‘’Towards Zero Carbon: A Comprehensive Evaluation of Conventional Renovation Strategies for Terraced Houses, Using Life Cycle Analysis (LCA) and Life Cycle Costing (LCC) to Enhance Decision-Making Support – accompanied by the design of a tool.”

SUPPORT FOR SHORT TERM AND LONG TERM DECISION-MAKING IN RENOVATION

TOWARDS A ZERO CARBON EXISTING BUILDING STOCK

MADEVI SEWNATH MASTER THESIS

MSC ARCHITECTURE, URBANISM AND BUILDING SCIENCES

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‘’Towards Zero Carbon: A Comprehensive Evaluation of Conventional Renovation Strategies for Terraced Houses, Using Life Cycle Analysis (LCA) and Life Cycle Costing (LCC) to Enhance Decision-Making Support – accompanied by the design of a tool.’’

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TUDelft

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CONTENTS

Overview chapters

CHAPTER 1| Introduction

This chapter serves as an introduction to the research, and reveals which topics are focused on within the study.

The chapter starts with the research background, in which the topics are addressed. Followed by a problem statement that specifies the focus of the research. The research question of the thesis and corresponding sub questions.

1.1 Research background

To reduce global warming the emission of greenhouse gases (GHG) must be net zero in 2050, Paris agreement (Kruit et al., 2020). Among greenhouse gases CO_2 is the largest contributor. In the Netherlands the building sector is responsible for 38% of total GHG emissions, 27% being operational carbon (related to energy use) and 11% embodied carbon (related to material use) (Dutch Green Building Council, 2021) (Sobota et al., 2022). In other words, 29% of the total carbon emission of the building stock is related to embodied carbon and 71% to operational carbon. A large portion of the GHG emissions in this sector originates from existing residential buildings and is for the majority related to energy for heating (Milieu Centraal, n.d.). Renovating existing residential buildings is a key element in reducing the operational carbon emissions from heating (Kruit et al., 2020). Compared to new construction, renovating, and extending the service life of existing buildings is more sustainable as it requires significantly less embodied energy (Vilches et al., 2017). Due to the environmental advantages of renovating, it acts as the first step to reduce carbon emissions (Netherlands Enterprise Agency, 2020). The general strategy to reduce carbon emissions first focuses on the operational carbon by transitioning from non-renewable, depletable energy sources to renewable, sustainable energy sources, also known as the energy transition, starting with replacing gas fuels for heating and cooking (RVO, n.d.). In the Netherlands the target is to reduce 49% of GHG emissions compared to 1990 by 2030, and 95% by 2050 (RIVM, 2019). In practical terms this requires a renovation of 1.5 million residential buildings by 2030 and 5.5 million residential buildings by 2050 (RIVM, 2019), to enable the use of sustainable energy sources and reduce the energy demand (Pagliano et al., n.d.). Each building is different and requires a tailored solution to reduce GHG emissions effectively (IEA, 2022). Therefore, it is hard to assess the effects of various renovation solutions, in a short period of time. The use of renewable energy sources is a measure that aims to reduce the operational carbon. The embodied carbon related to renovation is often not considered (Dutch Green Building Council, 2021). As the operational carbon decreases the proportional share of embodied carbon grows (Kruit et al., 2020) (Dutch Green Building Council, 2021) (Vilches et al., 2017) (Koezjakov et al., 2018). The importance of renovation strategies that consider both the embodied and operational carbon is growing. Unlike operational carbon which is only present during the in-use stage of the building, the embodied carbon touches all stages of a building's life cycle, production(A), construction(A), use(B), end of life(C), and beyond end of life (D) (Sobota et al., 2022). Due to the many variables in the life cycle of a building that take place in different stages, clear standards on the assessment of carbon emissions over the full life cycle of a building are missing (Toth et al., 2022) (Vilches et al., 2017). As a result, many studies don't consider the embodied carbon or use different approaches to assess the embodied carbon resulting in incomparable outcomes, because of this current strategies are not selected to reduce carbon emissions on the complete spectrum of carbon emissions (Vilches et al., 2017). The risk is that the overall carbon reduction of the building stock is less than expected. A comprehensive approach to assess the environmental performance is growing in popularity, due to the extraction of energy certificates based on only the operational carbon with the risk of higher carbon emissions when embodied carbon is included (Konstantinou, 2014). Although currently a standard protocol on assessing the embodied carbon is missing, there is no doubt that assessing the embodied carbon is beneficial, as it has the potential to enable trade off comparison between operational and embodied carbon (Nwodo en Anumba, 2019). Exclusion of the assessment of embodied carbon also indirectly discourages the development of low carbon materials (Toth et al., 2022). Existing buildings are already in the in-use stage of their life cycle. At this stage a building can undergo maintenance and repair, which also act as trigger moments for renovation (Kruit et al., 2020). Performing a renovation on a building will change the life cycle of the building and future emissions. Understanding the effects of different cycles for the use-phase scenarios can thus provide valuable information (Vilches et al., 2017). Therefore, planning the life cycle of the building until the end of life stage, taking into account the trigger moments, has the potential to improve the attractiveness to renovate and target decarbonization goals more effectively. Additionally, life cycle planning will benefit trade off comparison between embodied and operational carbon. The selection of a renovation is based on multiple criteria and is different for each context (Nielsen et al., 2016). A context-specific design tailored for a specific building is required to find suitable solutions (IEA, 2022). However, calculating the performance of all generated renovation designs, at an early design stage, for multiple criteria can be time consuming and requires a high level of information (Nielsen et al., 2016). This limits the number of renovation options explored and influences the effectiveness of a renovation. Information on the general performance of a renovation on multiple criteria is lacking. Simplified LCA studies have shown to be effective to select a renovation alternative for energy saving (Vilches et al., 2017). Additionally, studies in the field of renovation generally don´t sufficiently consider economic aspects (Vilches et al., 2017). Furthermore, renovations with high energy saving are related to high costs and often can't be performed in a single step, and are therefore in multiple steps, achieving a high energy saving in the end (Fritz et al., 2019) (Lang, 2016) (Maia et al., 2021) (Sibileau et al., 2021). The performance of renovations carried out in steps are often not included in studies. The performance of renovation strategies on the long term are therefore unknown. The aim of this thesis is to investigate how the assessment of renovation strategies can be simplified to support decision making.

The thesis investigates different renovation strategies and scenarios for the in use stage of a terraced house, to improve decision/making in renovation, by looking at the level of renovation, renovation measures, renovation execution and decision making. The insight gained is used to create a tool that supports decision making for renovation strategies. Data is obtained using various tools, and by performing among others a simplified Life cycle analysis (LCA) and life cycle costs (LCC) assessment. The performance of the renovation strategies are evaluated based on energy performance, environmental performance and costs. Which are the main criteria for decision making in renovation.

1.2 Problem statement & research question

It's urgent to reduce CO_2emissions and limit global warming. The use of renewable energy sources is a measure that aims to reduce the operational carbon and will reduce a large amount of CO_2 emissions related to the building stock. On the contrary, as the operational carbon decreases the share of embodied carbon increases, and there are no standard assessment methods that consider the embodied carbon now. Due to the lack of the assessment of embodied carbon the effects of current renovation strategies on total carbon emissions are unknown.

Secondly, carbon emissions are related to the full life cycle of the building. Renovation influences the life cycle of a building and future emissions. Therefore, planning the life cycle until the end-of-life stage and the moment of a renovation are critical aspects as it influences the overall total carbon emissions, and the decision to renovate. However, this is often not looked at.

Thirdly, the decision-making process for renovation is complex, as it depends on multiple criteria. Assessing the performance of all design possibilities for renovation on multiple criteria, that vary in importance is time consuming, especially in the early design stage when the level of data is limited. There is no insight on the general effects of a strategy on multiple criteria. And a simplified assessment is missing. This makes it hard to select a suitable renovation strategy and therefore complicates the decision making.

And at last the assessment of renovations performed in steps is often not considered in studies, despite it being the main approach to execute high energy saving renovations, due to a lack of budget.

This led to the following research question:

How can decision-making for renovation strategies take into account carbon emissions over the life cycle of a building, in the Netherlands?

This research question is answered with the following sub questions:

1. How can renovation strategies be created and which renovation measures should be included in the strategies regarding carbon emissions?
2. How do the renovation strategies influence the operational performance of a building?
3. How do the renovation strategies influence the buildings embodied performance?
4. How do the renovation strategies influence the buildings life cycle performance?
5. What renovation scenarios for a terraced house can be defined considering a buildings life cycle in the Netherlands?
6. How can decision making be supported with the results, through a design?

Objective: The main objective of the study is to understand which parameters influence the performance of a renovation over a buildings life cycle the most. To enable assessment of renovation strategies that contain measures that effectively target the performance of a building and reduce total carbon emissions. Additionally, the study investigates how the results could support decision making and be used in decision-making in renovation strategies, through a design.

1.3 Methodology

The method to answer the research question consist of a literature review on the topics renovation scenarios, strategies and measures, carbon emissions, and decision-making. After the literature review renovation strategies are created (chapter 3) and assessed on operational carbon and embodied carbon. The results are used for Life cycle assessment and parallel the life cycle costs are assessed. The results are combined to assess the overall performance of the strategies, to identify the strategy with low costs and carbon emissions. The strategies obtained were used to assign to the renovation scenarios obtained from the literature to investigate the parameters that influences the performance of a renovation when performed in steps. Additionally the assessment methods were used as input to develop a tool that helps in estimating the performance of a step by step renovation. An overview of the method is provided in figure 1.

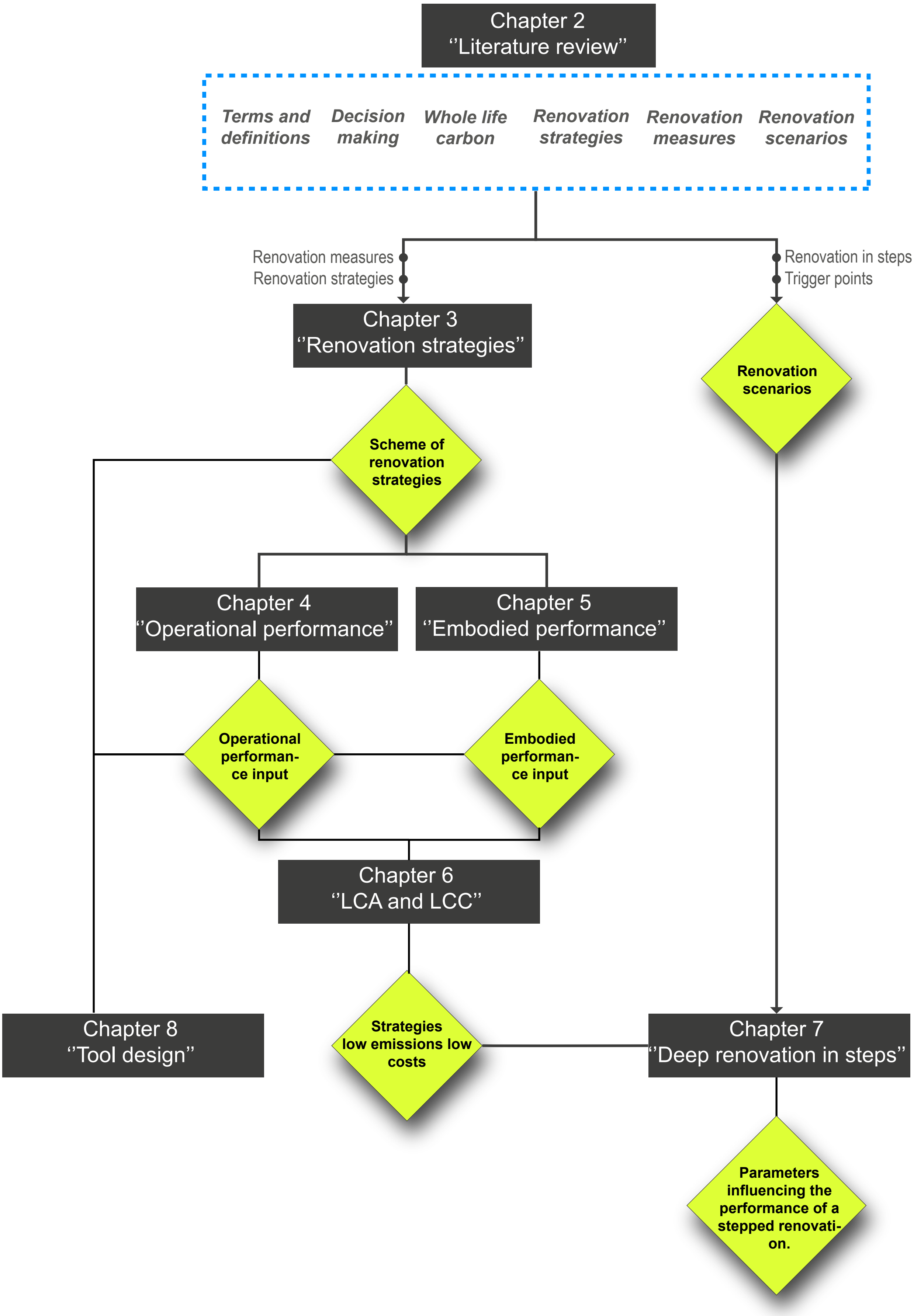


Figure 1. Overview methodology (by author).

1.4 Reading guide

Chapter 2 "Literature review"
The literature review starts with the definition of the terminology used in the thesis, such as renovation scenarios and renovation strategies. Then it discusses the main criteria for decision-making. It then dives into whole life carbon, to provide information on total carbon emissions, followed by renovation scenario's regarding a building's life cycle, renovation strategies and measures.

Chapter 3 "Renovation strategies"
Describes how renovation strategies are formed and what measures are considered in the strategy. Furthermore, it contains an overview of the input values.

Chapter 4 ''Operational performance'
In this chapter the operational performance of the renovation strategies is assessed, through assessment of the operational energy and carbon. The chapter describes the calculation method and input values used for the assessment.

Chapter 5 ''embodied carbon'
In this chapter the assessment of the embodied carbon is described. It considers the initial embodied carbon and the recurrent embodied carbon.

Chapter 6 ''LCA and LCC'
In this chapter the results of the operational carbon and embodied carbon are combined to perform a Life cycle assessment. Then the life cycle costs are determined. At last the results are combined to obtain an holistic performance of the strategies on costs and carbon emissions.

Chapter 7 ''Deep renovation in steps'
In this chapter 3 deep renovation strategies obtained from chapter 6 are assigned to renovation scenarios and assessed on their performance. The results provide insight in the parameters that influences the performance of a strategy, in case of a stepped renovation.

Chapter 8 ''Tool design'
In this chapter the design of the tool is described.

Discussion and Conclusion
The report ends with a discussion and an overall conclusion.

1.5 Boundary

Due to time constraints the study is narrowed down. Below, per subject is described what is considered in the research.

- Building typology - The renovation strategy for each building typology might differ. Therefore, the thesis focuses only on one building typology, a terraced house. The scale is demarcated to a building scale, regarding renovation measures.
- Renovation measures, and supply chain - The assessment of renovation measures

considers only a linear supply chain and conventional renovation materials. In other words, a circular supply chain, that considers recycled and reused materials or products, is not considered in renovation measures.

- Renovation measures - In the measures only physical building elements are assessed. Measures that aim to influence user behavior are not assessed.

1.6 Limitations

The research only serves as a first step in generalizing renovation strategies to help assist in decision making regarding selecting a renovation strategy in the early stage. The thesis only supports the decision-making process in renovation for terraced houses and can thus not provide support in decision making regarding other building typologies. The decision-making process is complex, as it is constrained by technical limitations embedded in the existing structure. The thesis does not investigate technical constraints regarding the existing structure, therefore evaluation of the obtained strategies regarding applicability remains a task for the decision maker(s). In other words, the study does not fully assist the selection of a renovation.

1.7 Social relevance

Reducing the environmental impact to a minimum is important to maintain and improve the living environment of future generations of humans and animals. On a short time span, switching from unsustainable and/or depleting energy sources such as gas to renewable energy sources is necessary to still foresee in human needs for water, heating and food preparation. Renovation is inevitable, but complex as it requires knowledge about a variety of aspects, ranging from practical knowledge about the current stage till abstract knowledge about mitigating carbon emissions and energy use. Furthermore, it is a sensitive topic as it influences the financial investment required from residents. Secondly, building owners do not always live in the houses they own. The selection and impact of a renovation strategy should therefore be clear to house owners, to be able to clearly explainable to residents what the investment is for. However, decision making in renovation is commonly based on energy saving, and thus does not fully support the main objective of renovation, which is reducing the environmental impact. Support for decision-making in the selection of renovation strategies is needed to deliver the environmental results that are promised, so the investment of residents is not in vain.

1.8 Scientific relevance

Current research focuses on different renovation strategies to mainly reduce energy consumption. Effective strategies that aim to reduce the operational carbon as well as the embodied carbon by 2050 are lacking. A gap is found in the literature, regarding the assessment of step by step renovations. Limited research investigates the performance of renovations executed in steps. Research on this matter mainly focuses on the time dimension, to determine when the steps should occur. Gaining insight in the performance of different renovation strategies on multiple criteria and for different execution scenarios, could support further studies on this matter, which is important as most renovations will be performed in steps.

CHAPTER 2| Literature review

This chapter presents the literature study including all topics relevant for the assessment of renovation strategies in later chapters.

To provide clearance in terminology, the chapter starts with defining the terms used throughout the thesis. Then it dives into decision-making in renovation, a study on carbon emissions over the life cycle of the building, and the different renovation scenarios. At last the most impactful parameters in renovation strategies are described and related measures for the strategies are defined.

2.0 Terms and definitions

Vilches et al. (2017) addressed the consequences of various terms such as retrofitting, refurbishment, renovation, repair, and restoration, used in research in the field of renovation, and that it causes a lack of clarity in the concept and therefore complicates the comparison of studies. Therefore, this chapter provides insight on the terms used in this thesis and their definition. Vilches et al. (2017) also tried to provide more clarity on the definition of terms. According to the study retrofitting can be defined as the act of adding new materials to a building without the specific aim to upgrade its performance. While refurbishment or renovation refers to specifically retrofitting measures that provide additional improvements. Furthermore, restoration refers to restoring something to its initial state while repair refers to restoring something without the intention to achieve the exact same original state (Vilches et al., 2017).In line with frequently used terms in policy, this thesis uses the terms renovation and repair instead of refurbishment and restoration, with the definition as described by Vilches et al. (2017).Renovation is further defined through the terms renovation scenarios, renovation strategies, and renovation measures. Renovation scenarios refer to alternative situations to evaluate their potential to meet renovation objectives (Wahi et al., 2023). More specifically, in this thesis the term refers to different execution plans for renovation, in terms of time, which is defined through a step-by-step approach or a single renovation. Renovation strategies refer to the approaches to address renovation scenarios, more specifically the level of renovation defined as a deep renovation or a shallow renovation and the parameters that influence the level of renovation. Renovation measures refer to the different ways of applying the renovation strategy (Wahi et al., 2023). In other words, the renovation strategy can be completed through various renovation measures and combinations of renovation measures, more specifically in this thesis defined through insulation levels, infiltration levels, ventilation systems, heating systems, tap water systems and insulation materials. In the field of renovation, LCA is used to assess the environmental performance of different renovations strategies to find the strategy with the lowest environmental impact (Vilches et al., 2017). The environmental impact is often assessed by obtaining the operational and embodied carbon. Operational carbon refers to emissions during the operation of a building. While embodied carbon refers to emissions related to the production, use and disposal of materials. Embodied carbon can be distinguished in recurrent and initial embodied carbon. Recurrent embodied carbon is the embodied carbon related to maintenance, replacement, and repair, and reoccurs after a certain period (Vilches et al., 2017). The recurrent embodied carbon grows when the service life is extended, making the recurrent embodied carbon a key aspect in trade of comparison between operational and embodied carbon. An overview of the terms and definitions used within this thesis is provided in table 1.

Table 1. Overview of terms and definitions used in this thesis.

Terms	Definition	Source
Retrofitting	The act of adding new materials	(Vilches et al., 2017)
Refurbishment or renovation	Retrofitting measures that provide additional improvements, for example in terms of aesthetics	(Vilches et al., 2017)
Renovation scenarios	Refer to alternative situations to evaluate their potential to meet renovation objectives	(Wahi et al., 2023)
Renovation strategies	Refer to the approaches to address renovation scenarios, such as a deep renovation or shallow renovation.	(Wahi et al., 2023)
Renovation measures	Refer to a set physical measures in line with the renovation strategies	(Wahi et al., 2023)
Operational carbon	Operational carbon refers to emissions during the operation of a building	
Embodied carbon	Embodied carbon refers to emissions related to the production, use and disposal of materials.	
Recurrent embodied carbon	The embodied carbon is related to maintenance, replacement and repair, and reoccurs after a certain period	(Vilches et al., 2017)

2.1 Decision making

This chapter focuses on answering the sub question: ‘‘How do the renovation strategies influence the building performance related to criteria for decision-making in renovation?’’. It aims to find the main criteria for decision-making. The section discusses the decision makers targeted, where in the renovation process support for decision-making is needed and what the support should consist of.

2.1.2 Decision makers, decision-making support and process

LCA is often applied in the early design phase, mainly by property developers, architects, and urban planners (Vilches et al., 2017). Renovation decisions can either be made by a single person or by a group of stakeholders (Pinzon Amorocho & Hartmann, 2022). This changes the decision-making process as stakeholders may have different desires, therefore finding common ground can be part of the decision-making process (Nielsen et al., 2016), which is not a requirement when the decision is taken by a single person. Regarding residential buildings, most renovation decisions are taken by a single person (Pinzon Amorocho & Hartmann, 2022).

The need for tools that support decision-making regarding decision makers with a large building portfolio is high (Nielsen et al., 2016). Renovation costs are often expensed over years (Pannier et al., 2021), and thus require sufficient financial planning to manage expenditures. Secondly, there is also a need for guidance and support in deep renovation, specifically for technical matters (IEA, 2022). Limited data is available on the performance of buildings, that is easy-to-access and transparent (IEA, 2022). The main limitations in large building portfolios regarding decision making in renovation can thus be solved by tools that provide insight in renovation costs over time, for at least a deep renovation and additionally provide information on the performance of the renovation strategy.

It is important to understand in which part of the renovation process these limitations occur, to understand at which moment the tool is needed. According to the study of Konstantinou (2014) the renovation process can be distinguished in the phases: Definition of refurbishment scope (phase 1); Concept strategy design (phase 2); Final strategy design (phase 3); Execution (phase 4); Refurbished building (phase 5). The concept strategy design phase refers to the available renovation measures in renovation cases and the possible alternative strategies that can be created with these. The final strategy design phase refers to selecting a strategy and therefore requires precise estimation of the performance of the strategy and the related costs, a support tool regarding the performance of different strategies should therefore be introduced in phase 2, concept strategy design (see figure 2).

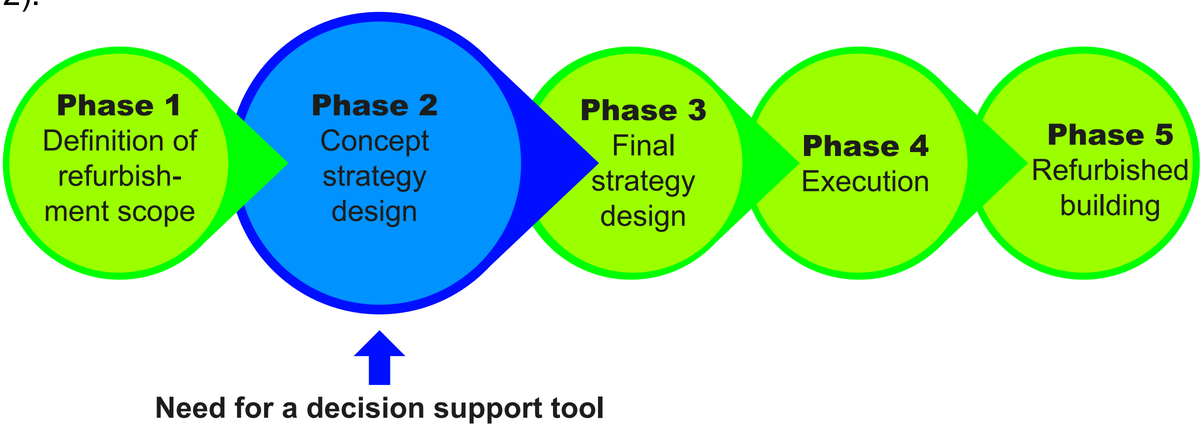


Figure 2. The phases of a renovation process, with in blue the phase in which support of decision-making is needed (adapted from Konstantinou (2014)).

In Large portfolio's the assessment of costs and energy performance is important (Pannier et al., 2021), to manage the expenditures. Also is the decision making in renovation mainly influenced by investment costs and payback time (IEA, 2022). In policy making, improving the environmental performance is the objective. A decision support tool should therefore consider costs, energy, and carbon emissions. The comprehensiveness of the assessment of renovation designs makes it hard to include all criteria in an early design stage, due to the level of data required and the time needed to assess all simulations and calculations (Nielsen et al., 2016). Simplification of the assessment of the performance of a renovation is needed, and could also be addressed through a tool. A simplified LCA has shown to be accurate for decision making in specifically energy renovations and includes the assessment of the stages production and construction (A1-2), replacement (B4) and the impact reduction during the in use stage (Vilches et al., 2017). Regarding the embodied carbon, the recurrent embodied emissions related to services and materials are crucial in decision making (Vilches et al., 2017). A simplified inventory accelerates the release of studies, but should not be used as a representative figure, and rather be used as an indication (Vilches et al., 2017).

On the contrary, current renovation studies mainly focus on economic and environmental aspects, but should also address social aspects, as economic and environmental aspects are most often not the reason to renovate (Pinzon Amorocho & Hartmann, 2022). The evaluation of renovation strategies should comprise of a comprehensive objective and criteria to suggest potential renovations (Pinzon Amorocho & Hartmann, 2022). However, most studies focus mainly on criteria weighting and alternative performance quantification, and limited studies focused on objectives, criteria setting and weights and performance integration despite their importance (Pinzon Amorocho & Hartmann, 2022). A review in decision support tools for renovation showed that limited attention is given to objective and criteria setting, and more attention should be given to sustainability goal setting and criteria setting (Nielsen et al., 2016).

Available decision-making support tools

There are multiple decision-making support tools available for renovation projects. A review paper that compared these tools, showed that (Bui et al., 2021):

- Limited decision support tools take in account the constraints and limitations of existing buildings and zero carbon problems;
- Tools focus mainly on ranking the solutions on economic benefits and environmental impact;
- There is a Lack of decision-making tools for the early design stages for renovation of buildings, that show how to reach zero carbon targets.

Other important conclusions to create successful decision support tools (that aim to support the reduction on carbon emissions) are (Bui et al., 2021);

- Linking the life cycle carbon performance to other project criteria, such as client requirements and stakeholder wishes/values;
- And integrating long-term strategies, for partial refurbishment. To establish the carbon budget that will be achieved over time.

Another study revealed that only 21% of decision-making tools for renovation include LCA, and 16% LCC (Nielsen et al., 2016). Combining the existing tools is useful to support decision making in renovation (Nielsen et al., 2016). Also, tools should be available, to stimulate knowledge sharing and provide transparency (Nielsen et al., 2016).

2.2 Whole life carbon

To assess the environmental performance of a renovation, it is crucial to assess the embodied and operational carbon emissions. Although there are no standards on the assessment of total carbon emissions, the life cycle analysis framework as per EN …. Provides information on the phases of the assessment to support carbon assessments. A building's life cycle is a critical part of the assessment, as it influences the emissions the most. This chapter provides insight in the assessment method based on the LCA framework, the critical aspect of a building's life cycle, the evaluation of such assessments and outcomes of earlier studies.

2.2.1 Operational and embodied carbon assessment – LCA in general

Whole life carbon refers to the carbon emissions over the full life cycle of a building. This includes the emissions related to energy use during the in-use phase of a building (operational carbon) and emissions related to the production of materials till their disposal (embodied carbon). While operational carbon emissions are fixed to the operational stage of a building's life cycle, embodied carbon emissions are present in variable amounts in all stages of a building's life cycle. Globally there is an aim to reduce the energy demand in the operational stage, which will result in an expected rise in the share of embodied energy of approximately 40% (Vilches et al., 2017). This makes the use of a life cycle approach inevitable to reduce carbon emissions effectively (Vilches et al., 2017). Building Life Cycle Analysis (LCA) is a tool that can help to define the total emissions of a building (Nwodo en Anumba, 2019), and consists of a methodology build up from phases. It is mainly used to assess the environmental impact of a design to support decision making during the design phase (Nielsen et al., 2016) (Nwodo en Anumba, 2019). Due to the large number of existing buildings and as renovation has shown to be more sustainable compared to new construction (Vilches et al., 2017), the use of LCA in specifically renovation is growing (Nwodo en Anumba, 2019). The LCA framework is defined by standards, ISO 14040:2006 and ISO 14044:2006 (Vilches et al., 2017).

