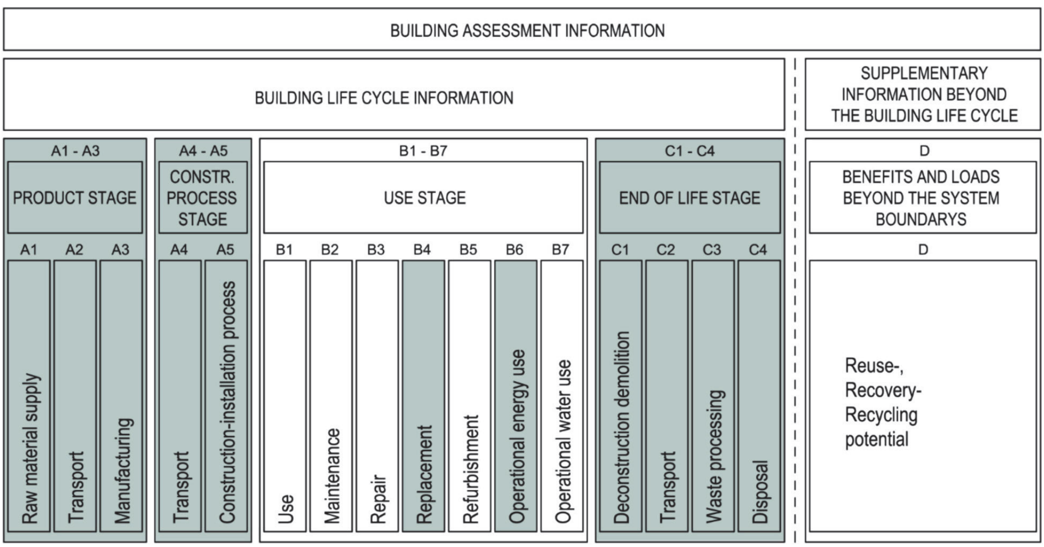

Fig. 8. The LCA modules included in the Estonian carbon footprint assessment method for construction works.

functional unit of the study is one square metre of net floor area of a refurbished building. While the GHG emissions from module A were allocated to the year of renovation, the module B4 impact was divided evenly over a 50-year life span. For residential buildings expected to fall out of use between 2020 and 2050, the assumed end-of-life emissions were 1.78 kg CO_2eq/net-m^2 for detached houses and 2.19 kg CO_2eq/net-m^2 for apartment buildings.

Embodied emissions were calculated using generic Estonian emissions factors, representing typical materials used in the Estonian construction sector. The embodied emissions attributed to the renovation cases for detached houses and apartment buildings are presented in Table 3. Carbon footprint results from the renovation cases have been partially published in recent studies [66–69], and the assessment of relevant renovation measures informed the selection of a conservative estimate to represent embodied emissions.

Assumptions regarding delivered energy before and after renovation are presented in Table 4. In Estonian practice, tenant electricity is included in the total delivered electricity. Consequently, the renovation cases satisfy the definition of deep renovation under the EU Renovation Wave Strategy [2], which stipulates a minimum 60 % improvement in primary energy performance [70].

The Estonian carbon footprint methodology does not provide specific guidance on assessing the GWP of renovation. Balouktsi and Lützkendorf [71] identify three alternative methodological approaches, of which this study adopts “Approach Zero”—the most commonly applied—which excludes the embodied emissions of existing building materials after renovation. Retrofit measures are treated as policy-driven additional investments in embodied emissions that extend the service life of buildings and reduce operational climate impacts, without assuming an indefinite lifespan for the materials added during energy-efficiency upgrades.

The Estonian Construction Roadmap 2040 [72] signals a strategic direction toward reducing embodied carbon by highlighting low-carbon materials and circular economy principles, albeit without setting explicit targets or outlining a future trajectory for embodied emissions. Therefore, this study’s future projection for embodied emissions in renovations draws on baseline values and future projections from scientific literature. Prior studies estimate that industrial decarbonisation—such as cleaner energy inputs and low-carbon cement, steel, and glass—could reduce embodied emissions by 36–42 % by 2040 [73,74], with further potential through circular economy integration, sufficiency strategies, and modern construction methods, yielding up to 84 % reductions by 2050 [75,76]. In the absence of national estimates, this study applies a conservative annual reduction of 1 % in embodied emissions from 2025 onward, reflecting anticipated gains from energy decarbonisation, process improvements, and market demand for low-carbon materials. This yields a cumulative 25 % reduction in embodied emissions by 2050.