Current LCA studies focus on the relation between embodied and operational energy (Vilches et al., 2017) and encompass mainly indicators for the environmental impact, such as carbon emissions, and energy among others (Nwodo en Anumba, 2019). Life cycle cost (LCC), in literature referred to as the overall costs over an entire life span, is another important objective in renovation (Nwodo en Anumba, 2019). According to Nwodo en Anumba (2019) Performing a LCA is inadequate to select a suitable renovation as other objectives such as LCC show conflicting results, and the methods to assess this data differs. Additionally, both LCA and LCC have uncertainties (Gonzalez-Caceres et al., 2023). Despite the valuable information LCA provides, LCA is criticized, for a variety of reasons. Starting with the use of terminology and differing objectives in studies (Vilches et al., 2017). Although this can only be prevented if standards are provided to enable the comparison of studies, this research aims to provide transparency by predefining the objectives and terminology to mitigate this effect.

2.2.2 Methodology- LCA framework

LCA is a methodological framework that consists of the phases: goal and scope (1), life cycle inventory analysis (LCI) (2), Life cycle impact analysis (LCIA) (3) and interpretations (4) (Nwodo en Anumba, 2019). The following paragraphs, organized by LCA phase, discuss the complications in LCA to provide insight on how to effectively perform an LCA.

1| Goal and scope

In the phase ''goal and scope'' the outline for the LCA assessment is set by determining:
- The objective(s) of the assessment;
- The moment of assessment (for example during the construction phase or in design phase);
- The buildings life cycle stages that will be assessed and how they will be assessed;
- The building scope (assessment of the whole building, or just a part);
- How Data is gathered and used;
- Which tools will be used for the assessment.

The starting point of the LCA study, regarding the scope of, and activities within the study is an important concept in LCA, also in literature referred to as system boundary. System boundary, literally the boundary or scope of the study, influences the outcome of the study greatly. Determining the buildings life cycle stages that will be assessed is a crucial step for reliable outcomes, as the environmental impact occurs during the full life cycle of the building (Zhang et al., 2006).

Building life cycle stages to assess
Studies also include different stages of a building's life cycle for the assessment of the environmental impacts (Vilches et al., 2017). While most studies assess the production stage and in use stage, the construction stage is often excluded. The end-of-life stage is assessed in various ways amongst studies (Vilches et al., 2017). An analysis of the emissions related to the building life cycle stages for specifically a terraced house typology, show that most emission are related to the production stage (A1) and secondly the operation stage (B) other stages show very limited and similar impact (Sobota et al., 2022). In other words, assessments where the objective is to investigate the impact of varying strategies, representative figures that reflect the impact are suitable, while in assessments where the objective is to gain insight in the actual performance of a strategy excluding life cycle stages would result in unreliable results.

2| Life cycle inventory (LCI)

During the Life cycle inventory (LCI) phase the inputs and outputs of a product or building are determined. The absence of a procedure in LCI, to determine the use of material data, building boundaries, and statistical extensions (Vilches et al., 2017), leads to various study approaches (Nwodo en Anumba, 2019). Furthermore, assumptions in building lifespan, material maintenance, repair and replacement among others lead to inaccurate results and additionally contribute to incomparable research outcomes (Nwodo en Anumba, 2019). The approach of LCI impacts later LCA phases in the assessment of the environmental impact and the interpretation of the results, causing a deviation in results up to 50%, and is therefore the main limitation within LCA studies (Vilches et al., 2017). Despite the lack of procedure, nevertheless LCA can provide insight in the environmental impact and remains a valuable tool in decision making towards renovation strategies with low environmental impact, when used carefully. To conduct a LCA effectively, choices must be justified to provide reliable results, and transparency in system boundary should be provided to stimulate further studies in LCA (Nwodo en Anumba, 2019). To minimize uncertainty an analysis that provides an indication of the quality of data and sensitivity analysis can be performed (Nwodo en Anumba, 2019). Below the uncertainties in LCI are described per subject.

Data
The data needed depends on the goal and scope definition, and among others could cover aspects such as: location, floor and/or wall areas, energy and water consumption, volume of materials, green area. (Zhang et al., 2006). Uncertainty in LCA material data quality can be reduced by using verified environmental product declaration (EPD)(Nwodo en Anumba, 2019).

Building type
A clear definition of the type of building can improve the comparison between studies. Residential buildings can for example be further defined as single family houses and multifamily houses (Vilches et al., 2017).

Building life span
The building lifespan used for assessment in studies varies from 50-150 years, influencing the relation between embodied and operational energy significantly among studies (Vilches et al., 2017). Reliable building lifespan should not be determined by common practice (Nwodo en Anumba, 2019), but by the expected lifespan (Vilches et al., 2017), through the science of the specific building typology (Nwodo en Anumba, 2019). For example, the lifespan of heavy fixed structures may exceed 50 years as it is more efficient to reuse the building and avoid the use of new products for construction and the waste due to demolition (Vilches et al., 2017). The end of the service life of a building is subjective and currently subordinate to the demands of building owners, its appearance, and the available budget (Ferreira et al., 2023).

3| Life cycle impact analysis (LCIA)
Nwodo en Anumba (2019), advocated for a more scientific way of LCIA. LCIA consists of the steps classification, characterization, and valuation (Zhang et al., 2006). During this phase the outcomes are assigned to impact categories (classification), the contribution of each impact category is defined to enable weighing (characterization), and at last the impact categories are weighted (valuation) (Zhang et al., 2006). For example, CO_2 results are translated to the impact category global warming potential, and the impact category is assigned a contribution to enable weighing impact categories. Below the uncertainties in LCIA are described.

Functional unit
As a functional unit, studies often use 1 square meter or the whole building, however considering the building type, technical and functional requirements, pattern of use and service life to define the functional unit is important (Vilches et al., 2017). Scholars often consider either a complete building or 1m2 heated area as a functional unit (Vilches et al., 2017).

4| Interpretations
In this phase the outcomes of the LCA assessment are reflected on, there is no specific format for this reflection as the results and objectives of studies differ. Among studies the

service life and the used functional unit, and LCI method are the main cause for incomparable results between studies (Vilches et al., 2017).

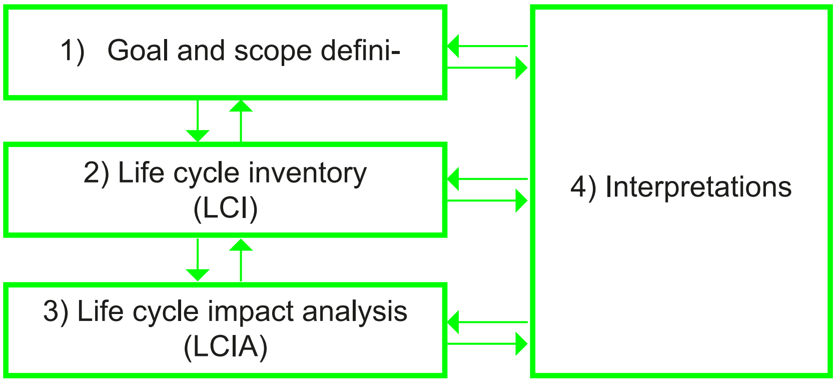


Figure 3. Phases of the LCA framework (according to ISO 14040, created by author).

2.2.3 Building life cycle stages

According to EN 15978 a buildings life cycle consists of the stages: Production stage (A), Construction stage (A), Use stage (B), and End of life stage (C) (Nwodo en Anumba, 2019) (see figure 2). Below all stages are discussed briefly.

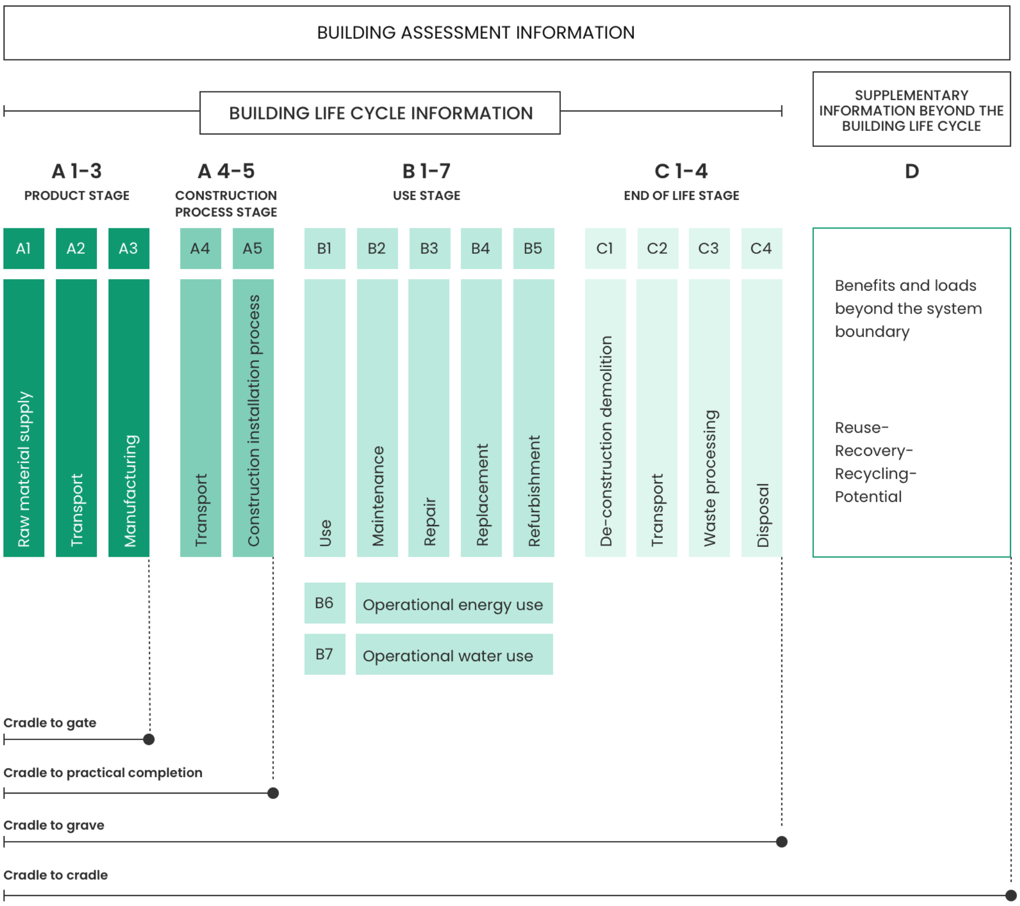


Figure 4. Life cycle stages according to EN standards (image from One Click LCA, n.d.).

A| Production stage (A)
The production stage addresses the extraction and processing of raw materials. Earlier studies revealed that concrete and steel (commonly used to construct buildings) have a significant impact on the environment, compared to wood. Studies also revealed that the use of insulation reduces the environmental impact in other building life cycle stages (Vilches et al., 2017).

A| Construction stage (A);
The construction stage refers to the construction of the building and the processes related to this stage. The construction stage often has a significantly low environmental impact, compared to the use stage and production stage (Vilches et al., 2017).

B| Use stage (B) and;
The use stage refers to the operation period of the building. Studies have shown that the gross of carbon emissions is related to this stage (Zhang et al., 2006) (Vilches et al., 2017), and that it's related to the energy demand (Vilches et al., 2017). As a result, multiple studies have focused on energy renovations (Vilches et al., 2017).The input parameters are also considered most influential in terms of LCA outcomes (Favi et al., 2018), therefore studying the effects of multiple use stage scenarios is essential (Vilches et al., 2017). To reduce the energy consumption of buildings, reducing the energy demand through passive measures is crucial (Vilches et al., 2017). On the other hand, energy supply systems have a significant impact on GHG emissions and energy use as well, and thus also influence the energy demand (Vilches et al., 2017). In other words active measures and passive measures are both needed to reduce emissions during this stage.

Module B5, Refurbishment
Module B5 covers the aspect refurbishment in LCA. As per BS EN 15978: 2011, The system boundary of module B5 consist of production, transportation, construction, waste management, and end of life of replaced materials (Vilches et al., 2017). End of life is often excluded, however to compare different renovation options, the end-of-life stage should also be included (Vilches et al., 2017). Visualization of substituted and new materials

C| End of life stage (C)
The end-of-life stage refers to the deconstruction and demolition of the building. Similar to the construction stage, this stage also has a significant low environmental impact, compared to the production and use stage (Vilches et al., 2017). Recycling and reducing waste are most essential in mitigating the overall LCA results (Vilches et al., 2017).

Overall all stages
Studies mainly focus on the life cycle stages production and use, because of their high influence on the environmental impact, although assessment of all stages is needed to determine the total environmental impact. Also for a terraced house the production and use stage have significant impact on emissions. Due to a lack of research, there are still a lot of uncertainties in the impact of transport and/or construction modules (A4, A5, C1 and C2) (Vilches et al., 2017). Despite its potential to reduce the environmental impact, limited studies focus on different scenarios for the use stage (Vilches et al., 2017). In case of LCA for renovation, a critical aspect is determining what is included in the assessment. Assessing only all stages for the new materials, is not representative for the embodied

carbon as the end of life stage for the original/substituted material is not assessed.

Interesting research outcomes of LCA studies

The majority of LCA studies focused on the reduction of energy use (Vilches et al., 2017). And the payback period is often used to evaluate a renovation strategy (Vilches et al., 2017). Studies differ when it comes to system boundary, with most differences in the approach of end-of-use phase, due to exclusion of this phase, assessing only the environmental impacts of substituted and/or new materials.

From earlier outcomes of LCA studies can be concluded that:

- Climate type and type of measure are key elements to reduce energy consumption, and that the reduction ranges from 30% to 82% (Vilches et al., 2017);
- Production and transport of renovation measures, take up 10% to 15% of primary energy for the full life cycle (in Irish buildings) (Vilches et al., 2017);
- Recent study shows that the embodied and operational carbon over a 20 year period don't differ significantly (Gonzalez-Caceres et al., 2023).

Conclusion

Instead of assessing all stages which is time consuming and also considers stages with higher uncertainties, assessing only the productions stage and use stage is enough to gain insight in the gross of carbon emissions. The operational carbon is related to the use stage and can be reduced by reducing the energy demand through active and passive measures. While the embodied carbon is related to the production stage and can be reduced by assessing the emissions due to extraction and processing of different materials and selecting a material. In renovation in particular, the outcome is influenced by life cycle emissions related to the assessment of added materials and existing materials. Building aspects that influence the outcome significantly are typology, life span, service life scenarios, and the data used to assess the material related emissions. Defining these parameters is therefore an important part to gain insights into the emissions of different renovation solutions. The end of life and beyond end of life stages are important but will not be considered, as it is context specific. And most emissions occur in the production and in use stage.

2.3 Renovation scenarios

This section focuses on the sub question: ‘’what renovation scenarios for a terraced house, can be defined considering a buildings life cycle in the Netherlands?’’. This sub question focuses on investigating different renovation approaches in terms of time. In order to do this different renovation levels are described in relation to time, as well as the life span of a building and the service life of renovation measures. The section first discusses the main renovation levels in the field of renovation then dives into the execution of a renovation and at last discusses the endurance of renovation solutions.

2.3.1 Renovation levels – deep and shallow renovation

A deep decarbonization scenario of the existing building stock focuses on reducing the primary energy use through deep renovations. This can significantly reduce the energy demand of buildings and management of the energy grid (Lang, 2016). In the Netherlands this scenario can be achieved if the energy use of 45% of all buildings is lower than 190 kWh/m²/year and the use of fossil primary energy is excluded (Sibileau et al., 2021). In other words, a combination of reducing the energy demand and using renewable energy is necessary. Deep renovations are necessary to provide this energy reduction, as the argument states that deep renovation should be the standard and the aim in each renovation project (Sibileau et al., 2021)(Lang, 2016). The Netherlands Enterprise Agency, advocates for all buildings to be deep renovated by the end of 2050 (Netherlands Enterprise Agency, 2020).In policy making, the implementation of deep renovation as the mainstream renovation approach is gaining more attention.

The current pace of deep renovations is too slow to meet the set climate targets (Sibileau et al., 2021). From the 1% of renovations carried out each year, the majority accounts for shallow renovations (IEA, 2022) (Kruit et al., 2020) (Nidam et al., 2023). The risk of performing shallow renovations to the envelope is an overall low energy reduction that is fixed in the building, due to the lifetime of the envelope which lasts 40 to 60 years (Lang, 2016). In a study that compared the building stock of different regions in different countries, it was found that in all cases deep renovations are necessary to reach the short-term climate target of 2030 (Nidam et al., 2023). This suggests that the rate of renovations of existing buildings need to increase and that the majority of these renovations need to be deep renovations. In a decade from now the rate of deep renovations should account for 70% of all renovations (Sibileau et al., 2021). Based on the climate targets and the differentiation between deep and shallow renovations the following pathways can be extracted (see figure 3):

- Path 1: Deep renovation before 2030
- Path 2: Shallow renovation before 2030
- To reach 2030s targets
- Path 3: shallow renovation before 2030 deep renovation towards 2050
- Path 4: Deep renovation after 2030
- To reach 2050s targets

Path 1, 3 and 4 should account for the majority of renovations, since these foster a deep renovation by the end of 2050.

Single step and step by step

For most existing buildings, a deep renovation can’t be performed in a single step (Sibi-

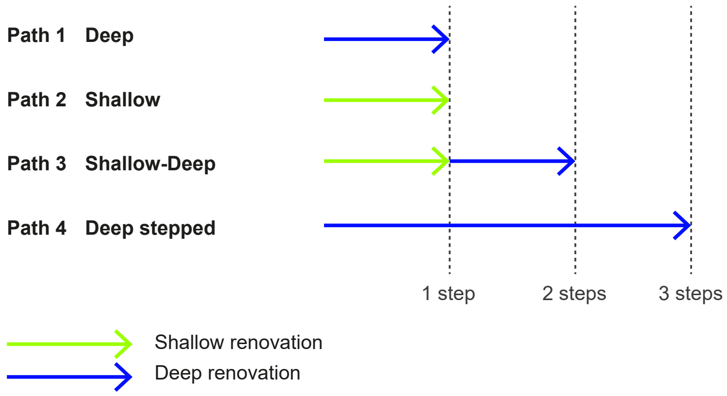


Figure 5. Generic renovation scenarios for shallow and deep renovations towards 2050 (created by author).

2.3.2 Renovation execution - single step and step by step renovation

leau et al., 2021), due to financial and logistic limitations (Lang, 2016). A solution to this obstacle is performing a ''step by step renovation'. In this approach renovation measures are not executed in one go but separately over a longer period of time, achieving the performance of a deep renovation in the end (Fritz et al., 2019) (Lang, 2016) (Maia et al., 2021) (Sibileau et al., 2021). By executing a deep renovation in steps, the high initial cost of a deep renovation is spread in time increasing the potential to foster a deep renovation when budget is a limitation. In this approach renovation takes place in several steps, positively increasing the buildings performance over time (Sibileau et al., 2021)(Maia et al., 2021). In order to guarantee the effectiveness of a step by step renovation, having a well-considered life cycle approach and long term strategy is crucial (Lang, 2016). According to Fawcett & Topouzi (2019), understanding the influence of the factor time could provide valuable insight in the different roads to renovate, and additionally help shape the energy transition.

Studies that compared step by step renovations and single step renovations, showed that both approaches can provide the same energy saving in the end, however a single step renovation results in a significant higher overall energy saving on the long term due to early establishment of the energy saving (Fritz et al., 2019) (Maia et al., 2021). This makes it efficient to reduce the time between steps to achieve an overall higher energy saving (Maia et al., 2021). A study revealed that a stepped approach containing 3 to 4 steps correlates with approximately 30% less energy saving compared to a renovation performed in a single step (ADEME, Dorémi, Enertech, 2020). The same study also revealed that excluding steps while still executing the renovation in a single go is potentially more energy efficient than a step-by-step approach. According to the study a deep renovation with a beneficial energy performance can be established in 1 to 3 steps (ADEME, Dorémi, Enertech, 2020). Regarding the Energy performance certificate in Salzburg (Austria), an amount of 3 steps is advised in step-by-step renovations (Maia et al., 2021). Due to limited budget, single measures are often carried out per step (Lang, 2016), and could be more cost-efficient when aligned with forced renovation actions in case of repair, replacement and maintenance also known as trigger points (Kruit et al., 2020) (Fritz et al., 2019). According to Sibileau et al. (2021) in a step-by-step approach with energy performance as its objective the first step should be the most impactful in terms of energy saving.

To summarize, 3 steps is an accepted number of steps in regards to energy performance, and could provide better energy performance when the time between steps is reduced and/or when the first step is the most impactful in terms of energy saving. However, the number of steps performed is highly dependent on the budget for renovation and could in practice be higher than 3 steps.

Conclusion
Due mainly to a lack of renovation budget, a deep renovation for most existing buildings can't be performed in a single go. However, a deep renovation performed in steps, is possible to achieve a deep renovation by the end of 2050, as it spreads the initial cost of a deep renovation. 3 steps have shown to be an accepted number of steps in terms of energy saving. Most studies focus on energy saving which affects the operational energy, and on the initial cost of renovation. However, carbon emissions are often not assessed within these studies, let a sight the embodied carbon. Secondly, the focus on the initial cost takes away the attention from cost related to the replacement of building components (such as the heating system, and ventilation system) at the end of their service life. Thirdly, uncertainty in energy prices for different energy sources (such as for a heating district and electricity from the grid) are not considered in the comparison of results. In summary a comprehensive assessment, that provides insight in total carbon emissions, total energy use and total cost could help in the selection of renovation strategies that satisfy the renovation objectives better.

Cost reduction strategies:
- Step by step renovation
- Planning renovation steps at trigger points

Energy reduction strategies:
- 3 steps maximum
- Most effective measure as a first step
- Reducing the time between measures

Trigger points
Planning how a step-by-step renovation will take place in the service life of an existing building is complex as there are no standard moments when renovation is performed. However, it is important to estimate the service life of renovation measures in years, as embodied carbon is calculated per year. The service life of a renovation measure is influenced by the service life of the building and when in the service life the measure is performed. It is therefore essential to plan the execution of a renovation to determine the overall carbon reduction in the end. This requires knowledge on what renovation measure will be performed at what specific time in the service life of the existing building. Trigger points represent when it is likely to undertake a renovation, and mainly relate to the availability of budget for renovation (Kruit et al., 2020). Trigger points for renovation are change of tenancy or sale of residence, non-energy related renovations (for example upgrading the bathroom or façade), change in household size (for example the arrival of a baby), and regular building check-ups. Change of tenancy and sale of renovation has the potential to promote renovation depth (Kruit et al., 2020). Another study, with a similar perspective, considers maintenance and repair as potential trigger points to enable cost efficient renovation strategies, as these offer the possibility to upgrade a buildings per-

formance through renovation, while avoiding investment in replacing building parts with similar performance compared to before (Fritz et al., 2019). Kruit et al. (2020) investigated when trigger points for most residential buildings in Europe will occur, the outcome revealed that around 2030 most house transactions will take place, and heating appliances are due for replacement (see table 3) (Kruit et al., 2020).The same research also provided an overview of trigger points and the period in which these occur, which could be used to estimate the trigger points of an existing building when insight in the occurrence of trigger points is missing. The renovation performed at this trigger point highly influences the rate and depth of renovation. Using this as an opportunity to establish deep renovations is crucial. The risk of not using this opportunity to upgrade the energy performance, is that the renovation measures performed provide low energy saving fixed to the entire service life of the measure, also known in literature as the lock-in effect.

Renovation does not only occur at trigger points but is also influenced by other factors. Renovation triggers, represent the indicators that leads to the decision to undertake an energy efficient renovation (Kapedani et al., 2017). In a study that investigated the triggers and goals of renovations from a house owner perspective, the outcome showed that a common trigger and goal for more than 50% of the participants for renovation is improving comfort and secondly energy efficiency (Kapedani et al., 2017). Environmental sustainability shows lower potential as a trigger for renovation for most house owners, and higher potential to become a goal of a renovation when house owners are already committed to renovate (Kapedani et al., 2017). In other words, energy efficiency, comfort and environmental sustainability show to be important objectives in renovation.
Comfort can be achieved through the environmental indicators such as temperature, air quality and noise (Kapedani et al., 2017).

Table 2. Trigger points and renovation triggers (data from Kruit et al., 2020).

Moments	Year
Predicted trigger points	
Change of tenancy	2038
House transactions	2030
Lifetime of infrastructure	2015
Lifetime of heating appliances	2033
Overview trigger points for renovation	Period
House transaction	29 years
Change of tenancy	18 years
Regular inspections	2 years
Heating appliances	20 years
Electric appliances	12 years
Gas distribution grid	50 years
New residential building	50 years

2.3.3 Renovation solution endurance - predicted life span

According to Andersen & Negendahl (2023) different building typologies show different life spans. As earlier explained, the life span of a building is one of the main uncertainties in LCA studies. Therefore it is important to select a specific building typology to investigate the environmental impact of a renovation. In the Netherlands the dominant residential building typology is the terraced house, accounting for 42% of the building stock (CBS, 2022). It is therefore used as a starting point in this study.

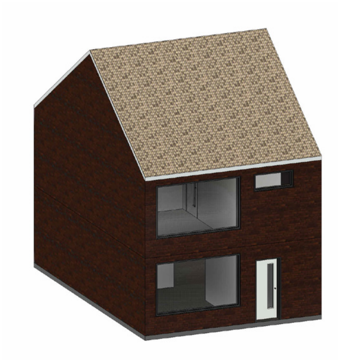


Figure 6. Typical 60s terraced house, in the Netherlands (created by author).

Most of these buildings were built between 1965 and 1986, and are referred to as ‘’jaren 60 rijtjeshuis’’ (60s terraced house) (Waard, 2021) or ‘’doorzonwoning’’ ‘’sunny house’’ (Kadastrale Kaart, n.d.). These houses can be recognized by their large windows at the front and back façade, which allows for sun to enter deeply into spaces. A sunny house has a typical width of approximately 6 meters, and a depth of 7 to 8,5 meters (Vossebeld, 2013). The structure consists of a roof constructed from wooden beams supported by brick load bearing walls, concrete separation floors and ground floor (AVANES et al., 2018). Most of these buildings were built directly on sand. The envelope consists of two leaved brick (external) walls including a cavity of 80mm, a roof constructed from wooden beams, a concrete ground floor and single glazed windows (AVANES et al., 2018). Although the described characteristics are specific to buildings in the Netherlands, it is likely that the described characteristics could also apply for terraced houses located in other countries, with similar climate conditions.

The building’s service life is of great influence in LCA studies, as it influences the results significantly and is in multiple studies agreed upon a sensitive parameter in building LCA (Vilches et al., 2017) (Andersen & Negendahl, 2023) (Nwodo & Anumba, 2019). The building lifespan used for assessment in studies varies from 50-150 years (Vilches et al., 2017). The recommended service life according to EN standards is a service life of 50 years. However, buildings could have a longer or shorter lifespan in practice. Therefore, a realistic building life span prediction is necessary to assess the environmental impact of renovation strategies (Nwodo & Anumba, 2019).

Andersen & Negendahl (2023) investigated the assessment of a building’s life span and stated that different building typologies show different life spans, multifamily houses for example have twice the life span of a single-family house. The same study found a correlation between the construction period of buildings and their life span, which seemed longer for old buildings compared to buildings constructed after 1990, in Northern Europe. According to the study this can be assigned to the historical, cultural or technical qualities of old buildings. The study concluded a predicted life span of 129 years for single family houses (Andersen & Negendahl, 2023).

Ferreira et al. (2023) notes that the service life of a building is inferior to the wishes of building owners, building aesthetics, and budget. Maintaining the uncertainty in service life of buildings. A mandatory minimum service life for buildings per typology could reduce the uncertainty in LCA and provide more valid indications of the environmental performance of a building.

Besides the service life of the building, the service life of materials used in renovation can also differ depending on the source. In energy renovations the envelope and services are mainly considered. According to Brand (1994) in general the service life of the skin is 20 years, while the service life of services is between 7-15 years (see figure 6).

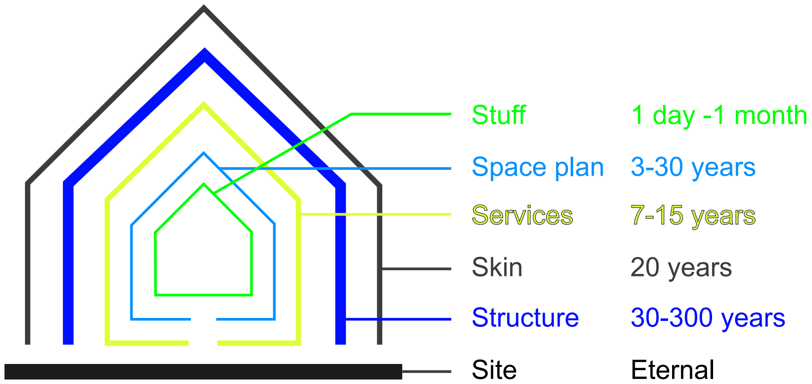


Figure 7. Layers of Brand and respective service life (Brand, 1994).

Terraced houses in the Netherlands often consist of brick leaves as the structural element in the facade, which has a life span of over 100 years (InterNACHI's standard Estimated Life expectancy Chart for homes, n.d.). This exceeds the service life as stated by Brand (1994). Stone like materials such as bricks and concrete, are recognized for their high embodied carbon. However, their long life span can on the long term result in similar emissions compared to other materials. Therefore the embodied carbon over time is greatly influenced by the life span of the material. From this can be concluded that material specific data is required to estimate the embodied carbon of renovation measures, in assessing the total carbon emissions of a building. For heating systems, such as heat pumps, gas boilers, and electric boilers a similar life span of 15 years can be estimated. The life span may be shorter or longer depending on the level of maintenance and the context.
In summary, the average building service life of a terraced house for LCA assessments can be set to 129 years. Regarding the service life of renovation measures, façade related materials should be assessed according to their material specific service life, while for services an average life span of 15 years is suitable.
This section focuses on answering the sub question: 'how can renovation strategies be created for the renovation scenarios, and which renovation measures should be included in the strategies regarding carbon emissions?'. The aim of this question is to develop strategies that aim to reduce total carbon emissions. Therefore the parameters that influence total carbon emissions need to be defined. Two levels of renovation were extracted

SHARED WALLS!
The latitudinal walls occupy the majority of the external wall surface, and connects the houses, making it beneficial to perform renovations that influence the thickness of the exeternal wall, to all houses in one go. This way joints between houses can be designed properly.

2.4 Deep renovation strategies

in section 2.2 ‘renovation scenarios’, a shallow renovation, and a deep renovation. This section describes which building parameters need to be considered in a deep renovation. The new stepped approach is used as a strategy to obtain renovation strategies with the aim to reduce carbon emissions.
This paragraph describes the requirements for renovation strategies towards carbon neutral buildings. The building stock needs to be carbon neutral by 2050, according to the climate targets. Carbon neutral buildings can be defined as buildings with low energy consumption and that use low carbon energy sources (Carruthers et al., 2013). In addition, carbon neutrality in buildings is achieved by compensating the remaining emission of the

2.4.1 Requirements for carbon neutral buildings

building by reducing emissions elsewhere, through for example investment in renewable energy, also known as carbon offsetting (European Parliament, 2023).

In policy making a deep decarbonizing scenario of the building stock is gaining popularity, which means most renovation should be deep renovations. A deep renovation provides an energy saving of 60% or more and can be achieved by at least reducing the heating demand. The remaining buildings of the buildings stock will have to undergo at least a shallow renovation that saves 3-30%. The way a deep renovation is defined differs for each country (figure 7). Although the definition differs, the aim is similar, to reduce the energy demand. To simplify, this thesis considers a renovation to be a deep renovation if an energy saving of 60% compared to the existing state is achieved. At the same time fossil fuels are depleting and need to be replaced with sustainable renewable energy sources, the energy transition. This requires traditional gas boilers in residential buildings to be replaced. In other words, renovation strategies for residential buildings towards carbon neutral buildings in 2050 need to:

- Avoid the use of natural gas;
- Focus mainly on deep renovations that provide an energy saving of at least 60%;
- And compensate for the remaining carbon emissions.

A popular approach to reduce energy demand is the three-step strategy, also known as the Trias Energetic. Tillie et al. (2009) reinterpreted this strategy to find a strategy that aims for carbon neutrality. This led to the New stepped strategy which excludes the use of fossil fuels completely and introduces a new step which focuses on the reuse of waste materials. In the same study the new step approach is translated to a building scale see figure 8.

Belgium – Flanders[34]	EPC label A (100 kWh/m²/year)
Belgium – Wallonia[35]	75-100% energy consumption reduction Czechiai
Czechia[36]	EPC label A or B (<107 kWh/m²/year, expected to be reduced to 79 kWh/m²/year as of 2022)[37]
Denmark[38]	60% primary energy consumption reduction
Estonia[39]	EPC label C (<150 kWh/m²/year)[40]
France[41]	Reference to Bâtiment Basse Consommation (BBC) Effinergie Renovation Label (80 kWh/m²/year) and to a scenario of 'rénovation performante' being equal to BBC stepwise renovation
Luxembourg[42]	Reference to renovation quality with EPC A/A to B/B and average 72% energy savings
Spain[43]	Primary energy savings > 60%
Sweden[44]	Level 3 'total energy renovation' = 50% improvement of energy efficiency for residential buildings and 40% for offices

Figure 8. Deep renovation definitions for different countries (Sibileau et al., 2021).

2.4.2 Essential building parameters for deep renovation strategies

The steps influence both the embodied carbon and operational carbon. The new stepped strategy is used to define the renovation strategies. Below is described per step how this approach has contributed to create the renovation strategies.

Step 00. Standard building
The energy consumption of a typical Dutch household is analyzed. And parameters that

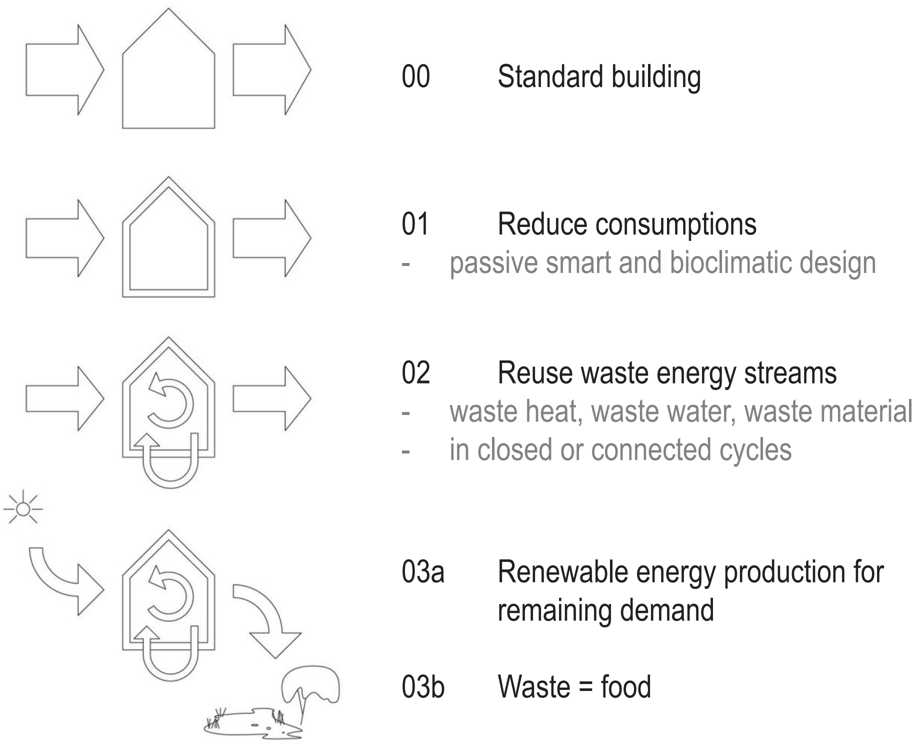


Figure 9. New stepped strategy at a building scale (adapted from Tillie et al., 2009).

influence the operational carbon the most are determined.

Step 01. Reduce consumption
The active and passive measures for renovation are determined.

Step 02. Reuse of waste streams
The reuse of the existing building materials is stimulated by incorporating renovation interventions that avoid the use of new structural materials.

Step 03a. Renewable energy generation
For the remaining energy demand, the production of renewable energy generation is limited to services that can be applied on a building scale. Photovoltaic panels are considered within this research, as this is a common approach.

~~Step 03b.Waste = food~~
Waste management is not included in the study as this could also exceed the physical building scope.

Step 00. Standard building: analysis energy use Dutch household

The objective of the energy transition is to reduce carbon emissions by reducing energy use and increasing the use of renewable energy, through renovating. To do this effectively, the most influential parameters need to be determined. The energy consumption of a Dutch household consists for approximately 32,7% of electricity use and 67,3% of gas use (Ortiz et al., 2017). In figure 9 the breakdown of the energy use of a Dutch household is visualized with percentages.
Gas consumption consists of heating (73%), domestic hot tap water (23%) and cooking (4%) (Ortiz et al., 2017).
The energy consumption of an average Dutch household is for a large part related to

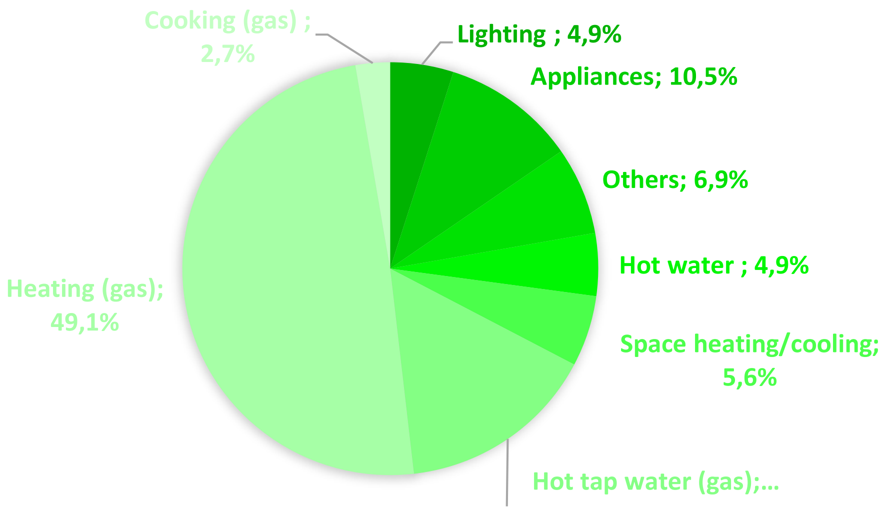


Figure 10. Dutch household energy use breakdown. Approximately, 75% of total energy use is related to heating and tap water (adapted from Ortiz et al. (2017)).

heating and tap water. Electricity consumption is largest for appliances, which can be reduced through many factors, among others implementing an energy efficient fridge, or lights. These factors are related to human needs and behavior and can vary per household. The second most influential parameter regarding electricity use is lighting. Also, lighting is related to human needs and behavior, and varies per household. Appliances and lighting both exceed the (physical) building scope and is therefore not further analyzed within this thesis. From this can be concluded that the most impactful parameters to reduce energy consumption relate to heating and tap water.
Currently natural gas is used for cooking, heating, and hot tap water. Therefore, cooking needs to be considered in renovation strategies as well to establish carbon neutral strategies. To summarize, the following needs to be considered in renovation strategies:

- Heating
- Tap water
- Cooking

Step 01. Reduce consumption: categorizing active and passive renovation measures.

This paragraph focuses on impactful measures found in literature, to define the building parameters that need to be considered in renovation strategies. As energy consumption is mainly determined by heating extra attention is given to define the building parameters that influence heating.

According to Asadi et al. (2018) heating demand can be reduced by limiting heat loss through the envelope. Heat loss of the envelope is mainly related to fabric heat loss, and ventilation heat loss. Fabric heat loss refers to heat loss through conductivity (heat transfer through layers with different mediums, for example the layers of an external wall), ventilation heat loss refers to heat loss through convection (heat transfer through escaping hot air) (Asadi et al., 2018). Fabric heat loss accounts for approximately more than 81% of total heat loss, and ventilation heat loss for approximately less than 19% of total heat loss (Najjar et al., 2019).

In a study by Venus et al. (2019), multiple packages of renovation measures were assessed to determine the energy saving of an apartment building. One package only considered envelope measures that affect the fabric heat loss including attic insulation, basement insulation, wall insulation and window replacement. Other packages also considered mechanical ventilation and reduced infiltration. For all packages at least 60% energy saving was achieved (figure 11). In other words, a renovation strategy that considers the envelope, ventilation and infiltration has the potential to provide 60% energy saving. According to the study of Najjar et al. (2019) fabric heat loss is 51.5% related to windows, 19,87% to external walls, 15,75% to the ground floor and 12,88% to the roof. The study of Venus et al. (2019) considered similar envelope elements, to achieve a high energy reduction. In other words, envelope elements that should be considered in deep renovation strategies are windows, external walls, the ground floor and the roof.

Two main approaches in building renovations can be distinguished: technical system measures (changing the services) (1) and envelope measures (such as adding insulation to envelope elements) (2) (Maia et al., 2021). Envelope measures are considered passive measures and can be organized by envelope element, studies include roof, external wall, windows, and ground floor (Konstantinou, 2014) (Maia et al., 2021). Technical system measures are considered active measures and contain among others the parameters:

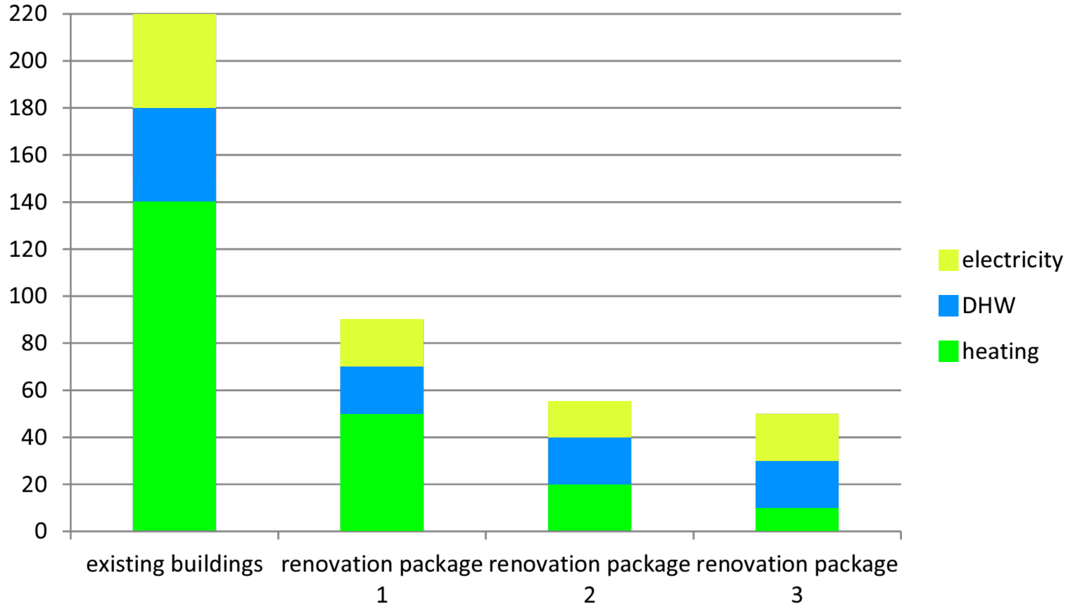


Figure 11. Potential energy saving, for renovations that consider at least envelope measures; attic insulation, basement insulation wall insulation and new windows, and additionally parameters ventilation and infiltration (Adapted from Venus et al., 2019).

domestic hot water, heating, mechanical ventilation, and lighting (Maia et al., 2021).

Reducing the energy demand through upgrading the envelope is a strategy that affects the operational carbon. The use of new materials and disposal of old materials however affects the embodied carbon. As earlier explained, a deep renovation provides an energy saving of 60-90%, demanding a significant upgrade of the envelope, resulting in higher material use and thus a higher embodied carbon.

Step 02. Reuse of waste streams

The reuse of existing building materials will be stimulated by limiting the demolishing of building elements and avoiding measures that require the use of new structural materials (further explained in 2.4 Renovation measures). Within this thesis the reuse of existing building materials is not considered, as this exceeds the scope of the research, further research is needed to investigate the possibilities to extend the life cycle of (initial) replaced building elements. Waste heat and waste water are also not considered, as the focus of the research lies on conventional renovation measures.

Step 3 a. Renewable energy generation

Renewable energy generation is a strategy to compensate for the remaining energy demand. On a buildings scale, photovoltaic panels are commonly used to generate energy, and therefore considered in this research.

Essential building parameters

The impactful building parameters defined by applying the stepped approach for deep renovation strategies are presented in table 3. And organized by technical system measures and envelope measures.

Building parameters deep renovation strategies	
Envelope measures (passive strategy)	**Technical system measures (active strategy)**
Roof	Domestic hot tap water
External wall	Heating
Windows	Mechanical ventilation
Ground floor	Energy system
Infiltration	

Table 3. Impactful building parameters that need to be considered in renovation strategies towards carbon neutral buildings. The parameters are categorized by envelope measures and technical system measures.

2.5 Renovation measures for a deep renovation

This section continues to address the sub question introduced in the previous chapter: 'how can renovation strategies be created for the renovation scenarios, and which renovation measures should be included in the strategies regarding carbon emissions?'. The objective of this question is to gain insight into how strategies can be formed that aim to reduce total carbon emissions and which renovation measures are essential to include in renovation strategies to meet the objective. In this section the focus lies on defining these essential renovation measures that aim to reduce carbon emissions.

In 2.2 ''whole life carbon'' is mentioned that carbon emissions can be divided into two categories, operational carbon emissions (related to energy use) and embodied carbon emissions (related to the use of materials), of which operational carbon emissions account for most carbon emissions in existing residential buildings and has a higher priority. As the measures to reduce emissions related to the two categories differ, this section is divided into two sections, 'renovation measures-operational carbon' and 'renovation measures-embodied carbon'.

2.5.1 Renovation measures - Operational carbon

The operational carbon accounts for the majority of carbon emissions and is a key factor in reducing carbon emissions over the full life cycle of the building. In chapter 2.4 renovation strategies, is described that the operational carbon is influenced by measures regarding the envelope (A) and technical services (B).

A) *Envelope measures*

There are different renovation interventions available for the roof, external wall, windows, and ground floor. Konstantinou (2014) categorized renovation interventions in: wrap it, add-in, replace, Add-on and cover-it (figure 12).

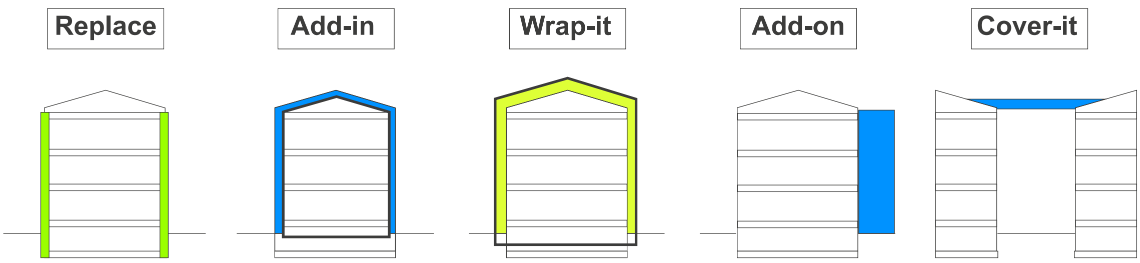


Figure 12. Categorizing interventions to the envelope (adapted from Konstantinou, 2014).

Add-on and cover-it, consist of adding new structural elements, for example adding a second façade, which requires a secondary structure, or adding a connecting roof, which requires an additional roof structure. In this thesis the deep renovation strategies focus on using as much of the existing materials as possible and avoiding the use of structural materials to limit carbon emissions. Therefore the interventions add-on and cover-it will not be explored. Also, these interventions require specific knowledge and skills, therefore the implementation of these interventions is less convenient. Nevertheless, these interventions have the potential to help establish a deep renovation and could still be a potential option in renovation practices.

In this study the focus lies on the renovation interventions ‘’wrap it’’, ‘’add-in’’, and ‘’replace’’. Replace, refers to replacing existing façade elements with new ones, this could be a complete replacement, or partial replacement of the façade, such as replacing the windows. Add-in refers to upgrading from the inside, through internal insulation, cavity insulation, or a box window. Wrap-it refers to wrapping the building with new elements, this refers to external insulation and a second skin façade. As earlier mentioned, measures that require structural materials are not considered, so a second skin façade is not investigated.

The envelope measures aim to reduce heat loss and thus target the operational energy. According to the study of Konstantinou (2014) adding insulation of the same thickness either inside or outside, results in the same heat resistance as this is defined by the Rc value. In other words, the placement of the insulation does not influence the heat resistance of the wall. Therefore in this study there is no difference made for where the insulation is applied, as this results in the same reduction in operational carbon and energy.

Technical constraints

Upgrading the envelope insulation requires space at roof level, and could require an extension of the roof, when a roof overhang is not available (Dodoo et al., 2017). For example, if external insulation is added to the wall, it becomes thicker, and needs to be covered at the top, so water doesn’t enter the cavity. Buildings built in the 60s are equipped with a gable roof, and usually don’t possess an overhang. It is likely that an extension of the roof is required when insulation changes to the external wall are made.

If the objective is to reduce infiltration (heat loss related to gaps at joints of building elements) there are several technical constraints to be considered. Internal insulation does not affect the joints of building elements and therefore has limited effect on the heat loss related to the airtightness of connections of building elements. To reduce infiltration effectively, outside insulation is more effective, as it offers the possibility to continuously apply the insulation and thus reduces cold bridges.

Obviously, it is context dependent if building elements can be upgraded independently, but from this discussion can be stated that upgrading the envelope in one go is in technical terms the most beneficial. If technical constraints such as limited overhang and insulation that can only be applied on the inside are present, the following can be done to reduce technical complications: upgrading the roof and integrating a sufficient overhang (1), upgrading the external wall in combination with the windows to reduce infiltration (2). However, to simplify the study, only upgrading the envelope in one go is considered.

Practical constraints

High energy saving can’t be achieved with limited insulation, such as cavity insulation, and is therefore not considered a deep renovation. Also, when external insulation is applied it is unlikely that cavity insulation is needed, as this requires extra costs, disrupts the occupants of the building, and can be easily compensated for by applying thicker external insulation.

Renovation interventions assigned to building elements.

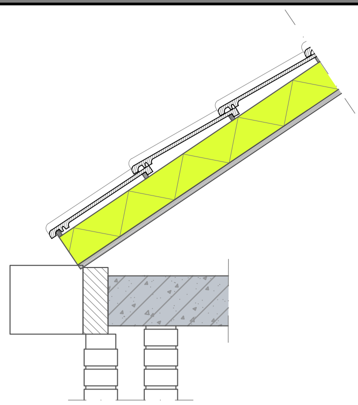
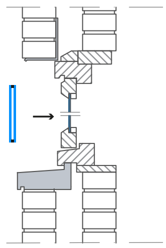
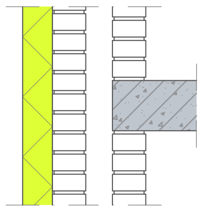
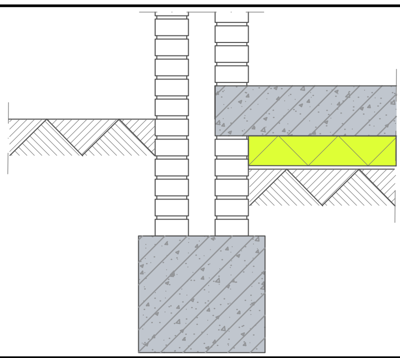
The renovation measures extracted from the renovation toolbox of Konstantinou (2014) besides the measures mentioned in technical constraints, that don’t include structural elements, and are convenient are:

- Window replacement (replace);

- Adding Cavity and internal insulation, (Add-in);
- Adding external insulation (Wrap-it).

The renovation interventions are assigned to envelope elements in table 4.

Table 4. Renovation measures to consider per building element in deep renovation strategies, to strategically reduce operational energy.

Envelope element	Renovation measure
Roof **Renovation measure:** Insulating the roof. **Renovation intervention:** adding internal or external insulation.	
Windows **Renovation measure/ in-tervention:** Replacing the existing windows.	
External wall **Renovation measure:** Insulating the wall. **Renovation intervention:** adding internal or external insulation.	
Ground floor **Renovation measure:** In-sulating the ground floor. **Renovation intervention:** adding internal or external insulation.	

Note: box windows, 2nd skins, overhangs to create an atrium, are not included. But could be an option. This research excluded these options and only looks at conventional approaches that are generic and applicable for the gross of terraced buildings built in the 60s with

minimum technical complications.
The performance of envelope measures regarding insulation is dependent on Rc value of the insulation layer. Depending on the material and thickness of the material different Rc values can be obtained. Different Rc values are recommended in renovation, by different sources. The different levels found are presented in table 9, chapter 3. A minimum level of insulation recommended for (intensive) renovations is provided by the building code. The Dutch enterprise agency recommends a moderate insulation level for new construction and a high insulation level as target value for a sustainable renovation in buildings. It also recommends a minimum insulation level for sources with a low supply temperature (50^{o}C).

Technical services measures

Ventilation – ventilation heat loss
Natural ventilation is the supply and exhaust of indoor air, through openable windows, and vents. This allows heat to escape the room. A study revealed that the heating capacity can be reduced significantly when the Air Change per hour (AC/h) is reduced (Gao et al., 2022). The AC/h can be influenced by ventilation systems. Ventilation system D offers the possibility to control the AC/h by a preprogrammed AC/h value, which prevents over-ventilation, through mechanically controlled air supply. According to Schell & Int-Hout (2001) another approach is to control air change with CO_2 sensors, CO_2 can be used as an indication of the occupancy of a space. This way standards on ventilation rates per person can be maintained, while excessive ventilation is avoided. Compared to a fixed AC/h value, CO_2 based ventilation offers more precise ventilation rates according to the use of a space, and therefore only ventilates when there is a need. In renovation practice ventilation system C is more commonly applied compared to system D, as in practice system D can be difficult to implement in existing buildings (WoonWijzerWinkel, 2023). Ventilation system C combined with CO_2 sensors offers the possibility to regulate the AC/h, without introducing extra ducts.

The AC/h is complex to estimate for naturally ventilated spaces. Natural ventilation allows high air changes per hour of 20-50, which can cause significant heat removal (Zhivov et al., 2020). Natural ventilation affects the heat load and can be adjusted by building occupants (Zhivov et al., 2020), causing high uncertainty in the air change rate used in calculations to estimate the energy use. A review of ventilation AC rates in European buildings concluded that naturally ventilated buildings are poorly ventilated (Dimitroulopoulou, 2012). The same study revealed the mean value for naturally ventilated residential buildings in the Netherlands to be 0,6 AC/h, and for mechanically ventilated buildings (balanced) 1,2 AC/h. Although ventilation system C and D offer the possibility to regulate air change, for most buildings this measure will increase heat loss related to ventilation, since existing buildings are under ventilated. The study also didn’t find a correlation between the exhaust volume and the ventilation rate, suggesting that the air change rate is more influenced by the operation of windows instead of the ventilation system. Although the implementation of ventilation system C and D don’t necessarily reduce heat loss, regulating the ventilation supply and exhaust is still beneficial as it provides a healthier indoor environment and increases comfort (Dimitroulopoulou, 2012). Also regulating the air supply, has the potential to avoid overventilation and make ventilation related heat loss measurable, and thus reduces the uncertainties in the actual heat loss related to ventilation. In this study an AC/h of 0,6 is used to calculate natural ventilation.

Ventilation system C
This ventilation system consists of natural air supply, through opening windows and mechanical air exhaust at the kitchen, bathroom(s), and toilet(s). This creates more comfort as it reduces the need to open windows due to uncomfortable smells or humidity and could additionally have a positive effect on heat loss reduction. However, the air supply is regulated manually and dependent on user behaviour, therefore the uncertainty in AC/h remains. As this system is still dependent on user behaviour, calculated reduction of heat loss related to ventilation system C are not representative for the actual heat loss. Although system C has the potential to reduce heat loss, due to the uncertainties this system is excluded in this study.