Table 3
Renovation cases and the respective production and construction stage (A-module) emissions.

Total embodied emissions for renovation cases	Renovation to EPC C, kg CO_2eq/net-m^2	Renovation to EPC B, kg CO_2eq/net-m^2
Detached houses		
pre-1940	91.4	97.3
1941–2000	86.1	102.2
Apartment buildings		
pre-1940	33.9	42.4
1941–1970	166.8	208.5
1971–1980	94.9	118.6
1981–2000	141.4	176.7

Table 4
Assumptions on average energy consumption before and after the renovation. Delivered heating energy includes both heating of spaces and domestic hot water.

Delivered energy		Not renovated	EPC C	EPC B
		kWh/net-m^2a	kWh/net-m^2a	kWh/net-m^2a
Detached houses	Heating	193	60	50
	Electricity	34	40	35
Apartment buildings	Heating	153	50	37
	electricity	34	40	35

2.5. Scenarios

Alternative scenarios (Table 5) were developed using the residential building stock model based on the LTRS and the LCA results from the renovation case studies to address the research questions. These scenarios were designed to analyse the influence of renovation rate, post-renovation energy performance, the carbon intensity of delivered energy, and heating sources.

The **Baseline (BAS) scenario** assumes that policy measures fail to accelerate the deep renovation of the existing residential building stock, and annual renovation rates remain at the levels observed between 2000 and 2020. Furthermore, the carbon intensities of grid electricity and average district heating are assumed to remain constant at their 2023 levels until 2050.

The **C scenario** builds on the LTRS projections and incorporates LCA results from representative renovation case studies. In this scenario, all detached houses and apartment buildings constructed before 2000 are retrofitted to achieve an EPC class C energy rating by 2050. The decarbonisation of grid electricity and district heating is assumed to follow the EKUK trajectories, representing the successful implementation of energy decarbonisation policies, projecting a 99.7 % reduction in the carbon intensity of electricity and a 90.4 % reduction in district heating by 2050, relative to the levels in 2000.

The **B scenario** builds on the same assumptions as the C scenario but assumes a more ambitious outcome from renovation policies: by 2050, all renovated buildings are expected to achieve an EPC class B energy rating (equivalent to nZEB without on-site electricity generation).

The **C_CI2023** scenario assumes that the entire residential building stock constructed before 2000 is renovated to an EPC class C energy rating by 2050, in line with the LTRS projections. However, it presumes that the decarbonisation of the energy supply does not progress as planned; in this scenario, the carbon intensities of grid electricity and district heating remain at their 2023 levels through to 2050.

The **B_CI2023 scenario** mirrors the assumptions of the C_CI2023 scenario but assumes that all buildings are renovated to an EPC class B

Table 5
A summary of the assumptions of the seven scenarios.

Scenario	Renovation rate	EPC	Projection for delivered energy	Projection for embodied
BAS	as in 2000–20	C	Constant, as in 2023	−1 % per year from 2025
C	100 % as in LTRS	C	EKUK scenario	−1 % per year from 2025
B	100 % as in LTRS	B	EKUK scenario	−1 % per year from 2025
C_CI2023	100 % as in LTRS	C	Constant, as in 2023	−1 % per year from 2025
B_CI2023	100 % as in LTRS	B	Constant, as in 2023	−1 % per year from 2025
C_43-43	43 % of LTRS	C	EKUK scenario	−1 % per year from 2025
C_HS2023	100 % as in LTRS	C	EKUK, heating sources as 2023	−1 % per year from 2025

energy rating by 2050. As in the previous scenario, it presumes no progress in the decarbonisation of electricity and heating, with carbon intensities remaining constant at 2023 levels.

The **C_43-43 scenario** assumes that deep renovations are undertaken in 43 % of detached houses and apartment buildings constructed before 2000, upgrading their energy performance to an EPC class C rating by 2050. This scenario adopts the EKUK assumptions for the decarbonisation of energy supply. The renovation rate reflects the requirement in the revised EPBD to target the worst-performing 43 % of the building stock. Due to prior renovations, the share of renovated buildings exceeds 43 % in 2050.