Ventilation system C + CO_2 based air supply
Ventilation system C with CO_2 sensors, compared to regular ventilation system C, has the potential to regulate the air supply without the need to implement extra ventilation ducts. In this system CO_2 levels are used as a measure of the occupancy, with the idea of measuring how many occupants are ‘’exhaling’’. The air supply is regulated through ventilation grills above windows, that are operated by a mechanical control system, which measures the CO_2 levels in a room. CO_2 sensors reduce heat loss, by regulating the AC/h. The AC/h can be estimated in different ways. According to the Belgium standard NBN D 50-001 (1991) the fresh air supply can be roughly estimated by the rule of thumb:

Fresh air supply = 3,6 (m3/h) x floor area (m2)
For the studied case building with a floor area of 129 m^2 this results in a fresh air supply of 464 m^3/h. The volume of the building is roughly 438 m^3, which gives an AC/h of (464/438=) 1,05. For operational energy calculations an AC/h of 1,05 is used, note that this number does not define the occupancy and is used as a rough estimation to assess the impact on heat loss of the different ventilation systems.

Ventilation system D (heat recovery)
Ventilation system D consists of mechanical air supply and mechanical air exhaust. Air supply can be regulated by a fixed AC/h, therefore the same AC/h estimated for ventilation system C with sensors is used to calculate the impact of this system. Different from system C, this system preheats fresh air and reduces heat loss significantly. According to Pecceu & Caillou (2019) efficiency of the heat recovery system is between 70-90%. In this study 80% is used in calculations. Which means that only 20% of the incoming air must be heating. As a downside, the implementation of this system can be difficult in practice and result in higher costs compared to system C.

Infiltration
In the standard NTA 8800 Infiltration is defined as the air exchange that takes place through seams and cracks of a building’s envelope and ventilation services. Infiltration is particularly high in old buildings, that are less airtight. Although an infiltration rate of 0,4 L/s.m2 (0,55 AC/h) is used in regulations, a better representative for buildings built in the 60s is an infiltration rate of approximately 0,8 L/s.m2 (Alavirad et al., 2022, p. 8). For a floor area of 129 m^2 this corresponds with an air supply of 279m3/h. Considering the volume 438 m^3 of the case study, this gives an AC/h of 0,6. Infiltration is affected by construction of and between building elements, such as internal roof connections, roof to

wall connection, window to wall connection and ground floor connections among others (NTA 8800). According to NTA 8800 renovating a single element is insufficient to improve air tightness. Renovation performance calculations that include infiltration should only consider significant changes when the whole envelope is renovated in one go. A moderate decrease in infiltration rate is assigned to renovation strategies that include wall and roof renovation in a single step, as this accounts for a large portion of the envelope and therefore has the potential to reduce infiltration significantly. For a moderate renovation an infiltration rate of 0,3 Ac/h is used and for a high renovation 0,2 Ac/h (Wahi et al., 2022).

Energy system (heating and hot tap water)
Most houses in the Netherlands contain a conventional gas boiler for heating and domestic hot tap water. Due to the energy transition a change in energy source is required. The prediction is that in 2050 in the Netherlands, 50% of the houses will be heated with district heating and the other 50% with heat pumps, of which 25% will be all electric and 50% hybrid, using clean gas and electricity (Beckman, K. & van den Beukel, J., 2019). The effects on carbon emissions of district heating are dependent on the energy sources used for district heating, and how the embedded carbon is compensated for to construct the system on a regional scale. Further research is needed to estimate the performance of district heating on carbon emissions now and over a longer span of time. The use of energy sources is not set in stone. Other sources such as an electric boiler could also be used to satisfy the heating demand. Blarke (2012) compared electric boilers and heat pumps. The results of the study revealed that heat pumps are more efficient and thus more cost effective, as the energy consumption is lower. Additionally, a heat pump could also cool (Blarke, 2012). However, an electric boiler is lower in investment costs (Blarke, 2012) and could for this reason be considered in renovation strategies.

Domestic hot tap water
The energy use for hot tap water is not only determined by the energy system, but also by other aspects. The distribution of water correlates with the flow rate of water, and can be influenced by the design of shower heads (Alkhaddar et al., 2007). Therefore, the design of a shower head is a major factor in reducing water use, while maintaining satisfying showering experiences among users. Alkhaddar et al. (2007) concluded that decreasing the water flow rate, isn’t desired without replacing the shower head. Therefore, the flow rate can be determined by the shower head. 3 shower heads/ flow rates can be distinguished: a rain shower head, a standard shower head, and a water efficient shower head (see table 5).

Tabel 5. Showerheads and there average water flow rate in Liters per minute (data from Adeyeye et al., 2017).

Shower head	Average water flow rate (L/min)	Used in calculations
High-flow shower head (rain shower head)	>9	13L
Medium-flow shower head (conventional)	7-9	8L
Low-flow shower head (water efficient)	5-7	6L

In the Netherlands 50% of the people use standard shower heads, 39 % water efficient shower heads, and 24% rainfall shower heads (CBS, 2023). The average shower time of a Dutch person is 7.4 minutes, and higher for the age group 15 to 24 years (CBS, 2023). In other words the volume of water needed for showering varies for each household size, and is dependent on their shower behavior and their preferred shower experience. The water volume needed for showering, can be determined with equation (0):

$$V = P \times t_{shower} \times Q \quad (0)$$

Where:

V represents the volume (m3)
P represents the amount of people showering per day
Q represents the flow rate of the shower head (L/min)
t represents the time (min)

Equation (0) represents the volume estimated by the product of amount of showers per day, shower time and flow rate of the shower head. The average volume needed for different household sizes based on an average shower time and standard shower head are presented in table 6. Assuming a maximum occupation of 4 people (parents and 2 children) for a terraced house.

Tabel 6. Estimated tap water volume, for different household sizes (2,3 and 4 people) based on the average shower time in the Netherlands and average flow rate of a standard showerhead.

Household size	Shower time (min)	Flow rate (L/min)	Volume (L)	Volume (m3)
2	7,4	8L	118	0,118
3	7,4	8L	178	0,178
4	7,4	8L	237	0,236

2.5.2 Renovation measures – Embodied carbon

The embodied carbon refers to the carbon emissions embedded in materials. In renovation materials are used in the envelope and services and can thus be distinguished in envelope materials and services materials. The embodied carbon is in practice estimated in CO_2e (Europe, EN standards) which refers to all greenhouse gas (GHG) emissions in relation to CO_2 (De Wolf et al., 2017), also referred to as the global warming potential (GWP) estimated in $kgCO_2eq$ (Bruce-Hyrkäs, n.d.). Data on the embodied carbon of materials and products varies, and reliable data is not available for all products and materials (De Wolf et al., 2017), the database used to estimate the embodied carbon therefore needs to be carefully selected. Data should be related to the location of the project, frequently updated and transparent (De Wolf et al., 2017), tools that enable the use of data of a specific location and use up to date data are therefore more reliable, such as One Click LCA. As the objective of the research is to reduce total carbon emissions over the full life cycle of the building, related to renovation strategies, only the embodied carbon related to renovation measures are focused on. The following paragraphs dive into the embodied carbon related to envelope materials (A) and services materials (B), to investigate which components impact the embodied carbon the most.

A) Envelope materials

To create renovation measures that reduce GHG emissions effectively, the components which are most responsible for the emissions need to be investigated. The production of materials in combination with the volume in which the material is applied determines total carbon emissions. The study of Longo et al. (2021) showed that the contribution of building elements to GHG emissions are highest for the ground floor (1), followed by the external walls (2), the windows (3) and the roof (4). The data is based on the assessment of the whole building element, including structural materials, which explains the higher GHG emissions related to the ground floor. In other words, the embodied carbon results are highly influenced by the inclusion of structural materials.

Secondly, building dimensions also influence the amount of material used and could thus vary for residential buildings. On the contrary, analysis of the materials used per building element (such as roof) does provide interesting results, as these proportions vary less per m1 for residential buildings. Further analysis of each building element by Longo et al (2021) showed that apart from the structural elements, in the roof the waterproofing membrane has a high contribution to GHG emissions followed by insulation and tiles. While for external walls insulation contributes most to GHG emissions, followed by gypsum which is negligible compared to the impact of insulation. A significant difference in GHG emissions was obtained using cellulose instead of XPS (Longo et al., 2021). And last, the external walls and windows contribute more to the emissions compared to the roof. The emissions related to the ground floor could not be obtained from the information in the paper but stating that only insulation is added and the surface being smaller than the external walls the contribution to GHG emission is probably lower than the windows and external walls and similar to the carbon emissions related to the roof, as these elements will have similar dimensions. To summarize, avoiding renovation that includes replacing the structural elements results in less carbon emissions. Secondly, the external walls and windows contribute most to GHG emissions, compared to the ground floor and the roof. Overall, insulation is responsible for a large portion of GHG emissions excluding structural materials.

Insulation materials

As earlier stated, the embodied carbon is mainly influenced by the insulation material. There is a wide range of materials on the market. Which is categorized by Konstantinou (2014) by organic, mineral, oil derived or other material. Another study organized insulation materials by the categories conventional, alternative, and advanced (Füchsl et al., 2022). The results of both studies is merged in table 7.

Table 7. Insulation materials organized by the materials properties organic, mineral, oil derived and other (data adapted from Konstantinou (2014)). In colors conventional, alternative and advanced options are marked (data adapted from Füchsl et al., 2022).

Organic	Mineral	Oil derived	Other
Flax	Rock wool	Expanded polystyrene (EPS)	Vacuum insulated panels (VIP)
Hemp	Glass wool	Extruded polystyrene (XPS)	Transparent insulation
Wood fibers	Mineral foam	Polyurethene (PUR)	
Wood-wool boards	Perlite		
Cork	Cellular or foam glass		
Reeds	Aerogel		
Sheep wool			
Cellulose			

Alternative
Conventional
Advanced

No colour = no information available

As the study focuses on conventional renovation measures, the conventional insulation materials are focused on. Furthermore, insulation materials can be selected on also among other costs, thickness, moisture properties, environmental impact etc. To obtain a variety of material performances, in perspective of environmental and economic objectives linked to renovation, cost-effective insulation options, and sustainable options are selected. Currently, cost effective insulation materials are dominating the market, in particular glass wool and stone wool for approximately 58% in Europe (Grazieschi et al., 2021). These are both soft insulation materials, the other insulation materials on the market are mainly hard insulation materials such as EPS, PUR/PIR and XPS (see figure 13).

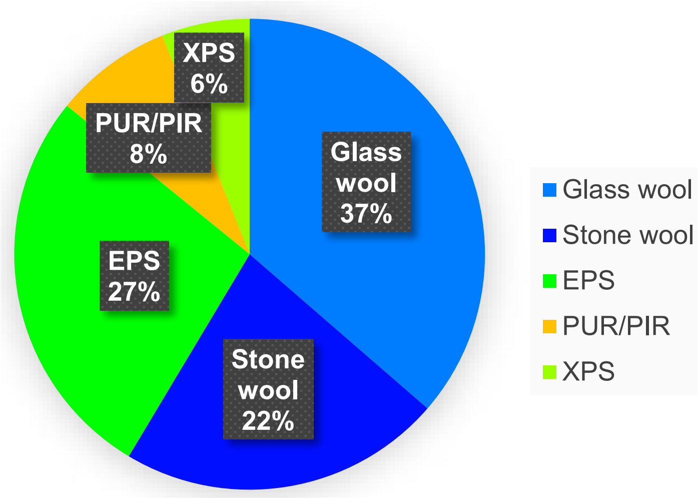


Figure 13. Insulation materials dominance (in %) in the market (Grazieschi et al., 2021).

Hard insulation is flexible in application, as it can be cut without the risk of losing its properties and comes in panels (Schiavoni et al., 2016). Therefore, in some cases hard insulation might be preferred. Within this study variety is obtained by focusing on one soft insulation material and one hard insulation material, in particular the market leading options glass wool and EPS. Both EPS and glass wool can be used as cavity insulation (Solvari, 2023). To be able to compare cost effective materials to materials that perform better on environmental objectives a low carbon organic material is considered as a renovation measure as well. Wood fibers, wood-wool boards, cork and cellulose are all conventional and organic materials (see table 8). Further analysis of these materials show that wood fibers low density and wood fibers high density or also known as wood-wool boards differentiate highly in CO_2 emissions. Also, the data reveals that besides wool fibers, cellulose is the second-best performing material on low carbon.

Table 8. Overview of conventional organic insulation materials.

Organic insulation materials	Embodied energy (Mj/kg)	CO_2 emissions (Kg CO_2 eq/m2)
Wood fibers	17	1,8
Wood-wool boards	10,8	10
Cork	26	43,8
Cellulose	7,6	4,6
	(Konstantinou, 2014)	(Kunič, 2017)

Some materials are more often used for specific building elements. From the organic insulation options cellulose is more commonly used for floors and roofs, while for external walls wood fiber is more commonly used (Milieu Centraal, n.d.). Both materials can be used as cavity insulation, and both options are possible renovation measures. However to simplify the assessment only cellulose is considered in the assessment of renovation strategies.

Insulation materials assessed:

1. Conventional soft insulation: glass wool
2. Conventional hard insulation: EPS
3. Low carbon: cellulose (in case of cavity) and wood- wool boards (as add-on insulation)

B) services materials

The earlier described renovation measures regarding building services, that should be considered in renovation strategies are ventilation, the heating system, and photovoltaic panels. The carbon emissions related to these measures are obtained from One Click LCA. The data is filtered on the Netherlands, generic data and LCA database, to obtain generic data for the Netherlands. The calculation period was set to 1 year. The results are presented in figure 14.

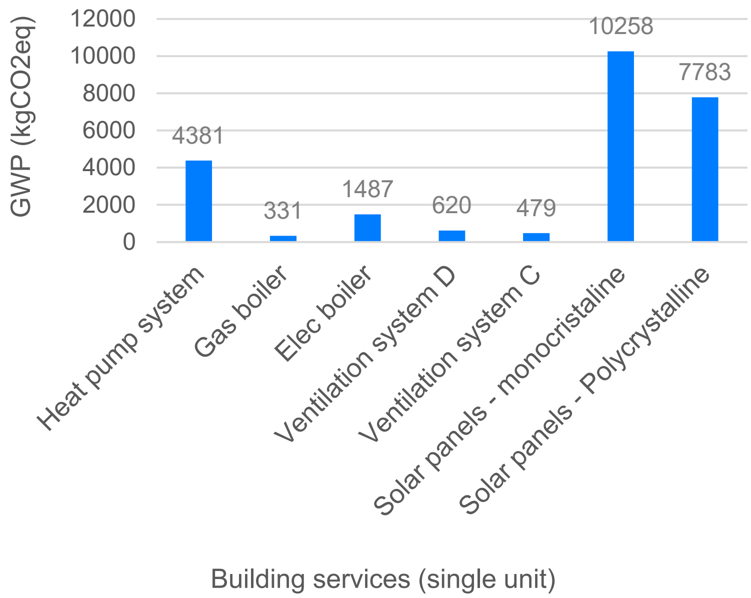


Figure 14. Embodied carbon in kgCO_2eq for different building services in a single unit considered in renovation strategies are presented (data from One Click LCA).

Figure 14 shows that the embodied carbon emissions is significantly higher for solar panels compared to other building services. Among the other building services assessed, the embodied carbon emissions related to a heat pump are significantly higher.

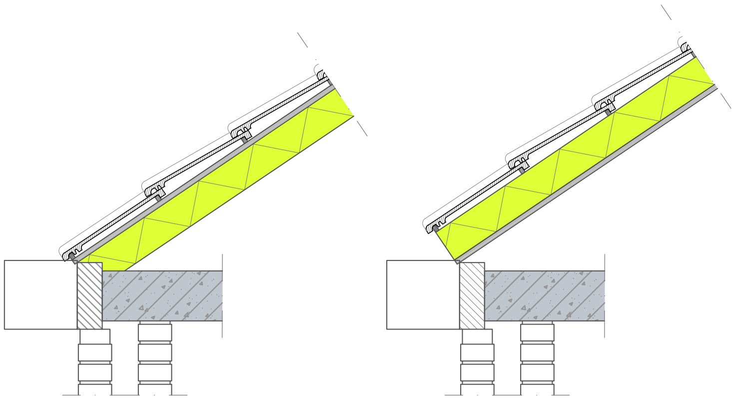
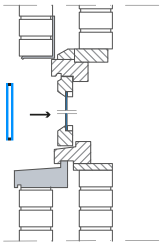
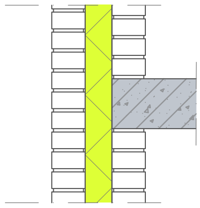
2.6 Shallow renovation strategies and measures

A shallow renovation provides an energy saving of 3-30%. In literature there is no clear definition of a shallow renovation in practical terms. In this paragraph multiple perspectives are described to determine measures that are likely to be undertaken in a shallow renovation. On a broad scale, shallow renovation is an approach to establish the energy transition through limited renovation measures (Zhivov& Lohse, 2021). This differs from the deep renovation approach, that aims to reduce energy demand. Using renewable energy sources in old buildings with a high heating demand, often requires reducing the heat loss of the envelope (Galimshina et al., 2021). Among envelope measures, highest heat loss is related to the roof, followed by the external walls and the ground floor (Alavirade et al., 2022, p. 8).

Another study defined shallow renovation through renovation measures with low investment costs, including external wall insulation and replacing window glazing. The study also revealed that shallow renovation measures often don't reach a return of investment financially (Semprini et al., 2017). The risk for this is especially high when limited energy saving is achieved, for example by applying limited insulation, which is the case for cavity insulation as this is determined by the size of the existing cavity. Another measure would be to add a glass pane to an existing window in case of single glass, this is however not possible when the size of the frame is not thick enough, it is therefore excluded in this study. However, replacing the windows is a measure that is often considered by building owners, when an initiative to renovate is present (Kapedani et al., 2017).

In the study of Galimshina et al. (2021) that investigated the optimal environmental and cost-effective renovation measures for buildings with a high and low heating demand, the heating source was in both cases selected as the measure that reduces the greenhouse gas emissions the most. Differentiating from buildings with a low heating demand, the optimal environmental and cost effective solution for buildings with a high heating demand also include envelope measures. In both cases replacing the existing double glazed windows, in terms of costs and environmental impact, revealed not to be an optimal renovation measure. In other words the most cost effective measure also depends on the current state of the building, and it's current energy performance. In table 9 an overview of the renovation interventions and the measures is provided for a shallow renovation.

Table 9. Renovation measures for a shallow renovation regarding the envelope, organized by envelope element.

Envelope element	Renovation measure
Roof **Renovation measure:** Insulating the roof. **Renovation intervention:** adding internal or external insulation.	
Windows **Renovation measure/ intervention:** Replacing the existing windows.	
External wall **Renovation measure:** Insulating the wall. **Renovation intervention:** adding cavity insulation.	

For the insulation level of shallow renovation measures minimum insulation is considered (see table 9).

CHAPTER 3| Renovation strategies

This chapter provides an overview of the renovation strategies extracted from the literature review. It is mainly an interpretation of the results obtained from the literature, and serves as a starting point for the performance assessment in later chapters.

The purpose of the chapter is to answer the sub question: How can renovation strategies be created and which renovation measures should be included in the strategies regarding carbon emissions?

The chapter starts with an introduction, which elaborates on the methodology used to compile renovation strategies. Then provides a brief explanation of the building typology of focus. Followed by an overview of the renovation measures considered, and ends with an overview of the renovation strategies that are further assessed on their performance in later chapters.

3.0 Introduction

Formulating renovation strategies, such as insulating deeply and replacing the windows, is complex as there are many levels of renovating a building. However, through defining a renovation strategy, the performance of a building after renovation can be assessed. Assessing multiple renovation strategies, enables the comparison of different renovation options on their performance, which supports decision-making for suitable renovation strategies.

To answer the sub question: How can renovation strategies be created and which renovation measures should be included in the strategies regarding carbon emissions?, a methodological approach was used (figure 14). The literature study provided insight on a representative building typology, and renovation measures that aim to reduce carbon emissions and are convenient for a shallow renovation and deep renovation. The data is further processed to create a scheme of renovation measures with specific criteria, to enable the estimation of the performance of a terraced house, when renovation measures are performed. The renovation measures can be combined in various ways resulting in various renovation strategies with different performances. The combination of renovation measures are translated into a scheme to provide a clear overview of the renovation strategies obtained.

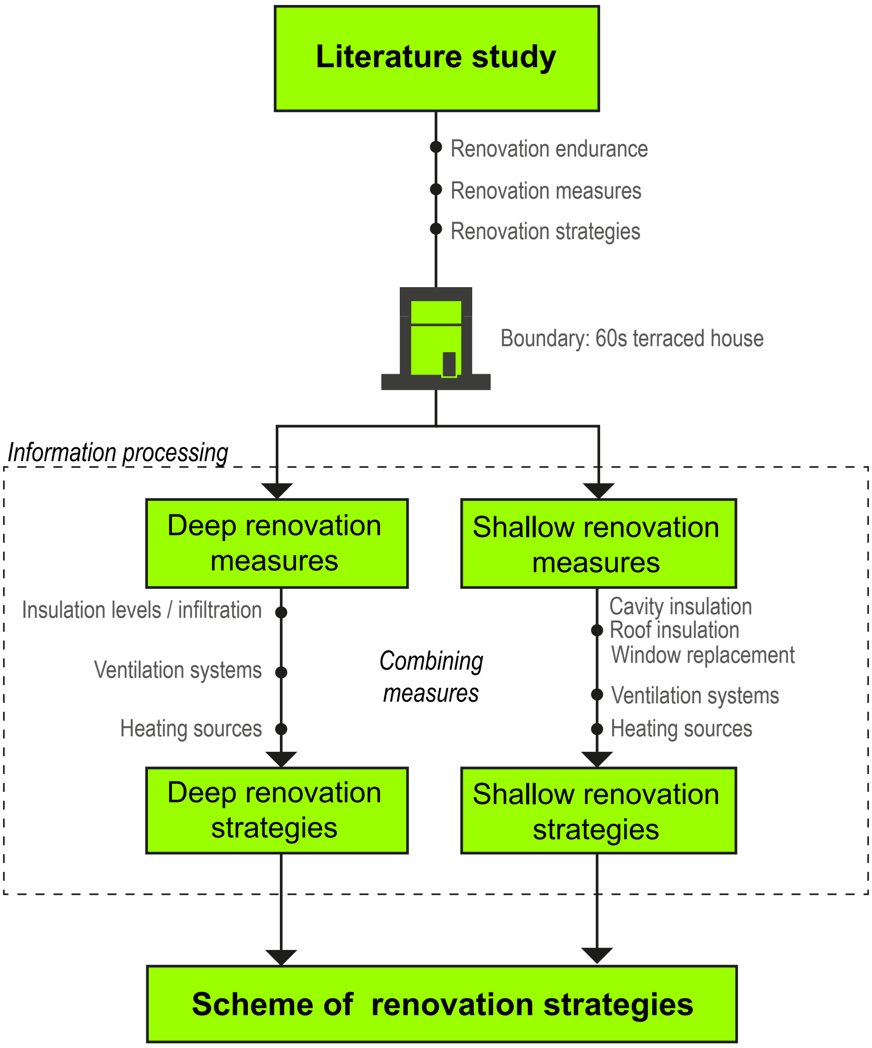


Figure 15. Methodology in generating renovation strategies.

3.1 Representative terraced house

Representative 60s Terraced house - characteristics

The performance of a renovation strategy varies per building typology, due to different building characteristics and its life span. To simplify the study only a single building typology is focused on, a typical terraced house accounting for the majority of residential buildings in the Netherlands (figure 16).

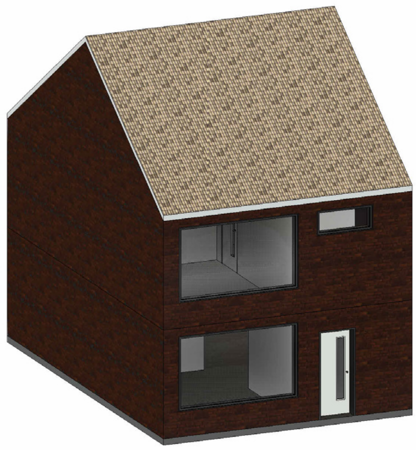


Figure 16. Typical 60s terraced house, in the Netherlands (created by author).

Building life span

According to the literature review the service life of a single family house is predicted to be approximately 129 years. The selected terraced house was built in 1966 and will according to the theory reach the end of its service life in 2095. In figure 17 the time line of a typical terraced house is sketched. In this time line the first trigger point for renovation and the climate target for 2050, obtained from the literature study are displayed.

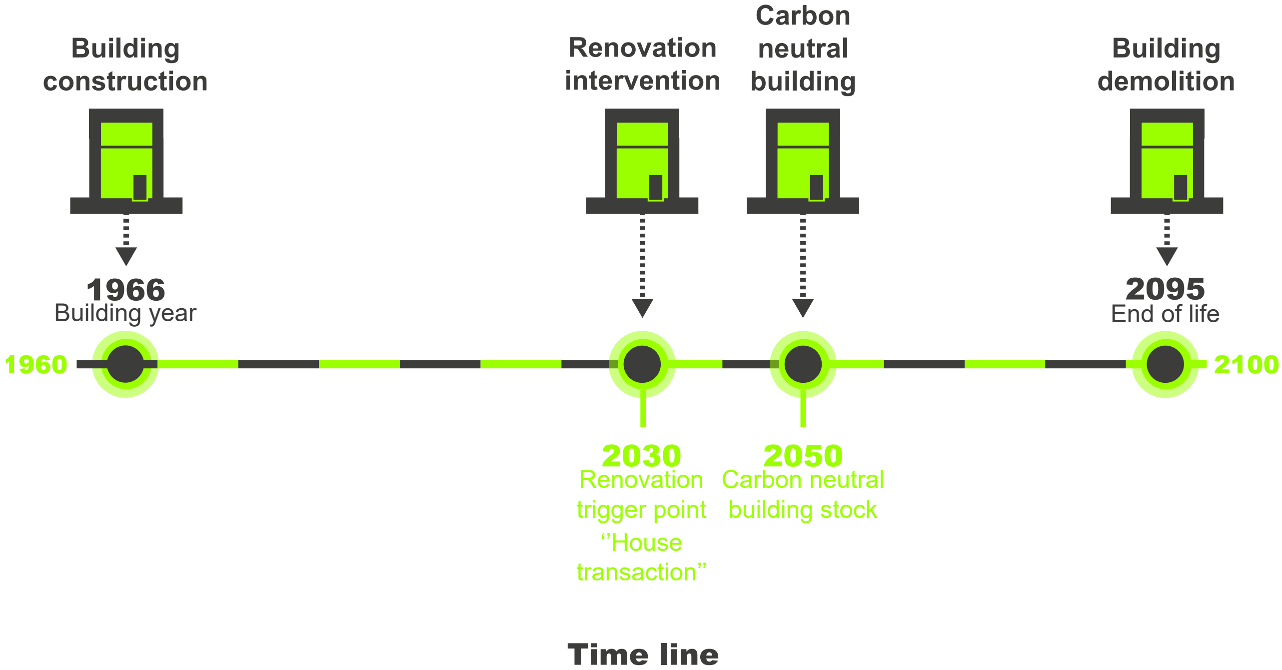


Figure 17. Time line sketch of a typical terraced house (created by author).

Building characteristics - state of the building

Building characteristics determine the performance of a building significantly. Selecting a representative terraced house is crucial. Prior to the selection multiple terraced houses located in the Province South-Holland were observed on architectural features such as shape, window positioning and dimensions, roof type, additional features such as dormers, balconies and canopies, and positioning towards other terraced houses (see appendix A). The analysis reveals that standard architectural features comprise a gable roof without dormers, window openings in latitudinal walls, and due to shared walls the majority are middle houses rather than corner houses. A representative building with the described features is shown in figure 16 and the floor plans are visualized in figure 18.

Figure 18. Floor plans and elevations of a typical 60s terraced house in the Netherlands (created by author).

A detailed overview of the characteristics of the building is provided in table 10. In its original state the building envelope is uninsulated and contains single glazed windows, resulting in a high energy demand. Domestic hot tap water demand and heating demand are satisfied by a gas boiler. Conventional heating appliances for a gas boiler are high temperature (70-90°C) water-based radiators.

Table 10. Building characteristics (original state).

General data		Source
Building type	Single family house	
Building year	1966	
Surface Area	129 m2	
Volume	438 m3	
Internal heat gain	4,5 W/m2	
Structure		
Inner load bearing walls	100mm bricks-40mm cavity–100mm bricks	(AVANES et al., 2018)
Outer load bearing walls	100mm bricks-80mm cavity–100mm bricks	
Ground floor	150mm concrete	
Separating floors	150mm concrete	
Roof	Wooden structure, 18mm wooden beams	
Envelope performance		
External walls	Uninsulated	(WoonWijzerWinkel, 2023)
Windows	Single glass	
Roof	Uninsulated	
Ground floor	Uninsulated	
Infiltration (AC/h)	0,6	See chapter 2.5
HVAC systems		
Ventilation system	Ventilation system A, AC/h= 0,6	See chapter 2.5 (WoonWijzerWinkel, 2023)
Heating system	Gas boiler	
Domestic hot tap water	Gas boiler	
Heat distribution system	Hot water radiators	
Heating supply temperature	70-90 °C	
Temperature (heating)	21 °C	

3.2 Renovation measures - deep and shallow

Two levels of renovation can be distinguished a deep renovation (energy saving of 60% - 90%) and a shallow renovation (energy saving of 3% - 30%). Whereas the focus in a deep renovation lies on high energy saving a shallow renovation aims for cost effective renovation measures. The literature study reveals which renovation measures match with a shallow and deep renovation. Renovation measures have been selected for their impact and convenience. The renovation measures can in general be categorized in active and passive measures. The following paragraphs dive deeper into the considered measures for a deep and shallow renovation based on the findings of the literature review, chapter 2.

3.2.1 Shallow renovation measures

Based on the literature review, a shallow renovation is considered a single measure, that includes either insulating the roof, insulating the cavity or replacing the windows (table 9). Insulating the roof and cavity insulation are selected renovation strategies because of their cost effectiveness. While window replacement is a selected strategy because it's often considered by house owners. Although a shallow renovation often consists of a single measure, it is possible that multiple measures are considered. Therefore also a combination of the presented strategies (figure 19) is considered a shallow renovation.

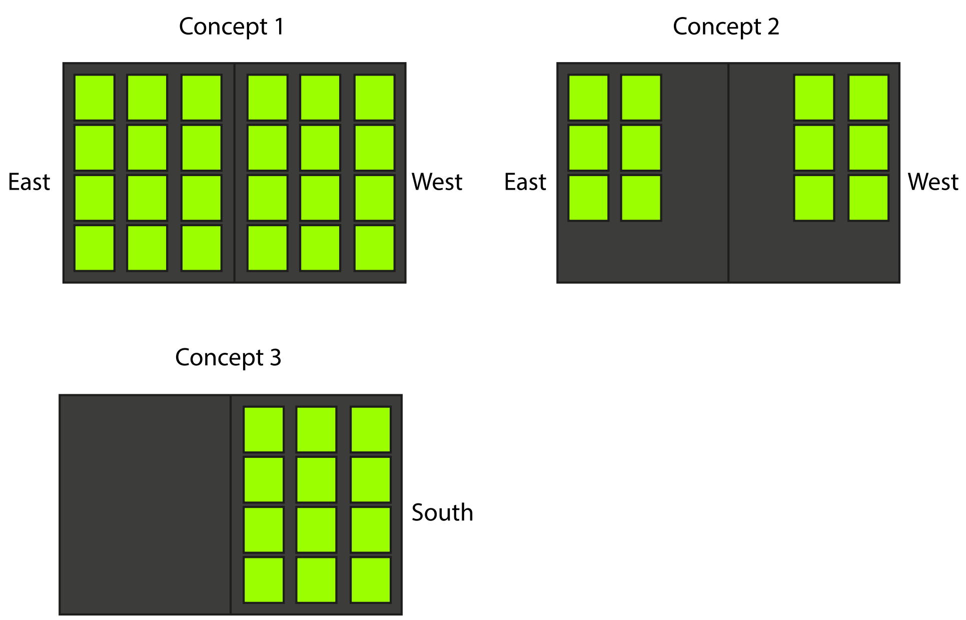


Figure 19. Shallow renovation strategies considered for a terraced house (created by author).

3.2.2 Deep renovation measures

The energy performance of a building influences the carbon emissions significantly. Therefore strategies are selected for their high impact on the energy performance of a building. This ensures that the renovation measures aim to reduce carbon emissions. The renovation measures for a deep renovation can be categorized into passive strategies for the envelope, and active strategies for the services (figure 20). External roof insulation, external wall insulation, window replacement, air tight connections (infiltration), under floor insulation, replacement of the energy source, and replacement of the ventilation system are strategies that target carbon emissions effectively. Furthermore, carbon emissions can be compensated for by generating energy. This is also needed to make buildings carbon neutral. The strategy considered in the renovation strategies is energy generation on a building scale by adding solar panels.

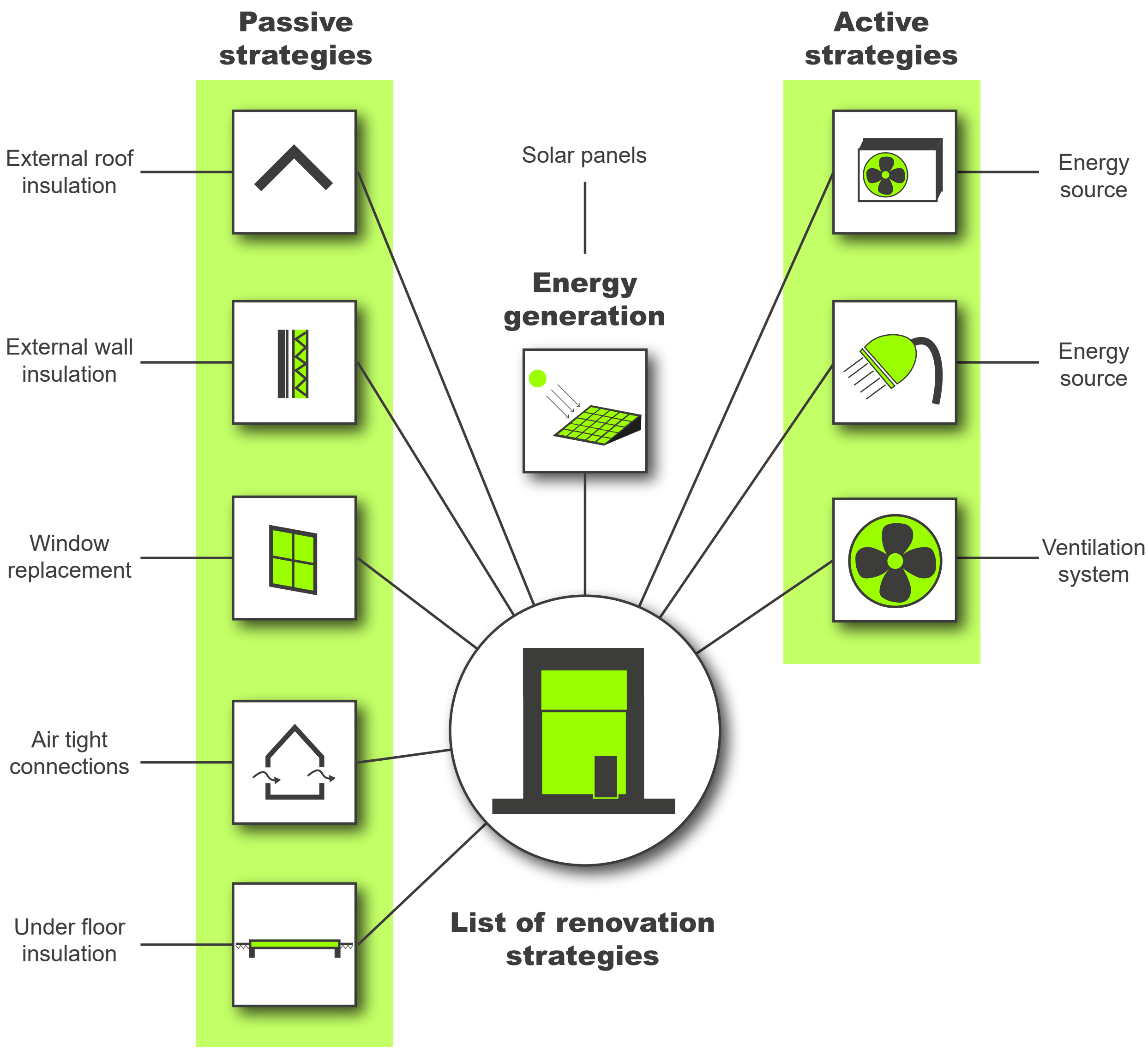


Figure 20. Deep renovation strategies considered for a terraced house (created by author).

3.2.3 Overview of renovation measures

The previously active and passive strategies presented can consist of different measures. For example insulating the roof, can be done by using different materials and different thicknesses. This on its turn influences how much energy is saved, and thus influences the operational carbon. Therefore it is important to define specific aspects that influence the energy performance. The use of different materials or levels is referred to as renovation measures. The use of materials on its turn influences the embodied carbon. The renovation measures for a deep and shallow renovation are provided in table 11. The upcoming sections further explain how the renovation measures selected influence the embodied carbon and operational energy.

Insulation measures
Roof insulation, external wall insulation and ground floor insulation all comprise of adding insulation. The Rc value achieved with insulation determines the energy saving. Different Rc values can be achieved depending on the level of insulation for each building element. For a shallow renovation single measures are considered and a combination of these measures. The measures consist of cavity insulation, roof insulation or window replacement and all measures combined. For a deep renovation insulation levels are derived from general advice provided by the Dutch Enterprise Agency (RVO, either on their website or through a secondary source) and the building code (see table 11). Secondly, the materials used for insulation influence the embodied carbon. Therefore, 3 different materials are considered per insulation level, EPS (hard insulation), glass wool (soft insulation) and Cellulose (organic insulation).

Infiltration measures
Adding insulation externally offers the opportunity to improve the connection between joints. Therefore in the deep renovation measures different levels of infiltration are considered for each level of insulation. Infiltration levels are derived from the literature review, 2,5 ‘’Deep renovation measures’’. In the shallow renovation measures, the option that combines the individual measures is accompanied by a reduction in infiltration, assuming that executing multiple measures could also result in better connections between elements.

Ventilation measures
From the literature review (2,5 ‘’Deep renovation measures’’) 3 ventilation systems were extracted: ventilation system A, ventilation system C with CO_2 sensors, and ventilation system D. Ventilation system A consist of natural ventilation through windows, and is the system used in the current state of the building. Ventilation system C and D require mechanical ventilation units to operate. Due to controlled ventilation, system C and D influence the energy use, which can be estimated with the air change per hour (AC/h). The values for the air change per hour that corresponds with each system are presented in table 11 and derived from the literature review. Secondly, the addition of ventilation units, increases the embodied carbon.

Energy system measures
The energy system also influences the energy saving. In this thesis energy system refers to a single system for heating and tap water. Efficient energy systems use less energy to

provide heat. Secondly the fuel, such as electricity and natural gas, used for the energy system related to different carbon emissions. Therefore 3 different energy sources were considered, an electric boiler, a heat pump and a gas boiler. An electric boiler and heat pump both use electricity while the gas boiler uses natural gas. With COP values the efficiency for the energy systems can be determined and used to estimate the energy use, numbers are derived from the literature review, 2,5 ''Deep renovation measures''.

Energy generation
For energy generation only solar panels are considered. 3 variations are assessed to obtain varying performances on energy yield, carbon emissions and costs (see figure 21):

- Concept 1 'full capacity': 12 PV panels each side of the roof, oriented to east-west.
- Concept 2 '50% capacity': 6 PV panels each side of the roof, oriented to east-west.
- Concept 3 '50% capacity': 12 PV panels one side of the roof, oriented to the south.

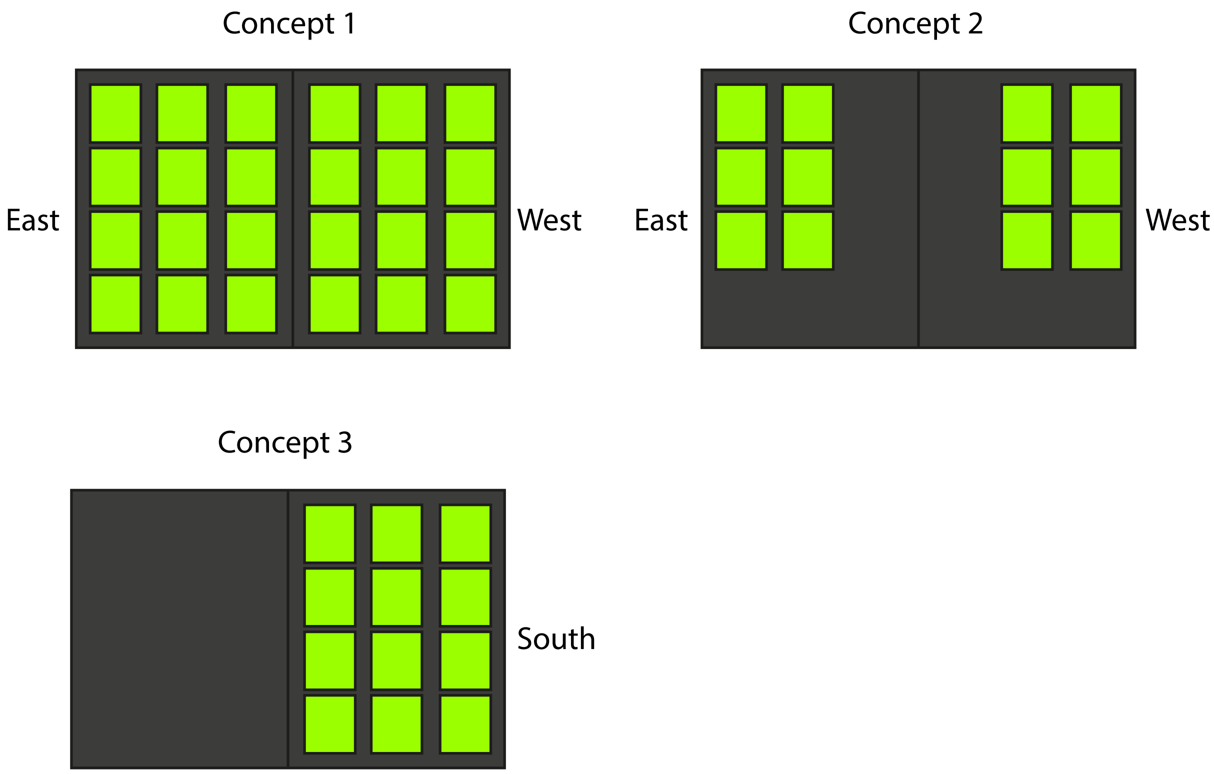


Figure 21. Roof sketch of photovoltaic panel strategies assessed.

Table 11. Renovation measures organized by shallow renovation and deep renovation. Shows the measures regarding insulation, infiltration, ventilation system, heating system and energy generation.

Shallow renovation measures				
Envelope measures	Insulation in Rc value (m²K/W) and windows in U value (W/m²K)			
Reference code:	**Level 0,1C**	**Level 0,1R**	**Level 0,1W**	**Level 0,1**
	Cavity ins.	**Roof ins.**	**Window replacement**	**All measures**
Roof		3,5		3,5
External walls	1,86			1,86
Windows			1,2	1,2
Infiltration (AC/h)	0,8	0,8	0,8	0,4
Deep renovation measures				
Envelope measures	Insulation in Rc value (m²K/W) and windows in U value (W/m²K)			
Reference code:	**Level 1 ''minimum''**		**Level 2 moderate**	**Level 3 high**
	70-90 °C (1)	*50 °C (1.1)*	*'New build''*	*'streefwaarden''*
Roof	2	3,5	6	8
External walls	1,3	1,7	4,5	6
Windows	1,2	1,2	1,2	1
Ground floor	2,5	3,5	3,5	3,5
Source	Building code	(WoonWijzerWinkel, 2023)	(RVO, n.d.)	(RVO, n.d.)
Infiltration (AC/h)	0,6	0,6	0,3	0,2
HVAC measures				
Ventilation				
Ventilation system A	Natural supply and exhaust through windows AC/h = 0,6			
Ventilation system C	With CO_2 sensors at windows, AC/h = 1,05			
Ventilation system D	With heat recovery efficiency 80%, AC/h = 1,05			
Heating and tap water system				
Option 1: Heat pump	COP 4			
Option 2: electric boiler	COP 1			
Energy generation				
Building scale option 1	Photovoltaic (PV) panels Orientation east-west, 100% covered roof			
Building scale option 2	Photovoltaic (PV) panels Orientation south-north, 100% covered roof			
Building scale option 3	Photovoltaic (PV) panels Orientation south, 50% covered roof			

3.3 Overview renovation strategies - deep and shallow

The earlier discussed renovation measures (table 11) are combined in different ways to form renovation strategies. The renovation strategies can be distinguished in shallow renovation strategies, deep renovation strategies and current state renovation strategies (see table 12).

Current state strategies
In the current state renovation strategies only the replacement of the heating system is considered, as the replacement of the heating system at the end of its service life will occur anyways. For the replacement a gas boiler and an electric boiler are considered. The current state strategies act as a baseline for comparison.

Shallow renovation strategies
The shallow renovation strategies that consider single measures, such as cavity insulation, roof insulation or window replacement, are combined with either a gas boiler or an electric boiler. Also renovation strategies are included that consider a combination of all single measures, referred to in table 12 as combined measures. The shallow renovation strategies that consider a combination of all single measures is combined with either a gas boiler or an electric boiler, and different ventilation systems, A, C or D. A heat pump is not considered in the shallow renovation strategies, as this energy source requires a minimum insulation level.

Deep renovation strategies
The renovation strategies for a deep renovation are obtained by combining each level of insulation with each heating source, and combining the obtained combinations with the 3 ventilation systems, A, C and D. The strategies presented aim to influence the operational energy and operational carbon emissions, which is the first step in reducing carbon emissions related to buildings.

Additionally, each renovation strategy presented in table 12 that contains an insulation measure has 3 variations, that consider different insulation materials: glass wool, EPS, and cellulose. Resulting in 110 deep renovation strategies, 18 combined shallow renovation strategies and 9 single measures shallow strategies, that provide different results regarding the energy performance and environmental performance.

Table 12. Renovation strategies (41 in total) organized by current state strategies, shallow renovation strategies containing a single measure or multiple measures and deep renovation strategies. The renovation strategies are compiled of different combinations of insulation levels, ventilation systems and heating systems. The strategies presented aim to provide a variety in performance regarding the operational energy and operational carbon emissions.

Current state renovation strategies	
	Current state
Elec. Boiler	A
Gas boiler	A
	2 strategies

Explanation

Overview of 2 current state strategies either combined with an electric boiler or a gas boiler, combined with ventilation system A, natural ventilation. Mechanical ventilation systems and varying insulation levels are not considered in these strategies.

Shallow renovation strategies			
Single measures			
	Passive measures, envelope		
	Cavity	Roof	Windows
Gas boiler	A	A	A
	3 strategies		

Overview of 6 shallow renovation strategies (3 envelope measures x 2 heating sources x 1 ventilation system = 6 options) that consider a single renovation measure, regarding the envelope. The measures comprise of cavity insulation, roof insulation or window replacement, combined with either a gas boiler or an electric boiler, combined with ventilation system A, natural ventilation. Mechanical ventilation systems and varying insulation levels are not considered in these strategies.

Combined measures	
	Passive measures, envelope
	Cavity + Roof + Windows
Elec. Boiler	A/C/D
Gas boiler	A/C/D
	6 strategies

Overview of 6 shallow renovation strategies (1 set of envelope measures x 2 heating sources x 3 ventilation options = 6 options) that consider multiple renovation measures, regarding the envelope. The measures comprise of cavity insulation, roof insulation and window replacement, combined with either ventilation system A, C or D, and either a electric boiler or gas boiler as energy source.

Deep renovation strategies			
	Passive measures, envelope		
	level 1	*level 2*	*level 3*
Heat pump	A/C/D	A/C/D	A/C/D
Elec. Boiler	A/C/D	A/C/D	A/C/D
Gas boiler	A/C/D	A/C/D	A/C/D
	27 strategies		

Overview of 27 deep renovation strategies (3 insulation levels x 3 heating sources x 3 ventilation options = 27 options) that are used to determine the operational energy. Heating demand is influenced with the renovation measures level of insulation, different energy sources and the 3 ventilation systems A, C and D. Hot tap water demand is added as a fixed value to each of the 27 strategies.

Note: each strategy contains 3 variations, glass wool insulation (1), EPS insulation (2) and Cellulose insulation (3). Resulting in 110 deep renovation strategies, 18 combined shallow renovation strategies and 9 single measures shallow renovation strategies.

Reference code strategies
Due to the wide range of strategies obtained, the renovation strategies contain a reference code to provide information on the measures it contains. The reference code is built as follows:

Level of insulation – ventilation – heating system – insulation material.

It contains abbreviations or numbers that refer to specific measures.

The reference number for the level of insulation are (also presented in table 9):

1	minimum insulation;
1.1	minimum insulation in case of a heat pump;
2	moderate insulation;
3	high insulation;
Current state	absence of insulation measures

The reference for the ventilation systems are:
A system A natural ventilation;
C system C, mechanical exhaust and natural supply;
D system D mechanical with heat recovery.

The reference for the heating systems are:
EB electric boiler;
HP heat pump;
GB gas boiler.

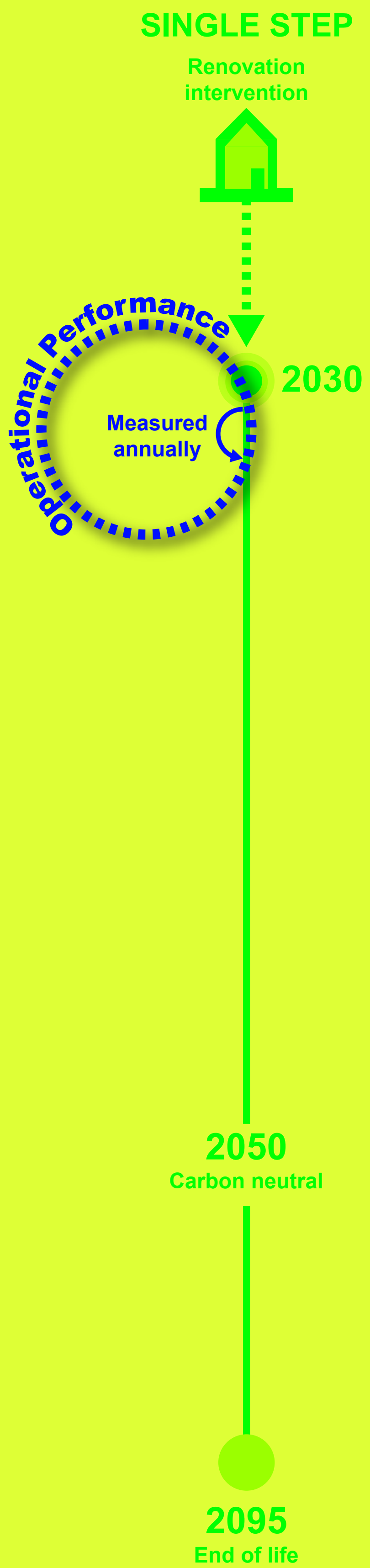
The reference for the different insulation materials are:
H Hard insulation, EPS;
S Soft insulation, glass wool;
O Organic insulation, cellulose.

Example:

Reference code: 3-A-HP-H

Explanation: the strategy considers a high level of insulation (3), Natural ventilation (A), a heat pump as energy source for heating and tap water (HP), and EPS is used as insulation material.

CHAPTER 4| Operational Performance



This chapter reveals how the previous presented renovation strategies perform on operational energy and carbon.

The chapter contributes to answering the sub question: "How do the renovation strategies influence the operational performance of a building?"

The chapter starts with an introduction describing the method to assess the operational performance. Followed by the operational energy assessment, elaborating on the calculation method and the results. With a similar approach the operational carbon assessment is explained after. The chapter ends with a short conclusion, presenting the main findings of the assessment.

4.0 Introduction

In order to understand how carbon emissions can be reduced over the life cycle of a building, assessing the performance of previous presented renovation strategies is crucial. The operational performance is an important aspect in decision-making for renovation strategies. This chapter presents how the operational performance can be assessed and reveals the operational performance of previous presented renovation strategies.

Methodology

To answer the sub question: "How do the renovation strategies influence the operational performance of a building?", a methodological approach was used (figure 22). The literature study shows that operational energy and carbon are important aspects to determine the operational performance of a building, and require different assessment methods. First the operational energy is assessed, with Design Builder and manual calculations. Then the results are used to calculate the operational carbon. The assessments led to graphs that reveal how the renovation strategies perform compared to the current state and other strategies. The assessment considers a year as calculation period starting from 2030.

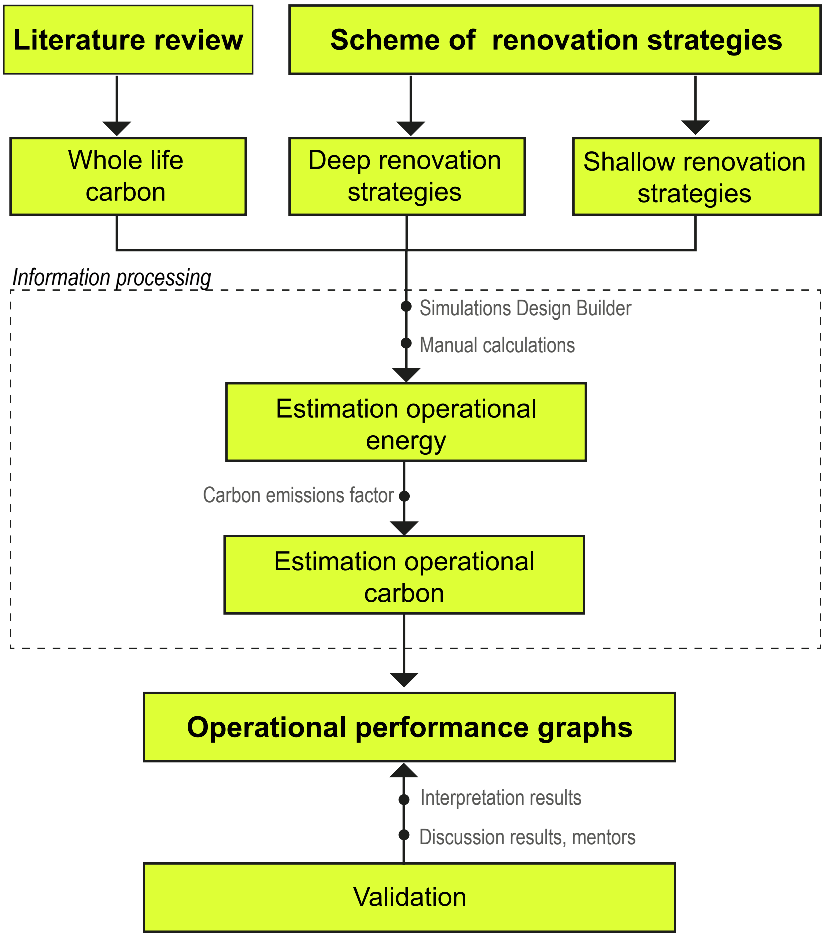


Figure 22. Method assessment operational performance

4.1 Operational energy

The operational energy refers to the energy consumption of a building in the use stage. The energy consumption nowadays mainly consist of energy use for heating and hot tap water. Renovation measures can affect energy consumption related to these aspects. By estimating the heating and tap water demand, the reduction in energy use for various renovation strategies can be investigated. This data can help decision making in renovation, where energy reduction is the objective.

4.1.1 Calculation method

The heating demand and tap water demand are estimated in different ways. An overview of the assessment method of the operational energy is provided in figure 23.