Finally, the **C_HS2023 scenario** models the full renovation of the pre-2000 residential building stock to an EPC class C energy performance, while maintaining the current distribution of heating sources. The carbon intensities of electricity and district heating are assumed to follow the EKUK decarbonisation trajectory.

3. Results

Fig. 9 illustrates the projected GHG emissions trajectory under Scenario C, which represents the successful implementation of the LTRS. The overall emissions trend closely follows the projected carbon intensity of grid electricity. Notably, the majority of emissions are attributed to apartment buildings located in regional centres, where district heating constitutes the primary source of heating. As shown in Fig. 10, the relative contributions of embodied and operational emissions shift significantly over time, with embodied emissions becoming more prominent by 2050 as the energy supply is progressively decarbonised.

The results for the various scenarios are presented in Table 6 and Fig. 11, while Fig. 12 illustrates the cumulative operational and embodied emissions through to 2050. The outcomes are strongly polarised, delineating two distinct trajectories that are primarily driven by the success or failure of energy supply decarbonisation.

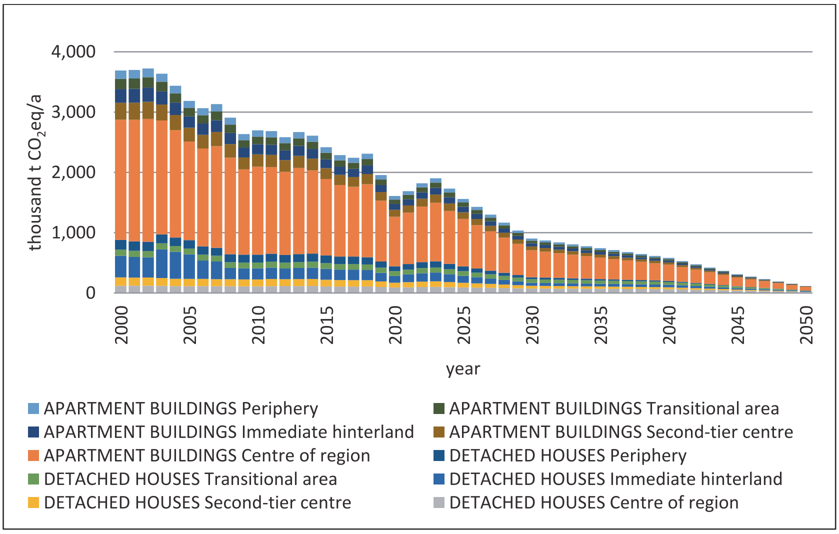

Fig. 9. Scenario C. In the residential building stock constructed before 2000, most of the operational GHG emissions originate from the apartment buildings in the regional centres.

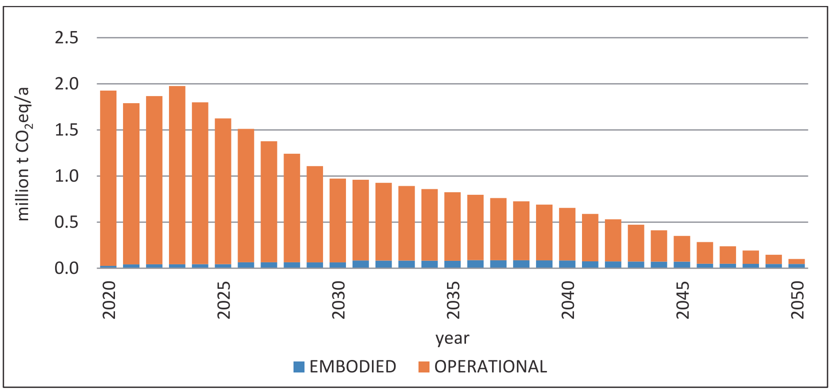

Fig. 10. The annual embodied and operational GHG emissions from the residential building stock according to the C scenario.

Table 6
Annual operational and embodied GHG emissions and the reduction of annual emissions from the year 2020 for the alternative scenarios.