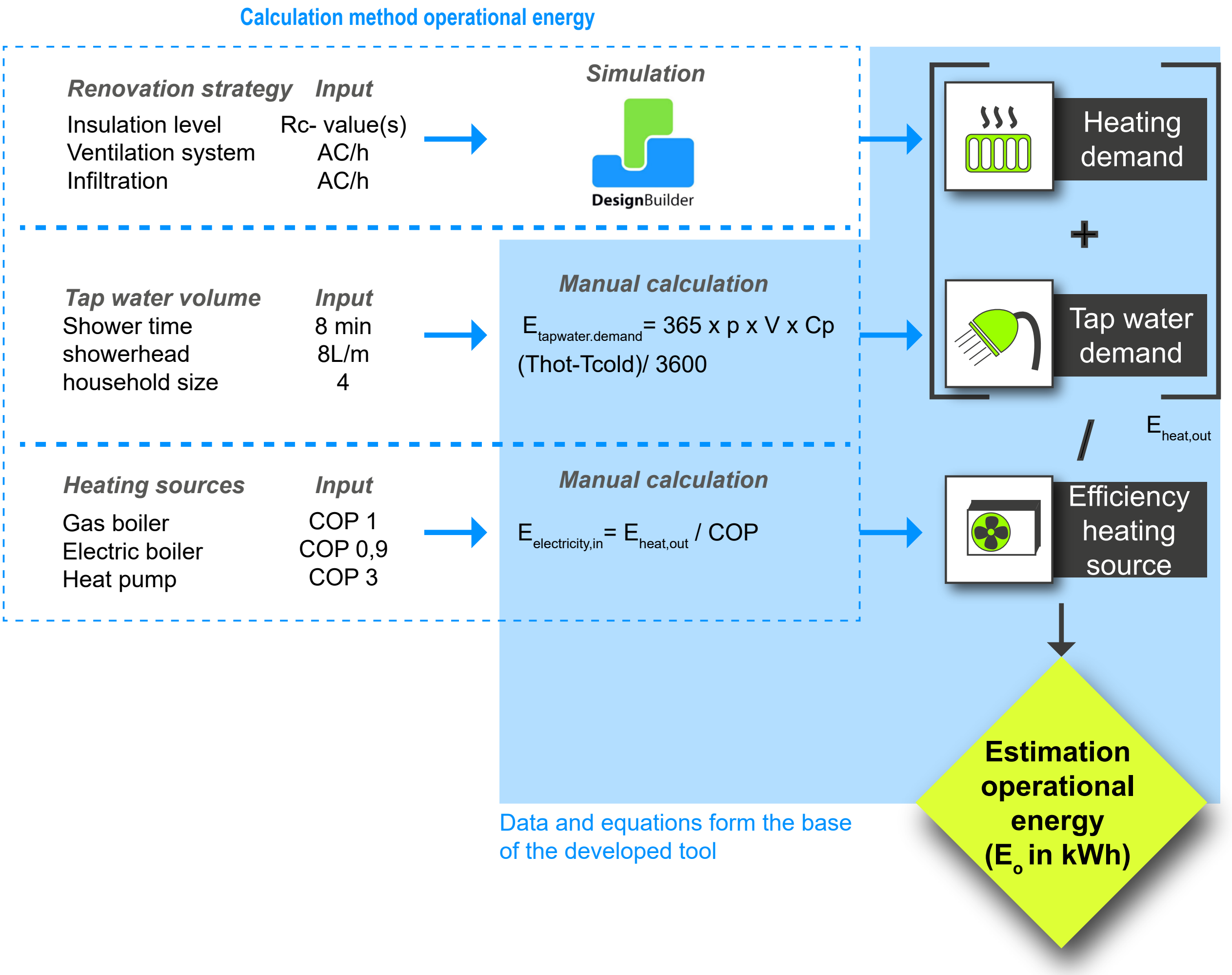


Figure 23. Calculation method operational energy performance

The heating demand is dependent on building characteristics and can be influenced through envelope measures. Due to the level of data needed the heating demand is estimated with Design Builder. In Design Builder a 3D model is created, and the building specific data could be automatically used to estimate the heating demand, for various strategies. This way the assessment time was reduced. On the contrary, assessments in Design Builder require a high level of data in order to provide reliable outcomes. It uses building specific data and takes into account it's surroundings by using climate data, site specific information, the presence of adjacent buildings etc. This is beneficial as it offers to calibrate the building to match the real performance of the building. For the energy calculation the setting simplified HVAC is used in Design Builder, further details on the settings used to calculate the heating demand are presented in table 13.

Table 13. Input values Design Builder used for the assessment of the heating demand.

Parameter	Input
Location	De Bilt, Netherlands
Activity - heating	21 °C
Activity - heating set back	17 °C
Activity - natural ventilation minimum temperature	21,5 °C
Structure	As provided in table 10.
Openings	As provided in table 10.
Gains	4,5 kWh
Schedule for heating, gains and ventilation	In full operation between 7-22h and operates at 50% for the resting hours
HVAC	As provided in table 11.

To evaluate if the outcome of the assessment is reliable, the current state was assessed on energy consumption, and the outcome was compared with an average gas consumption of a Dutch household in the Netherlands. Comparison shows an annual energy consumption of the case building, higher then the average consumption. This difference can be explained due to the fact that energy renovations are already executed and this data also contains data of recently build buildings, resulting in a lower average consumption. The outcome is therefore assumed to be reliable.

Unlike heating demand the domestic hot tap water (DHW) demand is related to user behaviour, which can vary per case. Shower time and the amount of people showering per day are the main cause for uncertainty. To investigate the impact of DHW use on energy consumption, representative assumptions had to be made. The amount of people showering per day is determined through the household size. The average household size in the Netherlands is estimated 2.12 in 2023 (CBS., n.d.). However, the building has by default 3 bedrooms, large enough to accommodate a household size of 4 people (parents and 2 children). This would result in a larger energy consumption. In the calculation a household size of 4 was used, to represent full occupancy. Furthermore a regular shower head was assumed, and for shower time an average shower time in the Netherlands, resulting in a hot tap water use of 237 Liters per day (table 6).

The system that ensures the energy supply of the heating system and the tap water system, is referred to as energy system. To simplify the assessment a single energy system is considered to power the building, on the contrary a separate system powering the hot tap water system and the heating system is not uncommon. The renovation strategies presented in chapter 3 consider a heat pump, gas boiler and electric boiler, providing varying results in energy use due to different energy efficiencies.

Overview equations

The heating demand is among others influenced by the level of insulation. The level of insulation is represented by the Rc value, presented in the overview of renovation measures, table 11. With the Rc value the thickness of the insulation is estimated. The Rc value is estimated with equation (1):

$$R_c=(\sum R_m+R_{si}+R_{se})/(1+\alpha) - R_{si}- R_{se} \quad (1)$$

Where:

R_c represents the heat resistance of the building element ($m^2 \cdot K/W$)
R_m represents the heat resistance of each layers of the element ($m^2 \cdot K/W$)
R_{si} represents the heat resistance inside ($m^2 \cdot K/W$)
R_{se} represents the heat resistance outside ($m^2 \cdot K/W$)
α represents a correction factor

Equation (1) represents the R_C value estimated by the sum of the heat resistance of all layers of the building element, the heat resistance inside and outside the element divided by α correction factor, minus the heat resistance inside and outside. From equation (1) the R_m value of a single layer can be derived, such as for insulation. The R_m value can then be used to estimate the thickness of the insulation material with equation (2):

$$R_m = D / \lambda \quad (2)$$

Where:

R_m represents the heat resistance of each layers of the element ($m^2 \cdot K/W$)
D represents the thickness of a material layer (m)
λ represents the thermal conductivity coefficient of the material (W/mK)

Equation (2) represents the Rm value estimated by dividing the thickness of a material with the thermal conductivity coefficient of the material. Hence, the thickness can be estimated as the product of the heat resistance of the material and the thermal conductivity coefficient of the material. This way the insulation thickness resulting in a certain Rc value for the wall is estimated and used as input for the simulations in Design Builder.

The DHW demand is less complex to calculate, yet contains variables. Automizing the calculation could enable estimation of the DHW demand of different cases (further explained in chapter 7). Therefore DHW demand is calculated manually and automized in Excel (Microsoft) with equation (3) (Van Bueren, et al., 2012):

$$E_{tapwater.demand}= 365 \times p \times V \times Cp\ (T_{hot}-T_{cold})/ 3600 \quad (3)$$

Where:

$E_{tapwater.demand}$ represents the annual energy demand for tapwater (kWh)
365 represents the days in a year
p represents the density of water (kg/m^3)
V represents the volume of the water (m3)
Cp represents specific heat capacity of water (°C)
T_{hot} represents the temperature of outgoing water (°C)
T_{cold} represents the temperature of incoming water (°C)

This formula (3) estimates the energy demand for hot tap water, by multiplying the amount of days in a year with the density of water, the volume of the water, the specific heat capacity of water and the temperature difference of the incoming and outgoing water in kWh.

The energy use of the energy system for heating and hot tap water is calculated manually and automized in Excel (Microsoft) with equation (4):

$$E_{electricity,in} = E_{heat,out} \; / \; COP \qquad (4)$$

Where:

$E_{heat,out}$ represents the energy generated (kWh)
COP represents the coefficient of performance of the energy source
$E_{electricity,in}$ represents the energy use in electricity (kWh)

Equation (4) estimates the energy use by dividing the energy output (the energy demand) with the efficiency of the energy system.

4.1.2 Operational energy performance single step renovations

The renovation strategies presented in chapter 3 contain measures that could result in establishing a deep or shallow renovation. To test if the strategies result in an energy saving related to a deep or a shallow renovation an assessment was performed. The energy saving is measured on energy saved for heating and tap water compared to the existing state of the building. After the assessment the found deep and shallow renovation strategies are analyzed on their operational energy performance.

Evaluating deep and shallow renovation strategies
To investigate ‘’deep’’ renovations and ‘’shallow’’ renovations, the assessed renovation strategies are filtered on energy saving, energy savings of 3-30% relate to a shallow renovation and energy savings of above 60% relate to a deep renovation.

Among the 110 strategies aiming for a deep renovation, 45 strategies revealed an energy saving that matches a deep renovation (see figure 24). The renovation strategies yielding an energy saving of above 60% had specific measures. Specific measures that resulted in a deep renovation can be distinguished as strategies that incorporated:

1. A heat pump;
2. High insulation (level 3) combined with a gas boiler;
3. High insulation (level 3). an electric boiler combined with either vent. system A or D;
4. Moderate insulation (level 2) with a gas boiler combined with ventilation system D.

Furthermore, the results show that out of the 14 shallow renovation strategies that considered only a single measure all strategies result in an energy saving of 3-30% (see figure 25). The measures identified resulting in a shallow renovation are: cavity insulation, replacing the windows with double glass, and adding roof insulation. The shallow renovation strategies that combined all the measures (cavity insulation, window replacement and roof insulation) provided an energy saving higher than 30%, resulting in a moderate renovation. In other words an energy saving of 3-30% is only achieved when strategies consider a single measures or a maximum of 2 measures.

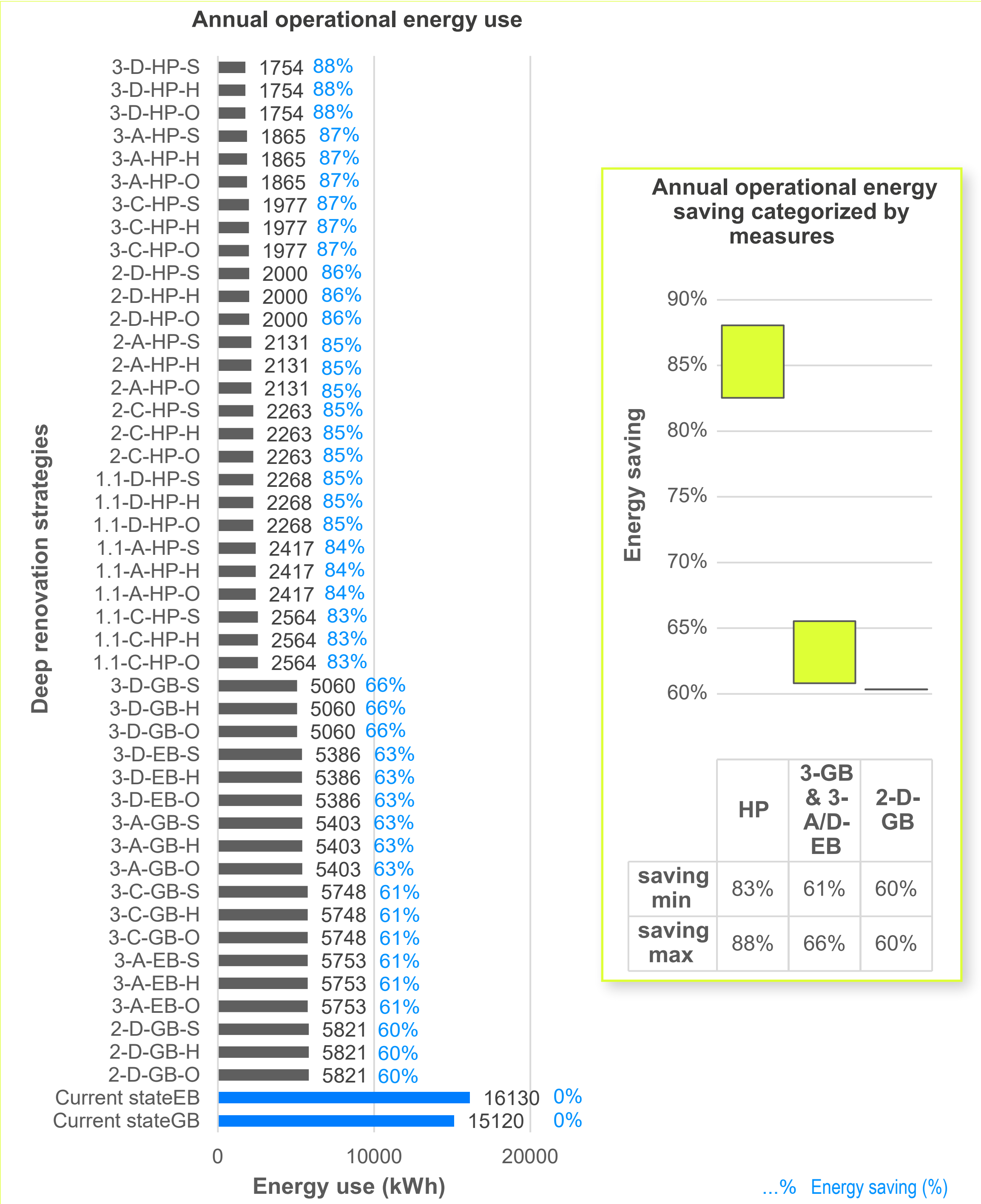


Figure 24. Renovation strategies containing Deep Renovation Measures and their estimated energy use in kWh and energy saving in % (data on the energy use related to heating is obtained from simulations with Design builder)(graphs by author, created in Excel).

Annual (operational) energy consumption

The deep and shallow renovation strategies extracted from the previous section are analyzed on their energy performance. The annual energy use of the current building is estimated 15120 kWh.

The annual energy use for deep renovation strategies (figure 24) varies between 1754 kWh to 5821 kWh. Within the strategies a significant difference can be seen between the strategies that consider a heat pump and the remaining strategies. Strategies that consider a heat pump yield an energy saving of 83%-88%, with a corresponding annual energy use varying from 1754 kWh to 2564 kWh. While the remaining strategies yield an energy saving of 60%-66%, with a corresponding annual energy use varying from 5060 kWh to 5821 kWh. The heat pump reveals to be the most effective renovation measures regarding energy reduction, and the most effective strategy consist of high insulation with ventilation system D and a heat pump.

For the 9 shallow renovation strategies the annual energy use varies between 13472 kWh to 12720 kWh. Within the strategies cavity insulation proves to be most effective, saving 5% more energy compared to other measures. Strategies considering roof insulation or window replacement showed the same energy reduction (8% energy saving).

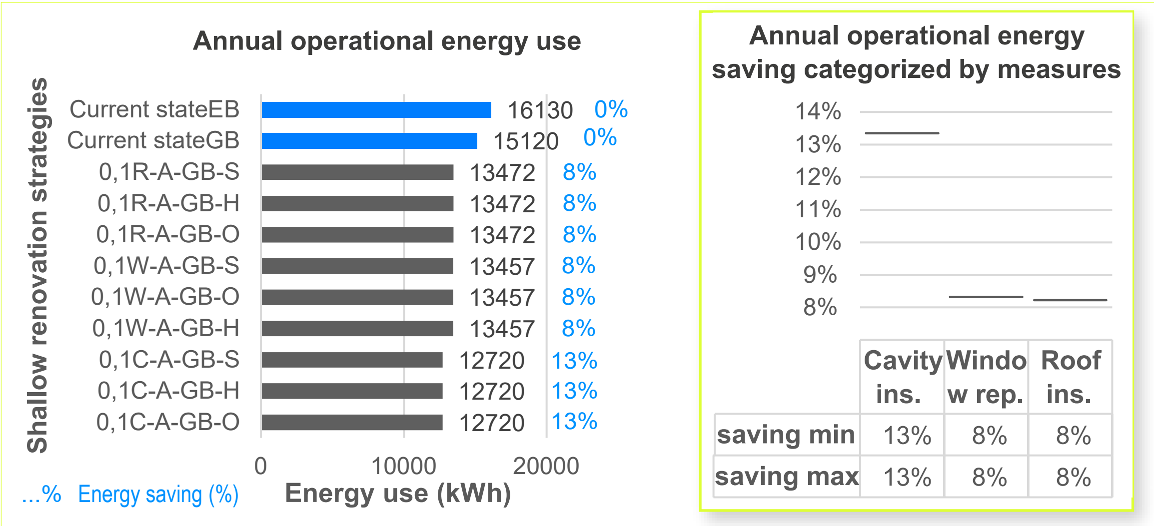


Figure 25. Renovation strategies containing Shallow Renovation Measures and their estimated energy use in kWh and energy saving in % (data on the energy use related to heating is obtained from simulations with Design builder)(graphs by author, created in Excel).

Conclusion

To summarize deep renovation with an energy saving of 60% in a terraced house is achieved by incorporating a heat pump, or high insulation combined with a gas boiler, or high insulation with an electric boiler and ventilation system A or D, or moderate insulation with a gas boiler and ventilation system D. Of which strategies considering a heat pump result in the highest (83%-88%) energy saving. A shallow renovation is achieved by executing a single measure or two measures, consisting of cavity insulation, roof insulation or window replacement. From all measures cavity insulation results in the highest energy reduction (13% energy saving).

4.2 Operational carbon

The operational carbon refers to the carbon emissions of a building related to the energy use in the use stage. It is influenced by the energy source (such as electricity and natural gas) and the energy demand. Insight in the operational carbon can improve decision making in renovation, where environmental performance is the objective.

4.2.1 Calculation method

The effects of different type of gases on global warming vary in impact. Therefore the environmental impact is measured in global warming potential (GWP). Which represents the impact of multiple gases in the same unit (CO_2e) by converting gases other than CO_2 to the equivalent magnitude of CO_2. The operational carbon is estimated by the energy use related to renovation strategies and the specific carbon factor related to the energy source (figure 25).

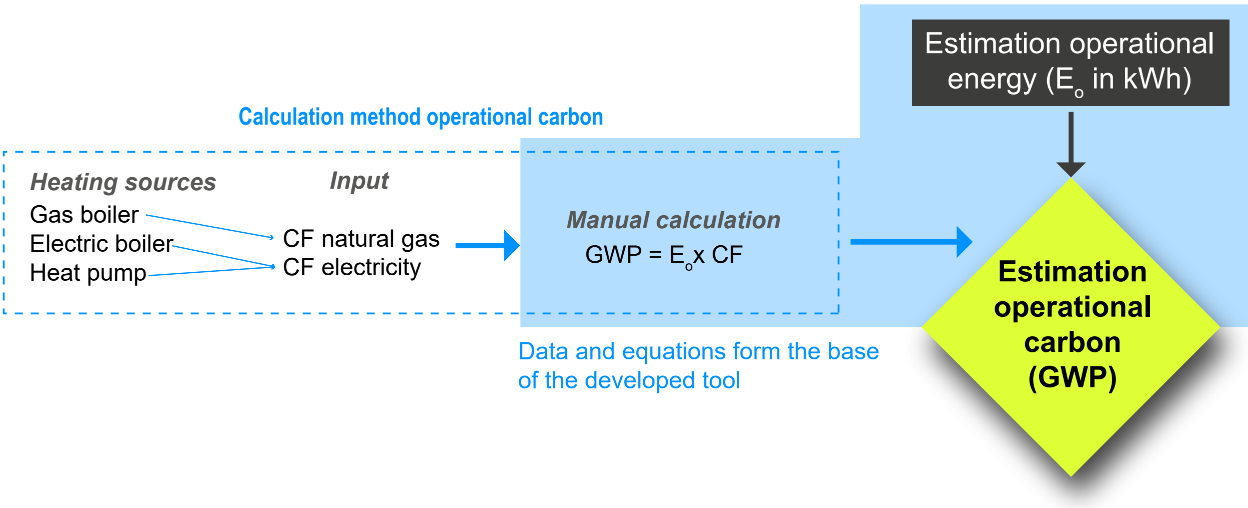


Figure 25. Calculation method operational energy performance

The carbon factor for natural gas is obtained from Rapportage CO_2-uitstoot (n.d.), and has shown to be stable over the past years. On the contrary, the electricity carbon factor shows a decrease, due to the increasing share of renewable energy. As the assessment period considers 2030 as a starting point, further research is done to obtain a reliable carbon emission factor for electricity. The prediction for 2030, is that the emissions related to electricity will decrease significantly compared to now. The input values for the carbon emissions related to the use of gas and electricity are presented in table 14.

Table 14. Renovation strategies containing Shallow Renovation Measures and their estimated energy use in kWh and energy saving in % (data on the energy use related to heating is obtained from simulations with Design builder)(graphs by author, created in Excel).

	2024	2030	Unit	Conversion	Unit
Electricity	0,270	0,094	kg/kWh		
Natural gas	1,788		kg/m3	0,15983123	kg/kWh
	(*Rapportage CO_2-uitstoot*, n.d.)				

Equation

The operational carbon is calculated with the in table 14 presented carbon emission factors and is estimated with equation (5):

$$GWP = E_o \times CF \qquad (5)$$

Where:

GWP represents the global warming potential (kg CO_2e)
E_o represents the operational energy use (kWh)
CF represents the carbon emission factor specific for the energy source (CO_2e/kWh)

This formula (5) estimates the global warming potential related to the energy use and is estimated as the product of the used energy and the carbon emission factor. Where the carbon emission factor is different for each type of energy source, such as gas and electricity.

4.2.2 Operational carbon performance single step renovations

The deep and shallow renovation strategies are analyzed on operational carbon emissions, also referred to as the global warming potential (GWP). The GWP of the current building is estimated 2417 kg CO_2e.

The GWP of shallow renovation strategies are presented in figure 27. Overall the strategies show similar GWP. Strategies that consider cavity insulation have the lowest GWP. The GWP is mainly determined by the energy source. For comparison reasons a strategy that considers replacing the gas boiler for an electric boiler is added to the graph. This shows that the use of electricity could significantly reduce operational carbon (in the prospect that the carbon factor for electricity decreases to 0,094 kg/kWh).

The GWP of deep renovation strategies are presented in figure 28. The graph shows a significant difference in GWP for different energy systems. Strategies considering a heat pump result in a low GWP and strategies that consider a gas boiler in a high GWP.

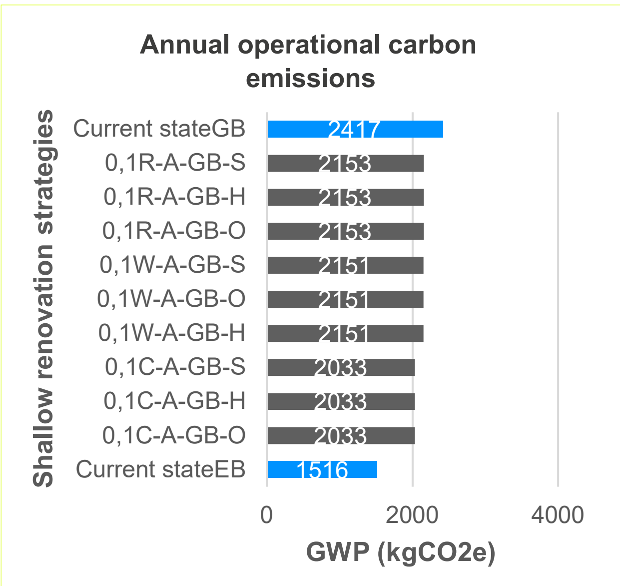


Figure 27. Shallow Renovation strategies and their estimated operational GWP in kg CO_2e (graphs by author, created in Excel).

Analysis of the GWP within strategies that consider a heat pump, a gas boiler or an electric boiler, reveals that other measures have limited influence on the GWP. Transitioning from gas to electricity is therefore the most effective way to reduce operational carbon emissions .

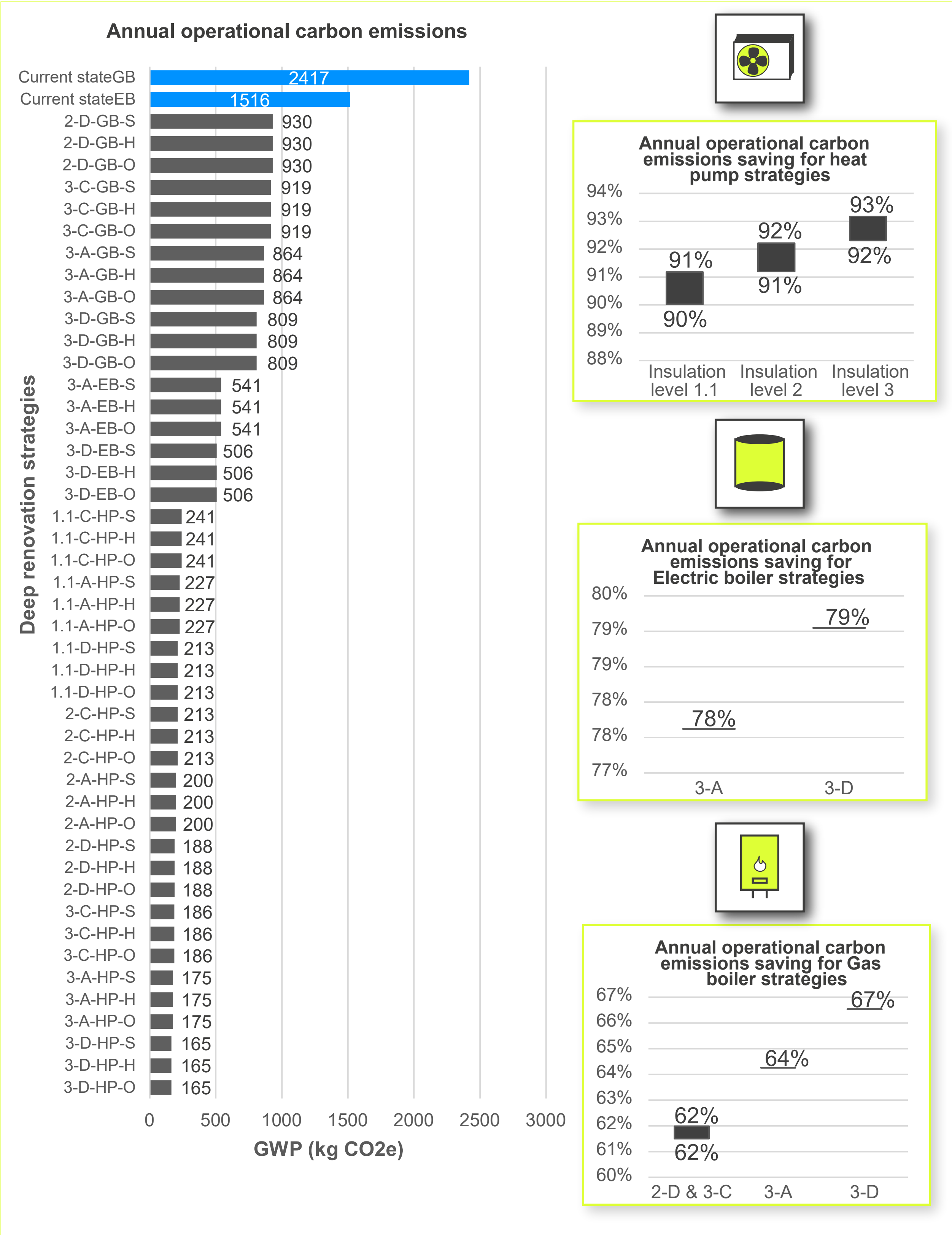


Figure 28. Deep Renovation strategies and their estimated operational GWP in kg CO_2e (graphs by author, created in Excel).

Overall conclusion operational performance

To summarize deep renovation with an energy saving of 60% in a terraced house is achieved by incorporating a heat pump, or high insulation combined with a gas boiler, or high insulation with an electric boiler and ventilation system A or D, or moderate insulation with a gas boiler and ventilation system D. Of which strategies considering a heat pump result in the highest (83%-88%) energy saving. A shallow renovation is achieved by executing a single measure or two measures, consisting of cavity insulation, roof insulation or window replacement. From all measures cavity insulation results in the highest energy reduction (13% energy saving).

The energy source determines mainly the operational carbon emissions, electricity resulting in lower operational carbon emissions and natural gas in higher emissions. The addition of a heat pump results in higher energy saving compared to the other strategies and therefore also results in lower operational carbon emissions.

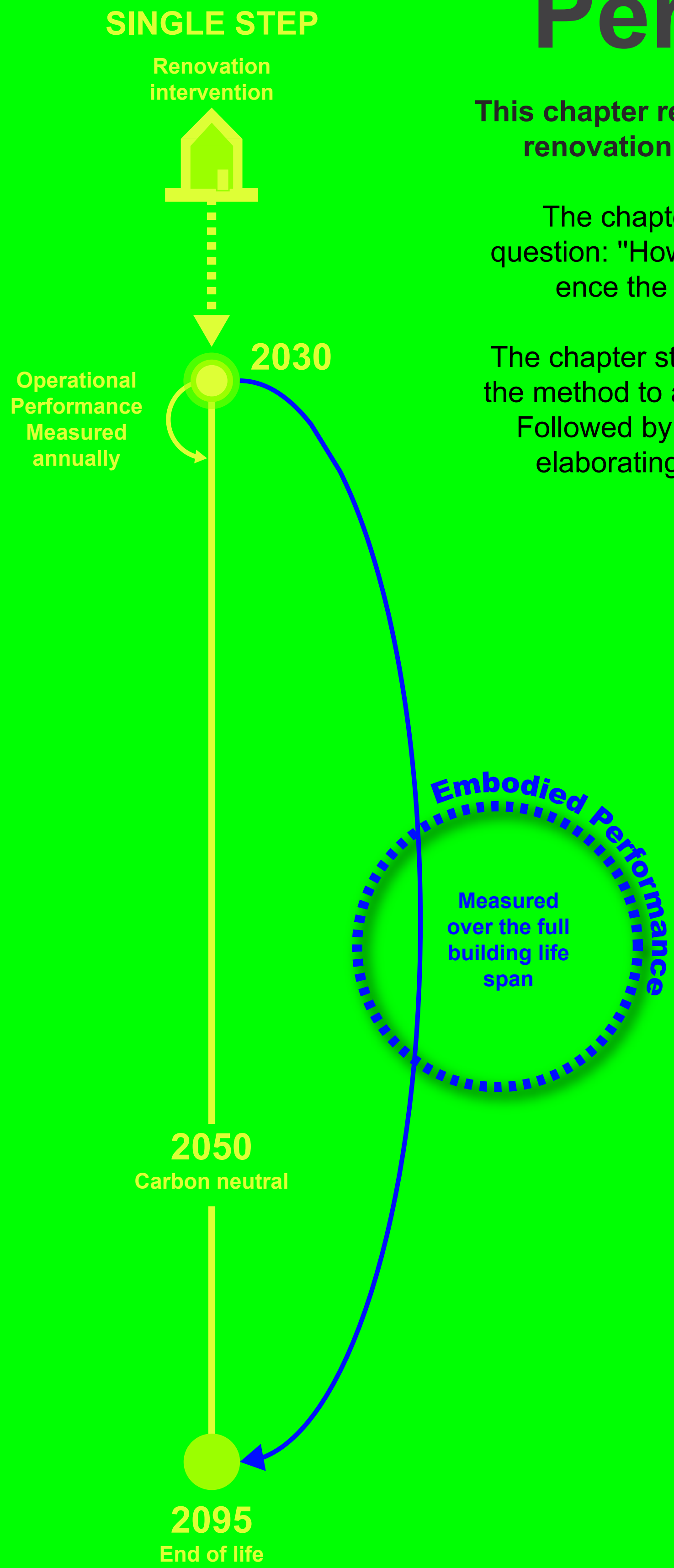
Overall high insulation, a heat pump and ventilation system D, has the best operational performance out of the deep renovation strategies. Within the shallow renovation strategies, cavity insulation has the best operational performance.

CHAPTER 5| Embodied Performance

This chapter reveals how the deep and shallow renovation strategies perform on embodied carbon.

The chapter contributes to answering the sub question: "How do the renovation strategies influence the buildings embodied performance?"

The chapter starts with an introduction describing the method to assess the embodied performance. Followed by the embodied carbon assessment, elaborating on the calculation method and the results.



5.0 Introduction

As the operational carbon decreases due to energy renovations, the importance to take into account the embodied carbon grows. In order to reduce carbon emissions over the life cycle of a building the embodied carbon needs to be assessed. This chapter presents how the embodied performance can be assessed and reveals the performance of the obtained deep and shallow renovation strategies.

Methodology

To answer the sub question: "How do the renovation strategies influence the buildings embodied performance?", a methodological approach was used (figure 29). The literature study revealed that the embodied carbon can be distinguished in the initial embodied carbon (related to the use of materials) and the recurrent embodied carbon (related to the replacement of materials at the end of service life). The embodied carbon of materials is estimated with One Click LCA. The assessments led to graphs that reveal the embodied carbon of the renovation strategies. As the recurrent embodied carbon is related to the replacement of materials, the assessment considers the remaining service life of the building as calculation period, 2030 - 2095.

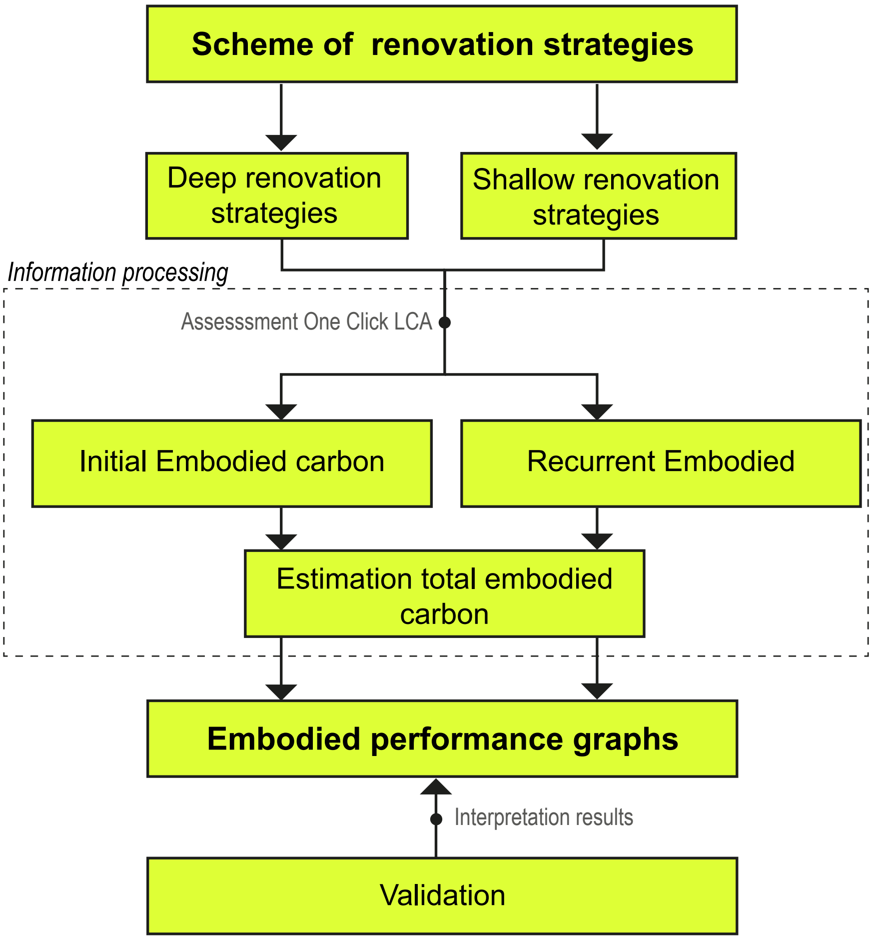


Figure 29. Method used to assess the embodied performance (by author).

5.1 Initial and recurrent Embodied carbon

Calculation of the embodied carbon is complex, as it requires a large amount of data, such as the volume of materials and materials types. Secondly, emissions are present in all building life cycle stages and are thus also influenced by transport and the disposal of the material. To reduce the assessment time, mainly stage A "Production" is assessed, which is responsible for most of the embodied emissions. Additionally, the replacement module of stage B "use" is assessed, to reflect the recurrent embodied carbon. The recurrent embodied carbon refers to the emissions related to repair, maintenance, and replacement of the materials and services used in the renovation strategies. From the literature study can be concluded that replacement influences recurrent embodied carbon the most, maintenance has in comparison a small impact and is therefore not included in the assessment. It is uncertain when repair will occur, and is therefore also not included in the assessment.

5.1.1 Calculation method

For the embodied carbon 3 insulation materials and the services are assessed, as these according to the literature review, are responsible for most of the emission. The insulation materials considered are glass wool (soft insulation), EPS (hard insulation), and Cellulose (organic insulation). The embodied carbon is estimated as the sum of the initial and recurrent embodied carbon. The calculation method for the initial and recurrent embodied carbon are presented in figure 30.
Data on the embodied carbon of materials is obtained from the database of One Click LCA, containing access to the majority of Environmental Product Declarations, which

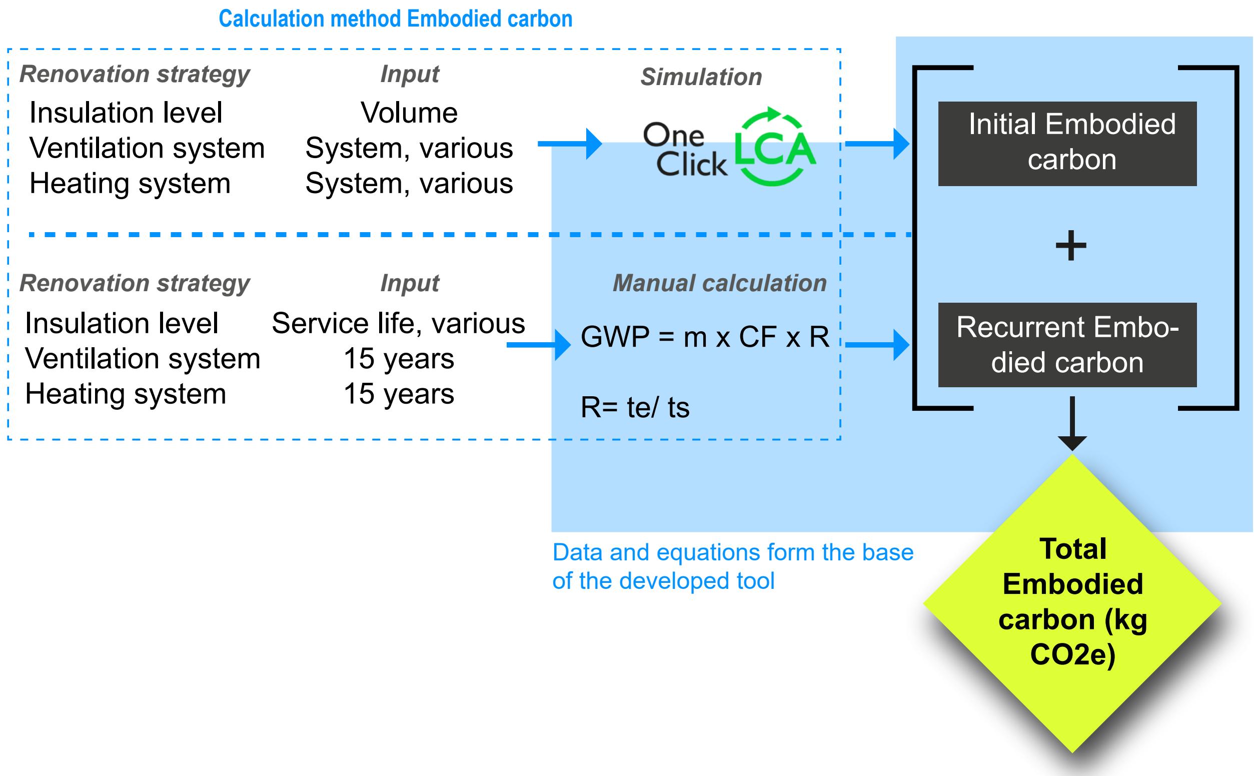


Figure 30. Calculation method embodied performance (by author).

contains verified data on the carbon emissions of materials and services. As input for One Click LCA the volume of the insulation for each insulation level and the shallow renovation measures are estimated with equation 1 and 2 (presented in the previous chapter). The embodied carbon related to services, contain only the emissions related to the service unit.
To obtain representative outcomes the material and product selection in One Click LCA is filtered on country specific data (Netherlands), generic data (as the exact product or material is unknown) and database (database One click LCA).

The recurrent embodied carbon is therefore only calculated based on the replacement of materials and services. In order to estimate when replacement occurs the service life of the materials had to be estimated. Table 15 contains information on the service life of materials and services used in the calculation.

Materials/services	**GWP (kg CO_2e)**	**Service life**	**Sources**
EPS	Varies for each insulation level, based on volume and Rc value.	40	(Kono et al., 2016)
Glass wool		55	(Kono et al., 2016)
Cellulose		50	(Kono et al., 2016)
Windows double glazed	1387	40	One click LCA
Windows triple glazed	1405	40	One click LCA
Ventilation D	620	25	One click LCA
Ventilation C	479	25	One click LCA
Electric boiler	1487	15	One click LCA
Heat pump air-water	4381	15	One click LCA
Gas boiler	331	15	One click LCA
Monocrystalline PV panels	259	20	One click LCA
Polycrystalline PV panels	197	20	One click LCA

Table 15. Overview of renovation measures and estimated GWP and service life used as input for the embodied carbon assessment.

Uncertainties remain, as emissions related to the transportation could not be estimated. Also the capacity of services may differ depending on the energy demand, and thus could in some renovation strategies be smaller, resulting in lower embodied carbon emissions. To simplify the calculation, the different capacities of services is not included in the assessment.

Equations
The frequency of replacement of materials and services is defined through the service life of materials, obtained from the database of One Click LCA and literature.

The initial embodied carbon is estimated with the formula (6):

$$GWP = V \times \rho \times CF \tag{6}$$

Where:

GWP represents the global warming potential (kg CO_2e)
V represents the volume of the material (m3)
ρ represents the density of the material (kg/m3)
CF represents the carbon emission factor specific to the material or product (CO_2e/kg)

This formula (6) estimates the global warming potential by multiplying the mass of the material with the specific carbon factor of the material. The mass of the material is estimated through the volume of the used material and it's density.

Recurrent embodied carbon
The recurrent embodied carbon, referring to emissions due to replacement of materials at the end of service life is calculated with the following equation (7):

$$GWP = m \times CF \times R \tag{7}$$

Where:

GWP represents the global warming potential (kgCO_2e)
m represents the mass of the material (Kg)
CF represents the carbon emission factor specific to the material or product (CO_2e/kg)
R represents the recurrence factor

This formula (7) estimates the global warming potential of a single material by multiplying the mass of the material with the specific carbon factor of the material. The product of the outcome and recurrence factor results in the GWP related to the replacement of the material over time. Recurrence of the measure over time due to replacement at the end of its service life is calculated with equation (8):

$$R = t_e / t_s \tag{8}$$

Where:

R represents the recurrence factor
t_e represents the endurance of a renovation measure, derived from the life span of the building (years)
t_s represents the service life of the material or product (years)

This formula (8) estimates the recurrence of a renovation measure due to reaching end of service life in the remaining life span of the building. In other words it calculates the number of times a measure is due for replacement, and thus how many times a measure reoccurs.

Calculation period
And lastly, to investigate the effects of renovation strategies on the performance of a building over the full life cycle of the building, the period for the assessment is set to 2030 till 2095, where (according to the literature review) 2030 relates to the first trigger point for renovation in Europe, and 2095 represents the end of life of the building based on the average service life of a terraced house, 129 years.

5.1.2 Embodied carbon performance - single go renovation

This section discusses the results of the embodied carbon assessment, and aims to identify characteristics of renovation strategies that result in higher and lower embodied carbon emissions.

Different than the operational carbon results, the embodied carbon results for a deep renovation (figure 32) show that emissions significantly vary between all strategies, due to different levels of insulation and material types. Strategies that consider a heat pump show higher embodied carbon emissions, due to the heat pumps high embodied emissions and short life span. Within the remaining strategies no clear categorization of measures can be found that relate to lower or higher embodied emissions. However, strategies that consider an electric boiler and soft insulation (glass wool) have higher emissions compared to strategies that consider gas boilers, and organic insulation (cellulose).

Within the shallow renovation strategies (figure 31) high embodied carbon emissions are related to window replacement and low emissions relate to cavity insulation.

Among the shallow and deep renovation strategies, the recurrent embodied carbon (over a building life span of 65 years) influences total embodied carbon the most.

Conclusion
The embodied carbon of heat pump strategies is significantly higher. And the recurrent embodied carbon causes most of the emissions. Within the shallow renovation strategies lowest emissions are related to cavity insulation and also related to highest operational carbon saving.

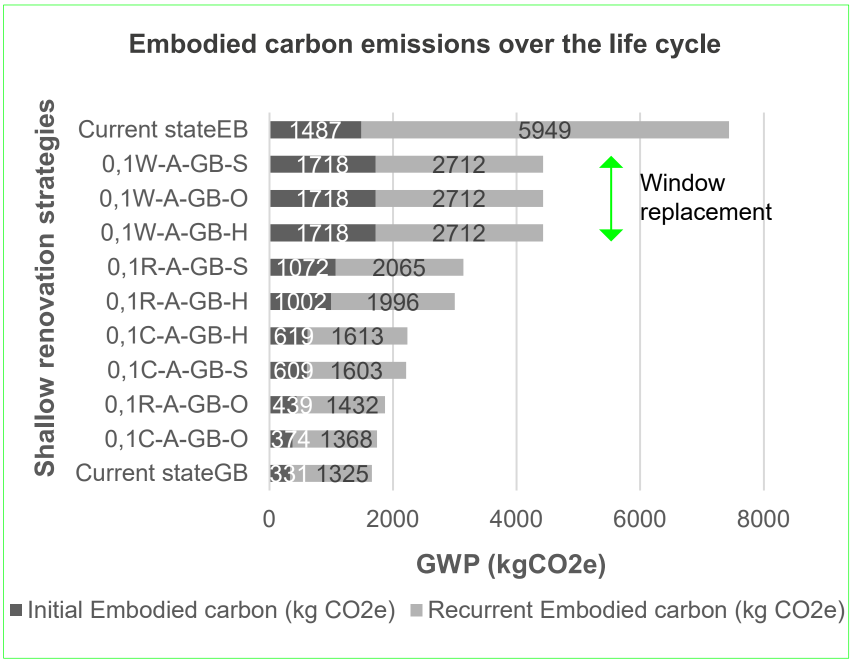


Figure 31. Shallow renovation strategies embodied performance (by author).

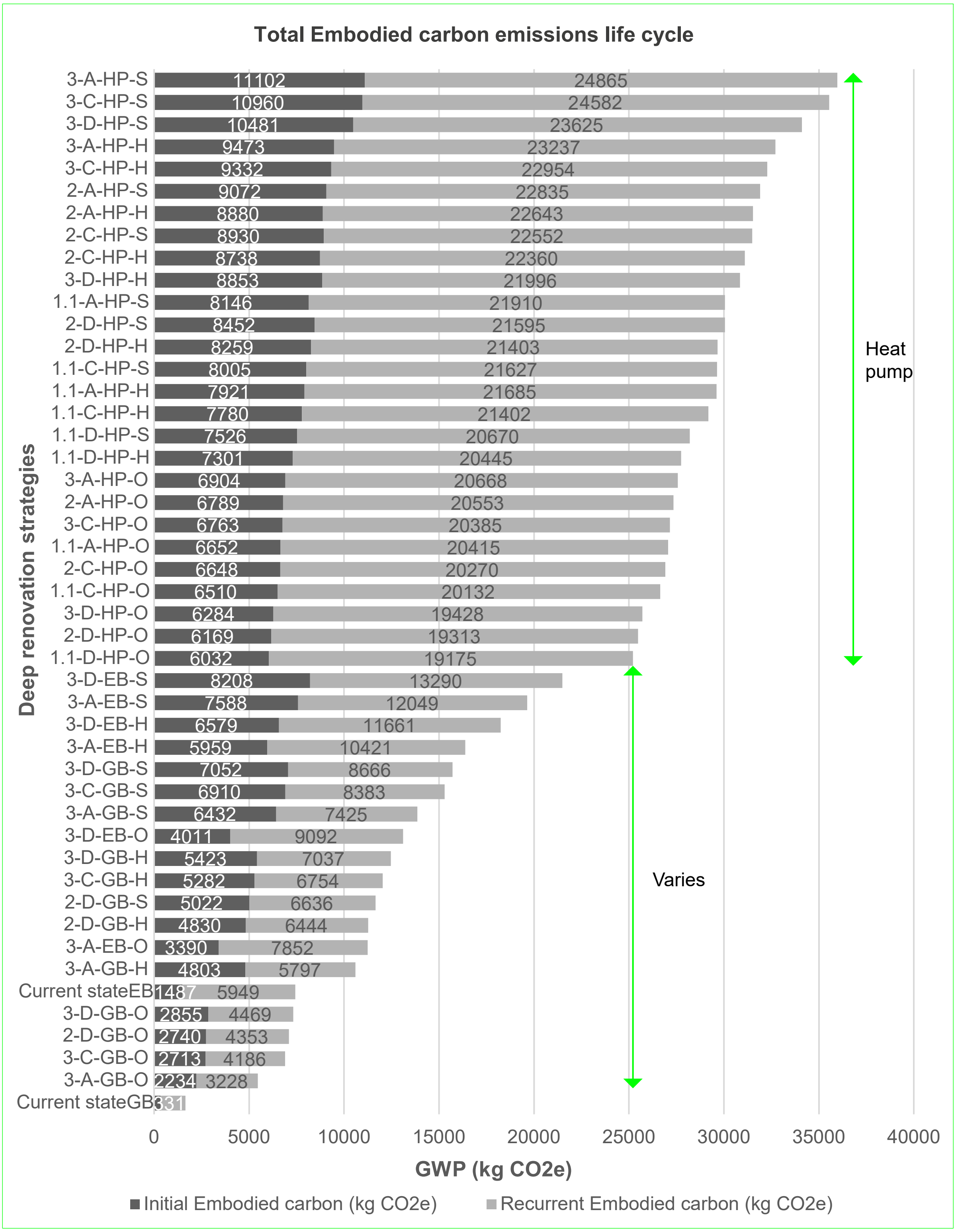


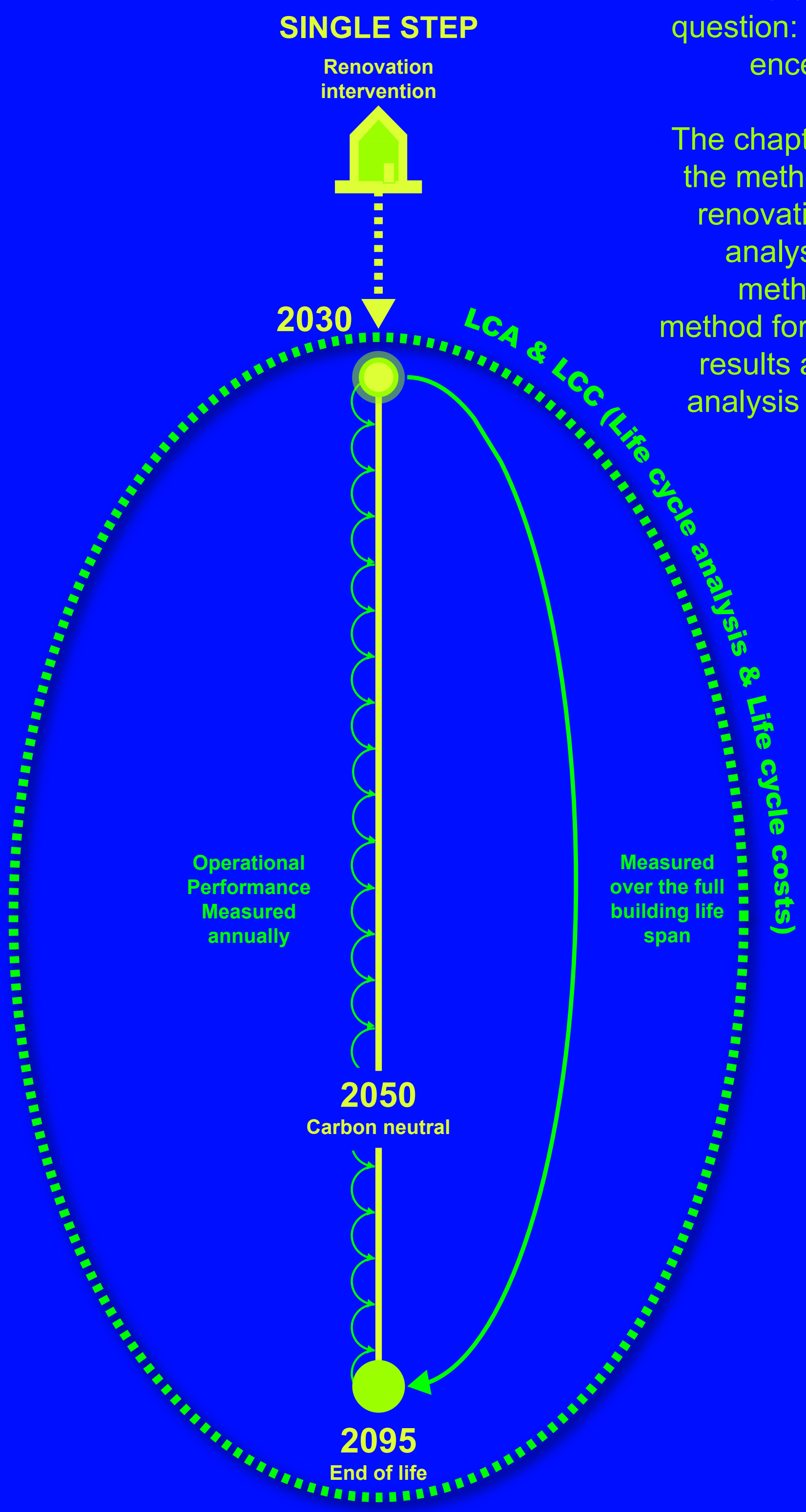
Figure 32. Deep renovation strategies embodied performance (by author).

CHAPTER 6| LCA & LCC

This chapter reveals how the deep and shallow renovation strategies perform over the full life cycle of the building, by analyzing total carbon emissions and total costs.

The chapter contributes to answering the sub question: "How do the renovation strategies influence the buildings life cycle performance?".

The chapter starts with an introduction describing the method to assess the overall performance of renovation strategies. Followed by the life cycle analysis (LCA), elaborating on the calculation method and the results. Then the calculation method for life cycle costs (LCC) and the obtained results are discussed. And last, an comparative analysis was performed taking into account LCA and LCC.



6.0 Introduction

Previous chapters revealed the performance of renovation strategies on operational energy, operational carbon and embodied carbon. The separate assessments are used as input to obtain insight in the holistic performance of renovation strategies. The holistic performance of renovation strategies can be determined by taking into account the main criteria for decision making which are costs, energy and carbon emissions. The energy performance is important for decision making as it determines the energy costs. As this is related to costs, the energy performance is not included in this chapter. The holistic assessment only includes costs and carbon emissions as starting point.

Method

The sub question "How do the renovation strategies influence the buildings life cycle performance?", is answered by using a methodological approach (figure 33). First an LCA analysis was performed by using data on the operational and embodied carbon emissions obtained from previous chapters. Then the LCC of renovation strategies are determined through assessment of the investment costs, recurrent costs and operational costs. The results of LCA ans LCC are combined to gain insight in the holistic performance of renovation strategies on costs and carbon emissions.