Scenario	Operational + embodied (t CO_2eq)				Change (%) from 2020		
	2020	2025	2035	2050	2025	2035	2050
BAS	1,926,658	1,957,475	1,904,862	1,596,193	2	−1	−17
C	1,926,658	1,624,655	824,647	100,681	−16	−57	−95
B	1,926,658	1,585,176	795,264	94,288	−18	−59	−95
C_CI2023	1,926,658	1,966,220	1,933,873	1,637,184	2	0	−15
B_CI2023	1,926,658	1,914,765	1,825,424	1,403,710	−1	−5	−27
C_43-43	1,926,658	1,624,655	830,619	243,336	−16	−57	−87

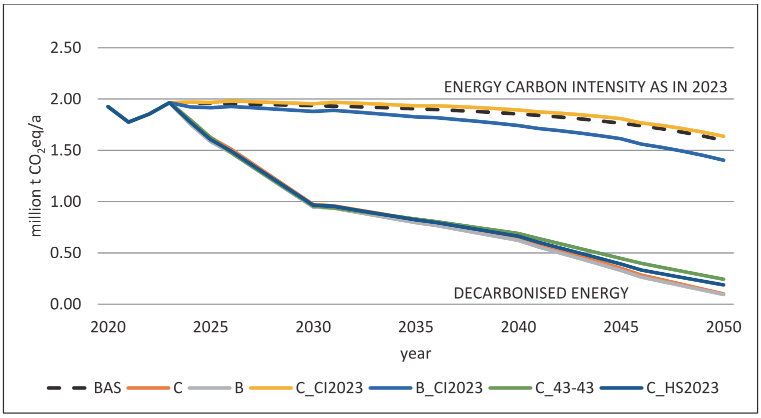

Fig. 11. Annual embodied and operational emissions from the residential building stock constructed before the year 2000: baseline (BAS) and alternative scenarios.

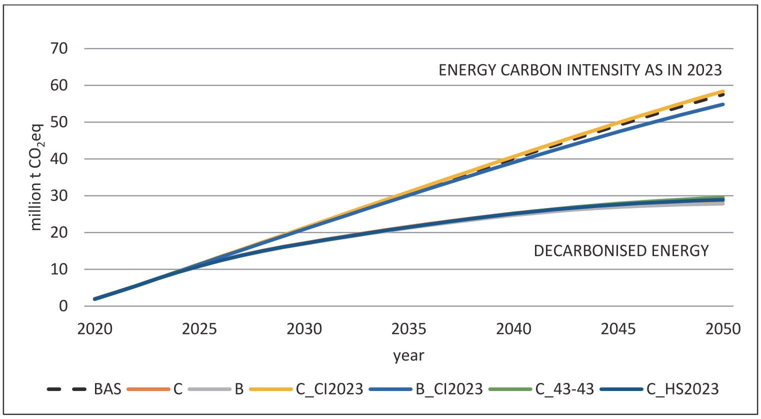

Fig. 12. Cumulative emissions for the residential building stock constructed before 2000 according to the alternative scenarios.

3.1. Life-cycle climate impact of renovating the entire residential building stock of Estonia by 2050

The scenario aligned with the LTRS (EPC C), encompassing both operational and embodied emissions, indicates that an 95 % reduction in combined operational and embodied greenhouse gas emissions from the residential building stock constructed before 2000 could be achieved by 2050, provided that the entire stock is renovated to energy class C and the carbon intensities of grid electricity and district heating follow the trajectories outlined in current energy scenarios. This emissions trajectory reflects the carbon intensity of grid electricity.

If the carbon intensity of electricity and district heating remains at current levels, deep renovation of the entire residential building stock to an EPC class C energy rating (C_CI2023) results in higher total GHG emissions than the baseline scenario (BAS), which assumes no increase in renovation activity and no progress in the decarbonisation of heating or electricity supply. Although the C_CI2023 scenario reduces delivered energy by more than half, it also shifts the heating demand towards electricity. In the absence of decarbonisation, this electrification leads to high emission factors that outweigh the energy savings, explaining the seemingly counterintuitive outcome.

3.2. Impacts of energy performance level, annual renovation rate and the carbon intensity of grid electricity

The overall impact of renovating to EPC class B or C does not differ significantly, because of the generally low emission rate from heating, and as the higher embodied emissions for EPC B partly offset the additional operational savings. However, embodied emissions represent a one-off impact, while operational emissions for B-rated buildings remain low beyond 2050.

If electricity and district heating decarbonisation progress to achieve a 99.7 % reduction in the carbon intensity of electricity and a 90.4 % reduction in district heating by 2050, relative to the levels in 2000, renovating only the worst-performing residential buildings (43 % to EPC C) could reduce total emissions by 87 %. This is likely an underestimate, as the study assumes uniform pre-renovation energy performance, which probably undervalues baseline emissions in the worst-performing segment.

The polarisation of the results indicates that decarbonising the energy supply is the principal lever for reducing emissions from the Estonian building stock. Without decarbonising the energy supply, an ambitious renovation strategy will fail to deliver the desired reductions in total GHG emissions. Conversely, renovation acts as an enabler of energy supply decarbonisation by reducing total demand and facilitating the integration of low-carbon energy sources.

3.3. Share of embodied GHG emissions in the renovation of the residential building stock in Estonia

The embodied emissions associated with the renovation measures applied in this study are relatively minor compared to the savings achieved in energy consumption and operational energy use. However, their relative significance increases considerably towards 2050. The issue of low-carbon renovation measures is particularly pertinent for the refurbishment of multi-storey apartment buildings in regional centres, where scaling up the use of low-carbon materials and construction processes could lead to substantial emission reductions, given the high proportion of such renovation cases.

It should also be noted that, according to the C and B scenarios, the entire residential building stock constructed before 2000 will have undergone deep renovation by 2050, after which the share of embodied GHG emissions declines sharply, comprising only the impacts from annual maintenance and replacements.

As expected, the sensitivity analysis indicates that scenarios with carbon–intensive energy are highly responsive to input adjustments, whereas the energy decarbonisation scenario renders the results largely insensitive to such changes.

4. Discussion

4.1. Interpretation of results

The findings of this study align with those of Gillet et al. [77], who highlight the need to combine large-scale building renovation with the integration of renewable energy technologies and the consideration of embodied GHG emissions in construction materials and components.

While the LTRS estimated a 90 % reduction in operational GHG emissions, a more detailed LCA-based analysis, including also embodied impacts, indicates a 95 % reduction by 2050 relative to 2020 levels. Importantly, this study shows that incorporating embodied emissions does not significantly degrade the overall decarbonisation potential of Estonia's residential building stock. The "carbon spike" detected, inter alia, by Galimshina et al. [78] appears almost non-existent in the results. However, as Estonia's energy supply becomes increasingly decarbonised, the relative importance of embodied emissions will grow. By 2048, the carbon intensity of the electricity grid is projected to approach that of Sweden's current level, prompting a critical question: how should renovation strategies be designed to prepare for a future where embodied emissions may surpass operational emissions in their climate impact? While today's high grid carbon intensity currently overshadows embodied emissions, the environmental burden of materials used in renovation remains substantial and warrants careful life cycle consideration in policymaking.

Estonia's current residential stock provides enough floor area to accommodate its shrinking population. Nevertheless, a significant share of buildings—particularly in peripheral regions—face challenges related to performance and are affected by ongoing urbanisation trends that shift population and services toward urban centres. Anticipated obsolescence and eventual abandonment may therefore create a substantial pool of reusable construction materials, which, if recovered effectively, could serve as a resource for future renovations and mitigate the embodied carbon burden.

Energy security and national resilience remain strong drivers of energy policy in Estonia, particularly due to the country's reliance on domestic fuels such as wood and oil shale. The interlinkage of energy and building decarbonisation policies is demonstrated by the results of this study. Foresight Centre [79] estimates that if Estonia's GHG

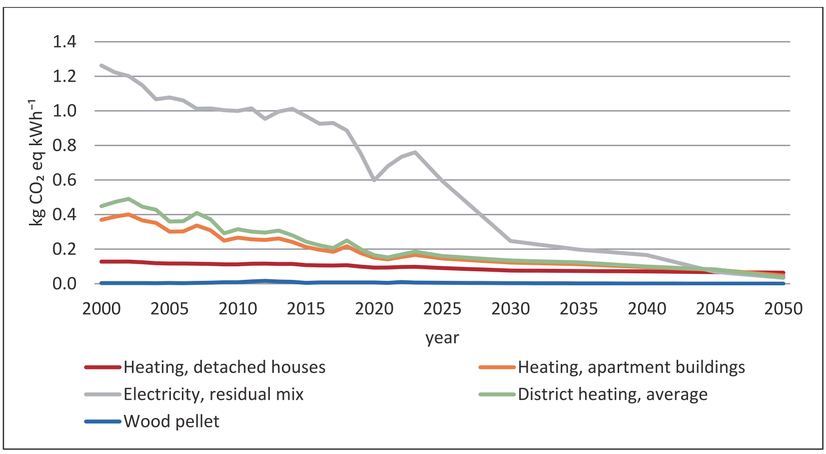

Fig. 13. The documented and predicted carbon intensities for grid electricity, average district heating, wood heating, and the average heating energy mixes according to the assumptions of this study.

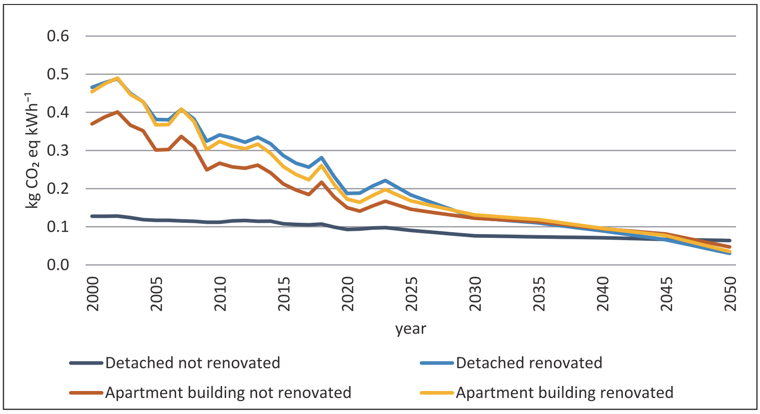

Fig. 14. Heating sources have a major impact on the average carbon intensities. A shift from the current fuel mix to district heating and heat pumps will lead to lower carbon intensities in heating only after 2045. As the comparison is based on one unit of delivered energy, the savings gained by heat pumps do not show in this graph.

emissions from electricity production were at the average level for the EU, its total emissions would be similar to the EU average and would already be below the target set for 2035.

This complexity is also reflected in heating systems. Detached houses are predominantly heated with wood-burning systems, and the associated carbon intensity scenario reflects the emissions profile of wood combustion. In contrast, most apartment buildings are connected to district heating networks. Thus, the projected carbon intensity of heating in these dwellings follows the average district heating trajectory (Fig. 13). These contrasting pathways highlight the importance of tailoring renovation and energy strategies to building typologies and regional energy infrastructures.

The emission factor for wood heating is extremely low, and, therefore, electrification of heating partially offsets the GHG reductions achieved through lower delivered energy (Fig. 14). The challenges associated with wood-based heating include a short carbon cycle and the generation of particulate emissions, which are not accounted for in LCA-based analyses that focus solely on GWP_{fossil}. Nevertheless, wood is classified as a renewable energy source and is therefore supported under the ZEB target and the EU Taxonomy [80].

As Gillet et al. [77] argue, substantial challenges remain in scaling up renovation efforts, securing financing for deep renovations, and decarbonising historic buildings without compromising their architectural and cultural value. For example, cost-effective retrofit solutions typically exclude masonry walls, implying that comprehensive retrofitting of the building stock could result in the loss of characteristic brick façades from the urban landscape. The findings of this study suggest that deep renovation of all heritage buildings may not be necessary from a climate impact perspective, provided that energy supply decarbonisation proceeds as planned. On the other hand, Kertsmik et al. [81] showed that deep renovation of historical wooden buildings in heritage area can significantly reduce its carbon footprint and make exterior renovation more cost-effective for owners.

4.2. Policy recommendations

The decarbonisation of Estonia's residential building stock is more contingent on the trajectory of national energy policy than on renovation efforts alone. Nonetheless, reducing total energy demand through renovation can help to moderate the scale of required renewable energy investments. Given the broad coverage of district heating networks and urban population density, the extent of heating system electrification remains a critical policy consideration. While electricity-based systems such as heat pumps increase the urgency of power grid decarbonisation, district heating offers flexibility through the integration of diverse heat sources.

Despite generous subsidies, motivating homeowners to undertake deep energy renovations remains a significant challenge. In addition to targeting the worst-performing buildings, scaling up successful examples of deep renovation in apartment blocks in regional centres — where property values are highest — could deliver substantial reductions in energy demand and GHG emissions.

The EPBD [3] mandates that new buildings be "solar-ready", i.e. optimised for on-site solar generation. Energy system decarbonisation could be supported by extending this requirement to deep renovations, for example by incentivising renovation to EPC class A, which necessitates investment in building-integrated photovoltaics.

Given the importance and ambition of Estonia's renovation targets, it would be beneficial to develop guidance on the GWP assessment of renovation, accompanied by low-carbon renovation guidelines that also address the impacts of construction materials and prefabrication.

4.3. Limitations of the study and the need for further research

It is important to acknowledge certain limitations in the modelling approach and underlying assumptions. Although the analysed buildings represent typical renovation cases, the number of archetypes used to characterise the entire residential stock is relatively limited and should be expanded in future research. In addition, specifying pre-renovation energy consumption by archetype would be essential for identifying the worst-performing segments and for improving the understanding of emissions distribution across building types. The upstream emission factor for Estonia's grid electricity should be calculated according to the IEA method [82], as multi-regional input–output models may not accurately reflect the climate impact of oil shale–based electricity generation. The application of LCA to renovation remains unharmonised, and the current generic material emissions dataset does not enable a detailed GWP assessment of technical installations. Assumptions regarding post-renovation heating sources are based on estimates that cannot be verified, as these decisions are market-driven and made on a project-by-project basis.

5. Conclusions

This study has investigated the overall climate impact of Estonia's decarbonisation strategies on residential buildings, including both embodied and operational GHG emissions. The decarbonisation strategies can reduce the annual GHG emissions of the existing residential building stock by 95 % from the 2020 level. The renovation of the residential building stock, the electrification of heating, and the decarbonisation of electricity supply exert partly opposing effects, making it challenging to intuitively assess their combined influence on total emissions. Embodied emissions resulting from deep renovation do not degrade the overall decarbonisation potential of the Estonian housing stock. Although deep renovation considerably reduces total delivered energy, changing heat source to heat pumps simultaneously increases reliance on electricity, which currently exhibits a significantly higher carbon intensity than wood combustion—the predominant energy source for heating of Estonian detached houses. Consequently, the successful decarbonisation of the residential building stock is highly contingent upon a substantial reduction in the carbon intensity of Estonia's electricity supply.

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CRediT authorship contribution statement

Kimmo Lylykangas: Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Kadri-Ann Kertsmik:** Writing – review & editing, Methodology, Investigation. **Damiano Cerrone:** Investigation, Formal analysis, Data curation. **Peter Walke:** Writing – review & editing, Investigation, Formal analysis. **Kalle Kuusk:** Writing – review & editing, Validation, Data curation. **Targo Kalamees:** Writing – review & editing, Validation, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix 1

Building materials emissions used in calculations.

		Parameters according to the Estonian method (2022)									
		A1-A3 GWP kgCO₂eq/kg		A4	A5	B4, life-age, years			C2	C3	C4
Building part layers	Material	$\text{average}_{\text{lowest}}^{\text{highest}}$	w/o local comp	km	%	BNB	(Goulouti, et al.)	Used in the study			
Air and vapor	Water vapour membrane	$2.81_{0.64}^{2.87}$	5.95	500	10	50	x	50	Default value 50km for materials to waste plant.	Materials divided: metal, mineral materials, wood-based materials. According to the Estonian waste management plan.	Materials divided: metal, mineral materials, wood-based materials. According to the Estonian waste management plan.
Installation (ETICS)	Mechanical fixing	xx	5.79	3000	8	x	30	30			
	Glue	xx	1.09	3000	10	x	30	30			
Frame, insulation for roof and external wall	Glass wool, 18 kg/m³	$1.32_{1.13}^{1.80}$	1.8	500	8	50	x	50			
	Stone wool, 35 kg/m³	$1.27_{1.11}^{1.58}$	1.5	500	8	50	x	50			
	Cellulose, 50 kg/m³	$0.94_{0.51}^{1.58}$	0.2	500	8	50	x	50			
	Timber frame	$0.11_{0.05}^{0.21}$	0.1	500	18	40	x	50			
	EPS (ETICS) 24 kg/m³	$3.04_{2.64}^{3.71}$	3.09	500	4	50	30	30			
	Stone wool, (ETICS) 60 kg/m³	$1.30_{1.06}^{1.58}$	1.58	500	8	50	30	30			
Wind barrier	Glass wool 63 kg/m³	$1.85_{1.20}^{2.20}$	1.0	500	10	50	x	50			
	Wood fiberboard	x	0.7	500	10	50	x	50			
External wall finish	Facade board	$1.21_{0.94}^{1.79}$	0.97	500	5	40	40	50			
	Facade paint	$2.59_{2.12}^{3.00}$	1.75	500	10	10	10	10			
	Reinforcement mesh	$2.20_{1.00}^{3.05}$	2.80	3000	10	4	x	30			
	Plastering mortar	$0.40_{0.21}^{0.94}$	0.25	500	13	50	30	30			
Roof finish	Stone tiles for roofing	x	0.4	3000	5	50	x	50			
	Steel sheets, cladding	$2.40_{1.85}^{3.32}$	2.80	3000	3	50	40	50			
Basement floor	XPS	$3.04_{2.64}^{3.71}$	2.70	500	18	50	x	50			
	EPS	$3.04_{2.64}^{3.71}$	3.09	500	10	50	x	50			

		Parameters according to the Estonian method (2022)									
		A1-A3 GWP $kgCO_2eq/kg$		A4	A5	B4, life-age, years			C2	C3	C4
Building part layers	Material	$\text{average}_{\text{lowest}}^{\text{highest}}$	w/o local comp	km	%	BNB	(Goulouti, et al.)	Used in the study			
Windows	Triple glazed, U=0.8 W/(m²K)	$2.27_{1.66}^{3.47}$	2.08	500	0	40	30	40			
	Triple glazed, U=0.6 W/(m²K)		1.66	500	0	40	30	40			
	Double glazed, U=1.1 W/(m²K)	$1.65_{0.97}^{2.14}$	1.15	500	0	40	30	40			
	Double glazed, U=1.4 W/(m²K)			500	0	40	30	40			
Services	HVAC, apartment	38.5_{35}^{42}	42	3000	0	xx	25	25			
	PV-panel	21_{19}^{25}	23	3000	0	xx	20	20			

Appendix 2

The following table presents definitions of the key concepts most frequently used in this doctoral thesis, together with their official sources, to ensure clarity and comprehensibility.

Carbon footprint (CF)	“The building carbon footprint refers to the sum of greenhouse gas emissions, expressed as CO_2eq, arising across all relevant life cycle stages of a building.” (EN 15978:2011, 2011)
Cost-optimal	“Means the energy performance level which leads to the lowest cost during the estimated economic life cycle.“ (European Parliament and the Council, 2010)
Deep renovation	“Means a renovation which is in line with the ‘energy efficiency first’ principle, which focuses on essential building elements, and which transforms a building or building unit: (a) before 1 January 2030, into a nearly zero-energy building; (b) from 1 January 2030, into a zero-emission building;”(European Parliament and the Council, 2010)
Global Warming Potential (GWP)	“Means an indicator which quantifies the global warming potential contributions of a building along its full life cycle;” (European Parliament and the Council, 2010)
Major renovation	"The renovation of a building where: (a) the total cost of the renovation relating to the building envelope or the technical building systems is higher than 25 % of the value of the building, excluding the value of the land upon which the building is situated; or (b)more than 25 % of the surface of the building envelope undergoes renovation. Member States may choose to apply point (a) or (b);" (European Parliament and the Council, 2010)
Operational Greenhouse Gas emissions	“Means greenhouse gas emissions associated with the energy consumption of the technical building systems during the use and operation of the building.”(European Parliament and the Council, 2010)
Whole Greenhouse Gas emissions (GHG)	“Means greenhouse gas emissions that occur over the whole life cycle of a building, including the production and transport of construction products, construction-site activities, the use of energy in the building and replacement of construction products, as well as demolition, transport and management of waste materials and their reuse, recycling and final disposal.” (European Parliament and the Council, 2010)

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