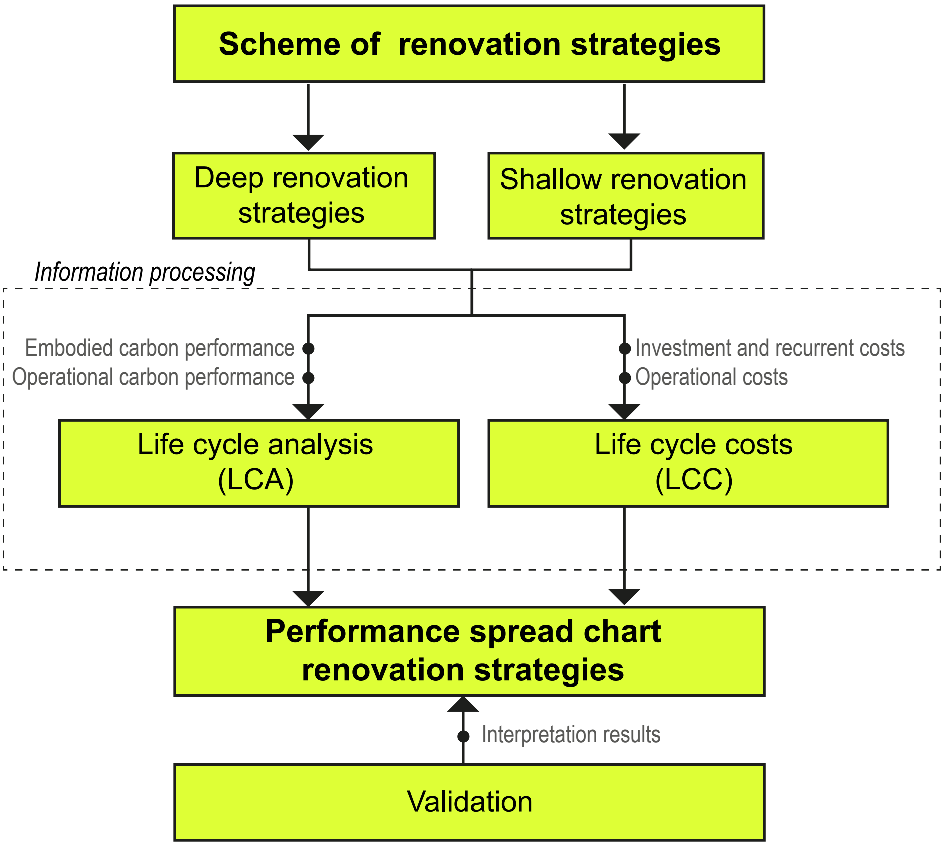


Figure 33. Method comprehensive assessment of renovation strategies (by author).

6.1 Life Cycle Assessment (LCA)

The LCA framework is an accepted and recognized method to assess the environmental performance of a building. To stay in line with previous research in the field of LCA and provide clearance on the environmental assessment, the LCA framework is used in this study. Although the LCA framework is standardized in ISO 14044, it still contains uncertainties in the scope of the phases used in the framework. The phases consist of ‘’Goal and scope’, ‘’Life cycle inventory (LCI)’’, ‘’Life cycle impact assessment (LCIA) and ‘’Interpretations’’, with most uncertainties related to LCI that covers among others the service life of the building. To provide transparency on uncertainties, this section provides detailed information on what is included in each phase of the framework, limitations of each phase, as well as persisting uncertainties. With as aim to support further research in this field by providing clearance on the assessment in a format (LCA framework) that is widely recognized. This section is organized according to the phases of the LCA framework. In figure 34 all subjects that are covered per LCA phase are presented.

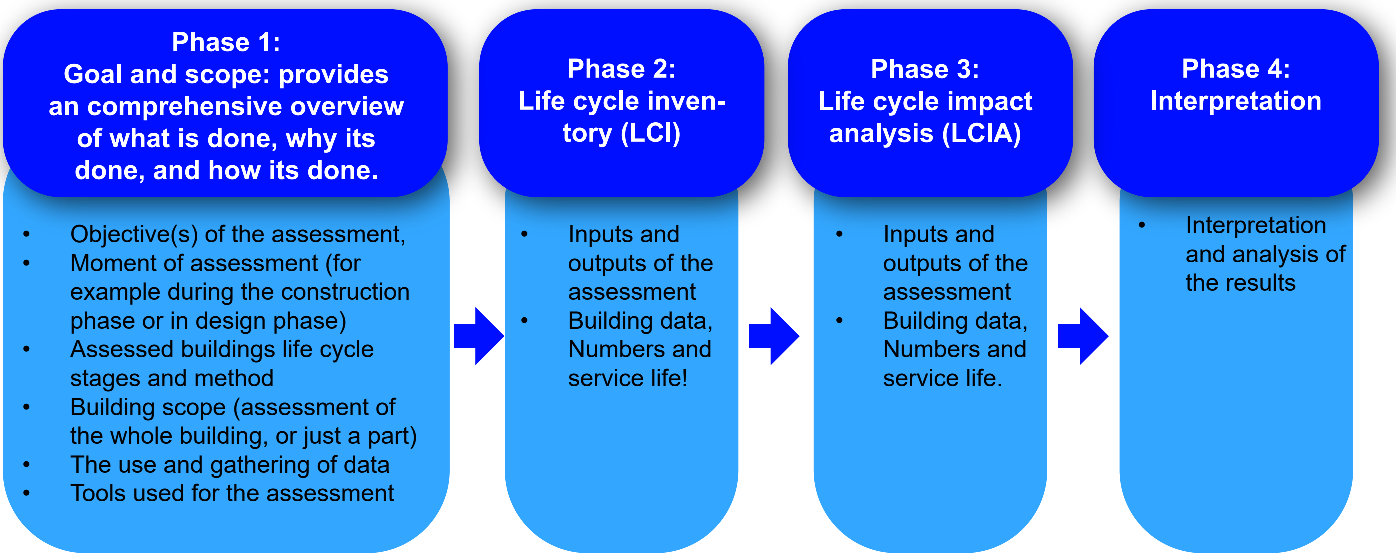


Figure 34. LCA framework overview (created by author).

6.1.1 LCA Framework applied

Phase 1| Goal and scope

The goal and scope provides insight in the objective of the LCA assessment and what is and isn't included in the LCA assessment. It also provides insight in how data is selected, gathered and used.

Objective assessment

The objective of the LCA assessment is to gain insight in the performance of various renovation strategies, to be able to compare their environmental performance. A variety in renovation strategies is a key factor to gain insight into the performance differences of renovation solutions. In this assessment variety is achieved through assessing different levels of energy reduction, different energy sources, and different materials.

Moment of assessment
This LCA assessment is performed in the concept design phase, which means that representative data is used to assess the environmental performance as well as the energy performance of renovation strategies. The actual energy performance and environmental performance after executing a renovation strategy will deviate from the calculated performance. To minimize this affect parameters that are considered are carefully selected, and explained further in this paragraph.

Assessed building life cycle stages
Operational carbon emissions occur in the in-use stage of a building’s life cycle. Embodied carbon emissions occur in all stages. From the literature review can be concluded that a significant large portion of the emissions is related to the production stage and the use stage. Studies disagree on the impact of the construction stage and the end-of-life stage, arguing that the impact might be larger. As these stages are both affected by transport, the impact on carbon emissions could vary from case to case. As the purpose of the study is to gain insight in the performance of various renovation strategies compared to each other, and not the exact achieved performance of a strategy on a specific building, the end-of-life stage and the construction stage are excluded in the assessment. So, the assessment only focuses on the production stage and in-use stage of a building’s life cycle.

Secondly, by selecting specific renovation measures the impact on emissions in the assessed stages is influenced. However, to simplify the assessment the renovation measures assessed had to be minimized. To understand how the selection affects carbon emissions in the stages, some important starting points for the selection are discussed here:

- Renovation measures that include structural elements, such as second skins, are avoided in renovation solutions, avoiding high embodied carbon emissions related to structural elements. For renovations measures that include structural elements in a building that already has a high energy performance, trade off comparison becomes more critical, and assessment of multiple stages could provide valuable insight. Further research is needed to enable trade-off comparison, in cases where the operational carbon is already low.
- The assessment of the embodied carbon considers only the insulation and services. Insulation can be applied to cover a large portion of the envelope, compared to other renovation measures considering materials this is in volume the largest. Therefore it’s considered to be an impactful measure considering the embodied carbon. The literature study revealed that the emissions related to insulation is second highest besides structural elements. On the contrary, cladding systems could be supported by a secondary structure and influence the emissions. Also stone like claddings could result in higher emissions. To keep the assessment simple it’s not included, and further research on this matter is needed.
- The starting point for the assessment is the original state of the building, without any renovation performed, besides the addition of a gas boiler for heating, which is common for most buildings. However, in practice renovation work could have already been performed on the building, resulting in a different starting point, and therefore different emissions. Further research is needed to understand how to approach cases where renovation acts are already performed on.

Building scope
The assessment is performed on a typical terraced house to ensure representative results for the majority of residential buildings. Further research is needed to investigate how this approach applies to other building typologies. The assessment considers the whole building, including the whole volume, and the whole envelope. The functional unit is the building. A detailed description of the building is included in chapter 3 "renovation strategies". The renovation measures considered for the building can be categorized in active and passive measures. As passive measures different levels of insulation and infiltration are considered, and as active measures different ventilation systems, heating systems and photovoltaic panels are considered. According to the literature review these measures influence the energy demand the most. Furthermore, the relation between energy performance, costs and environmental performance isn't necessarily linear and therefore different levels of insulation, insulation materials, ventilation systems, heating systems and photovoltaic panels are considered in the assessment. The obtained measures are then compiled to form renovation strategies with each their specific energy performance, environmental performance and related costs. A detailed description of the input values related to the measures and strategies is provided in chapter 3.

Use and gathering of data
The assessment of the operational carbon requires a different method compared to the embodied carbon, as it is related to the energy use in the in-use stage of the building, which is influenced by building parameters. While the embodied carbon is mainly related to the energy use during the production of the material and is not influenced by building parameters. Available tools don't allow quick assessment of renovation options regarding the embodied and operational carbon. Therefore, for the assessment different tools and methods are used.

Tools used for the assessment
The tools used for the assessment are shown in table 16.

Table 16. Tools used for the assessment of the environmental performance, energy performance and renovation costs over the life cycle of the building.

	One Click LCA	Design Builder	Excel (manual Calculation)
Heating demand		X	
DHW			X
Embodied carbon	X		
Operational carbon			X
Energy saving			X
Recurrent embodied carbon	X		X
Costs			X
Recurrent costs			X
Building life cycle			X
Energy generation			X

Phase 2| Life cycle inventory (LCI)
Life cycle inventory specifically serves to provide information on the inputs and outputs of the assessment. The inputs of the assessment are represented in earlier chapters. Information on the building typology (table 10), the inputs for renovation measures (table 11), the combinations of renovation measures (renovation strategies, table 12) are provided in chapter 3. Chapter 4 and 5 provide insight in the calculation method of the embodied and operational emissions. The output consists of the operational carbon, the initial embodied carbon, recurrent embodied carbon, and total life cycle carbon emissions.

Building typology ''Representative 60s Terraced house''
Specific characteristics of a terraced house influences the performance of the building, such as the life span and the moment when renovation will take place. The life span is one of the main uncertainties in LCA, and should be selected based on the representability of the actual lifespan. The literature review provided insight in a representative life span for the building. Based on the literature study the life span of the terraced house is assumed to be around 129 years. The selected terraced house was built in 1966 and will according to the theory reach the end of its service life in 2095, which is used in the calculation setting.

Phase 3| Life cycle impact analysis (LCIA)
First, the energy saving potential of all renovation strategies is analyzed to investigate which strategies fall under a deep renovation, a moderate renovation or shallow renovation, by dividing the energy demand after renovation with the current energy demand. The environmental impact is further analyzed on the embodied carbon, operational carbon and total carbon emissions estimated as the Global warming potential (GWP) in kgCO_2e. The environmental impact is calculated for a year, and for the full life cycle of the building. This way also the recurrent embodied carbon can be analyzed. Lastly, the energy generation potential is used to estimate if the carbon emissions related to the operational and embodied carbon can be compensated for on a building scale.

Phase 4| Interpretations
The interpretation of the results are separately presented in chapter 4 (operational carbon), chapter 5 (embodied carbon) and chapter 6 (LCA).

6.1.2 Life cycle assessment (LCA) single step renovations

The environmental performance is analyzed through the operational carbon emissions and embodied carbon emissions related to the renovation strategies. The results for a shallow renovation are presented in figure 35. The carbon emissions over the full life cycle of the building for a shallow renovation range from 133887 kgCO_2e to 144230 kgCO_2e. Cavity insulation provides the highest reduction in carbon emissions over the full life cycle of the building, approximately 133887 kgCO_2e. The renovation measures, roof insulation and window replacement, provide similar reduction in carbon emissions. Replacing the heating system with an electric boiler proves to be more effective in reducing total carbon emissions. Overall the life cycle carbon emissions in shallow renovations are determined by the operational carbon, and are lower for solutions that provide higher energy saving.

The results on carbon emissions for a deep renovation are presented in figure 36. The carbon emissions over the full life cycle of the building in case of deep renovation varies from 37109 $kgCO_2e$ to 75008 $kgCO_2e$. A heat pump provides the highest reduction in carbon emissions over the full life cycle of the building, varying from 37109 $kgCO_2e$ to 47621 $kgCO_2e$. The lowest reduction in carbon emissions is related to the use of a gas boiler. In other words, the choice of heating system influences total carbon emissions the most. A heat pump shows lowest carbon emissions, followed by and electric boiler and a gas boiler.

The strategies that contain a heat pump have significantly higher embodied carbon emissions, compared to other deep renovation strategies. Furthermore, the embodied carbon emissions of heat pump strategies are over two times higher than the operational carbon emissions. In other words, adding a heat pump results in lower operational carbon emissions yet increased embodied carbon emissions. The large emissions are related to the production of the heat pump, as well as it's short service life. Within strategies that consider a heat pump, further reduction in carbon emissions can be obtained by increasing the service life of the heat pump or reducing the emissions related to the production of heat pumps.

Last, the results show no relation with the insulation level and ventilation system, as these vary in strategies with low carbon emissions and high carbon emissions. On the other hand, organic insulation (cellulose) corresponds with lower carbon emissions. Thus besides a heat pump, the insulation material influences the total carbon emissions the most.

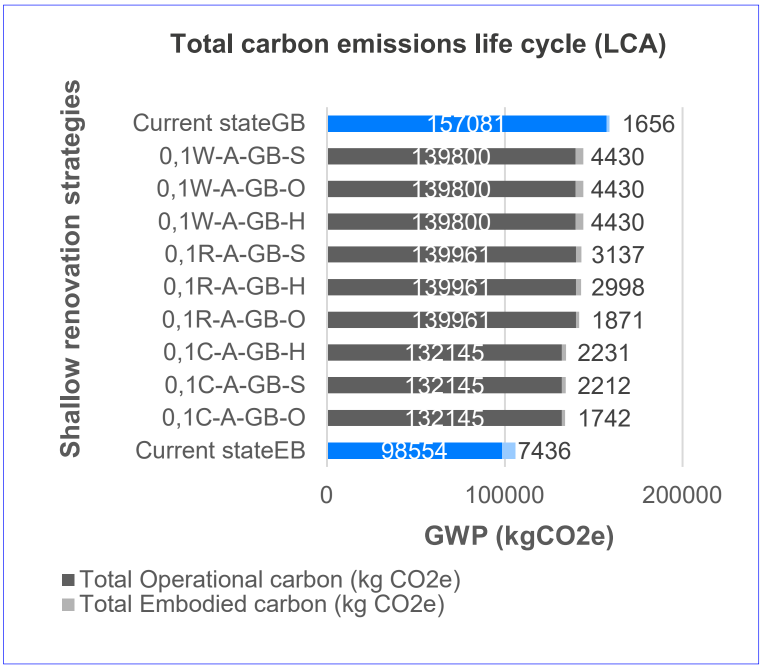


Figure 35. Total carbon emissions consisting of the embodied and operational carbon, presented for all shallow renovation strategies and the current state (data on the embodied carbon is obtained from One Click LCA) (insight on the operational carbon is obtained from data of Rapportage CO_2-uitstoot (n.d.), the national climate monitoring database and Design Builder simulations) (graphs created by author, in Excel).

Conclusion

Within shallow renovations the embodied carbon emissions are of neglectable magnitude, the operational carbon is therefore a good representative for total carbon emissions. In contrast, deep renovation strategies show higher embodied carbon emissions. Particularly, strategies that consider a heat pump relate to embodied carbon emissions that are over twice the operational carbon emissions. In these cases life cycle assessment is more important to determine the environmental performance, rather than an energy assessment. Overall the total carbon emissions are determined by the energy system. Heat pumps offer the highest reduction in carbon emissions, followed by electric boilers and gas boilers.

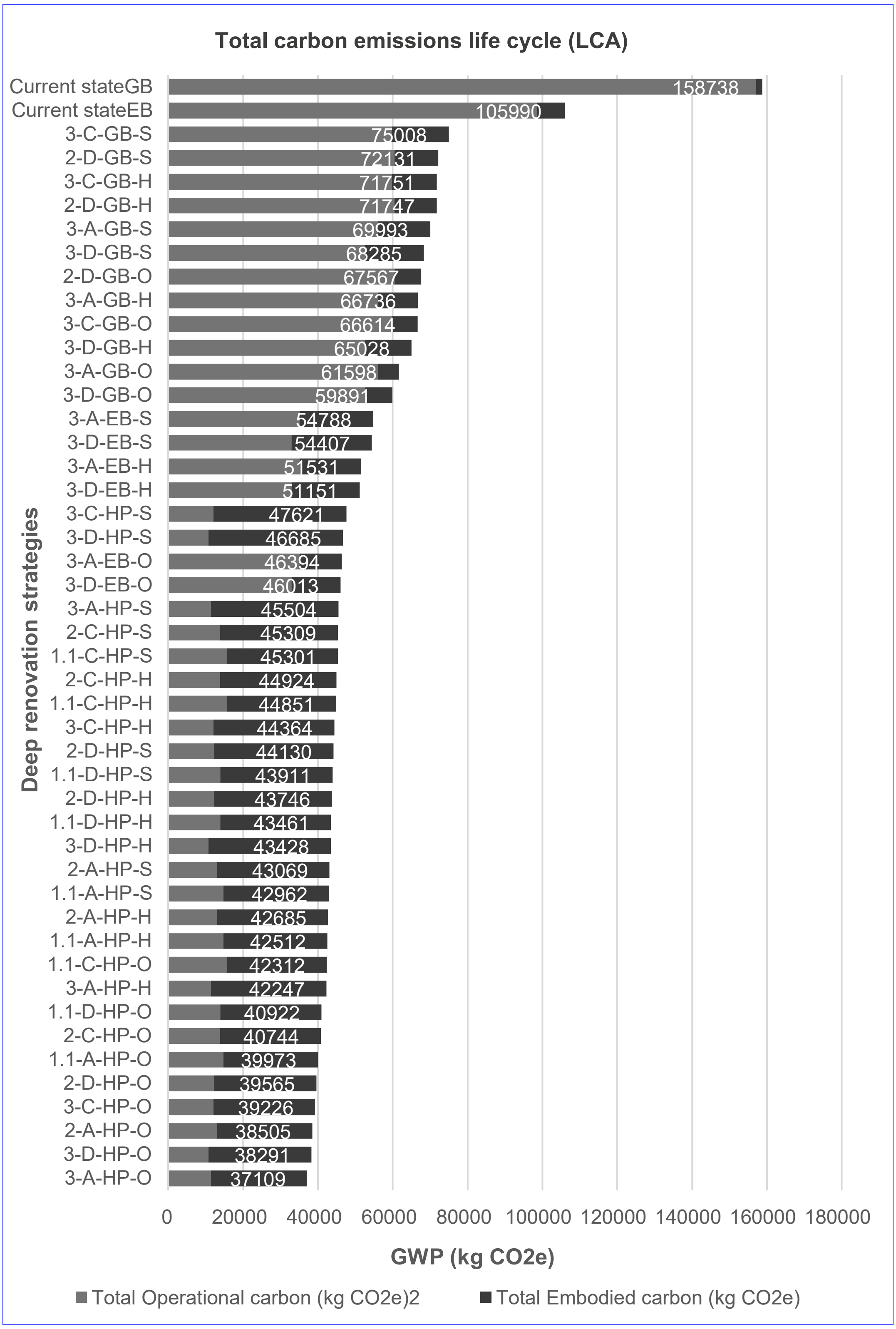


Figure 36. Total carbon emissions consisting of the embodied and operational carbon, presented for all deep renovation strategies and the current state (data on the embodied carbon is obtained from One Click LCA)(insight on the operational carbon is obtained from data of Rapportage CO_2-uitstoot (n.d.), the national climate monitoring database and Design Builder simulations) (graphs created by author, in Excel).

6.2 Life cycle costs (LCC)

LCC offers insight in the total costs over the full life cycle of the building, and can be distinguished in operational costs and embodied costs. The operational costs are the costs for energy consumption and the embodied costs refer to the costs related to the use of materials.

6.2.1 Calculation method operational costs

Over the past years the energy prices for electricity and natural gas have been unstable. Overall for both gas and electricity an increase in energy price can be concluded (figure 37). Particularly, the energy price for natural gas increased significantly. Assuming energy prices will increase when the energy transition progresses, recent energy prices are considered in the assessment. In 2022 the energy price for natural gas is estimated €0,18 per kWh and the electricity price €0,46 per kWh (figure 37).
The obtained energy prices are used as input for the assessment. For renovation strategies that consider an electric boiler or heat pump, the electricity price is used and for strategies considering a gas boiler, the natural gas price is used.

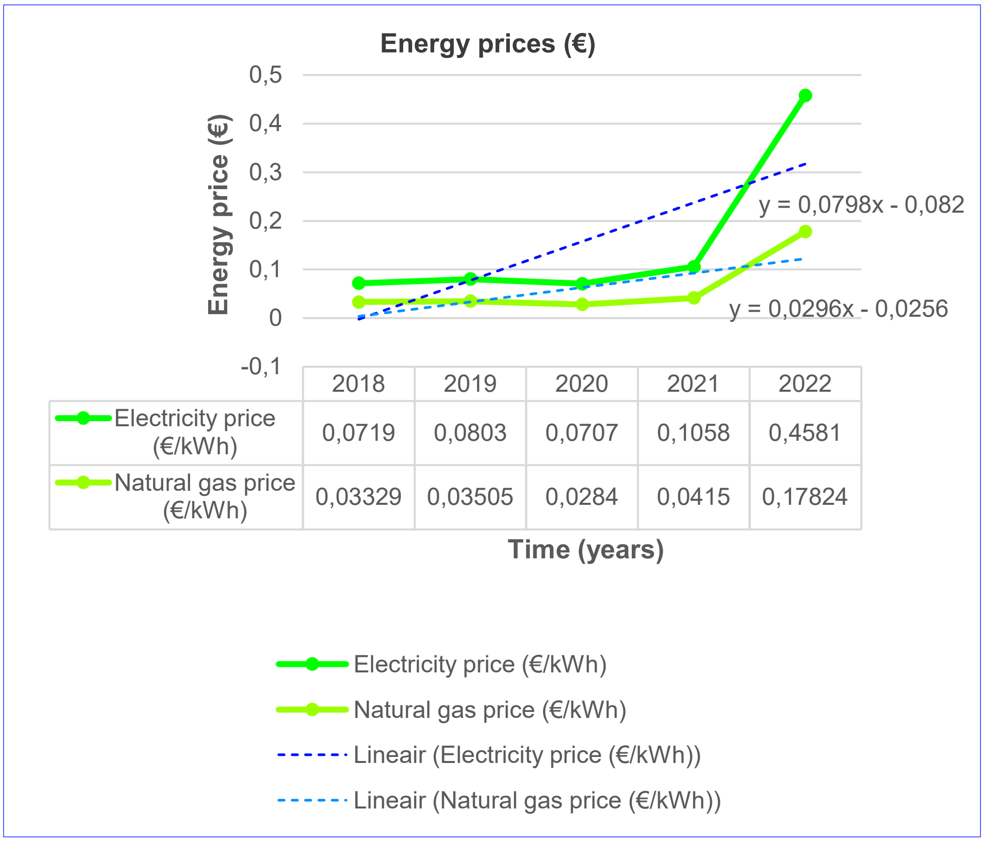


Figure 37. Calculation method operational costs (data adapted from CBS Statline, n.d.).

Besides the energy price the energy use is used to obtain the operational costs. The energy use is obtained from the operational energy assessment in chapter 4.

Equation
The operational costs are estimated with equation:

$$C_{operational} = E_{operational}\ x\ C_{energy} \quad (9)$$

Where:

$C_{operational}$ represents the operational costs (€)
$E_{operational}$ represents the operational energy use (kWh)
C_{energy} represents the energy price (€)

This formula (9) estimates the operational costs by multiplying the operational energy use with the energy price .

6.2.2 Calculation method embodied costs

Embodied costs can be separated into costs for materials and services. It consists of the investment costs and recurrent costs. The recurrent costs refer to the replacement costs of materials and services at the end of service life. The costs of materials and services for the calculation are presented in table 17, and provided by the Dutch Enterprise Agency (RVO). Costs may vary in the future as the energy transition progresses, more research is needed to determine future costs of services and materials.

Table 17. Estimated costs for services and materials, included in renovation measures (data adapted from Kostenkentallen RVO (n.d.)).

Materials and services obtained from renovation measures	Investment cost (Including installation and the use of additional materials)	Unit	Specific replacement cost (for services lower than investment, includes only the unit costs)
Heat pump	€12.236	1	€ 4.460
Gas boiler	€ 2.380	1	€ 1.779
Elec boiler	€ 5.852	1	€ 4.400
Ventilation system D	€ 5.453	1	€ 1.300
Ventilation system C	€ 3.043	1	€ 577
Monocrystalline	€ 248	m2	As investment
Polycrystalline	€ 190	m2	As investment
Glass wool	€ 91	m3	As investment
EPS	€ 91	m3	As investment
Cellulose	€ 63	m3	As investment
Glass wool (cavity)	€ 12	m3	As investment
EPS (cavity)	€ 23	m3	As investment
Cellulose (cavity)	€ 63	m3	As investment
Double glazed windows (HR++)	€ 168	m3	As investment
Triple glazed windows (HR+++)	€ 207	m3	As investment

Costs is one of the main criteria in decision making and therefore included in the assessment of renovation strategies. The highest cost in general consists of the investment costs and the recurrence of these cost throughout a buildings life cycle due to the end of service life. Rough data was obtained from RVO. The costs do not include costs for installation and construction. The energy costs are not considered in the assessment as this fluctuates and is considered to be unreliable. Also, the price reduction of materials and services is not included, but could obviously influence decision making significantly. On the contrary, the energy assessment and replacement frequency of elements could be used as an indicator for the reduction in energy costs and replacement costs. The costs for insulation, services and ventilation are included in the assessment. The investment costs for services are estimated per unit. While the investment costs for the materials are estimated by the corresponding volume. Other materials that are also important to assess such as the cladding, is not assessed in this study, to simplify the assessment, but should be included to gain full insight in the costs.

Equations

Investment costs related to building services are estimated with equation (10):

$$C_{investment} = C_{unit+materials} \times U_{services} \quad (10)$$

Where:

$C_{investment}$	represents investment costs services (€)
$C_{unit+materials}$	represents the costs per unit including additional costs for materials to integrate the unit into the building (€)
$U_{services}$	represents the number of services (units)

Equation (10) estimates the investment cost by multiplying the unit cost and the number of units. The replacement costs are estimated as:

$$C_{replacement} = R \times C_{unit} \quad (11)$$

Where:

$C_{replacement}$	represents the costs for replacing the services over the remaining life span of the building (€)
R	represents the recurrence factor
C_{unit}	represents the cost per service unit (€)

Equation (11) estimates the replacement costs by multiplying the recurrence factor with the cost per service unit. The recurrence factor is estimated with equation 8 (see chapter 5). Material related investment costs are estimated with equation (12):

$$C_{investment} = C_{material} \times V \quad (12)$$

Where:

$C_{investment}$	represents the investment costs services (€)
$C_{material}$	represents the costs of the material (€/m^3)
V	represents the volume of the material (m^3)

Equation (12) estimates the investment costs related to materials by multiplying the material cost per m^3 with the volume of the material. The replacement costs related to materials due to the end of service life is calculated with equation (13):

$$C_{replacement} = R \times C_{investment} \qquad (13)$$

Where:

$C_{replacement}$ represents the costs for replacing the services over the remaining life span of the building (€)
R represents the recurrence factor
C_{unit} represents the investment costs of the material (€)

Equation (13) estimates the replacement costs by multiplying the recurrence factor with the investment costs of the material. The recurrence factor is estimated with equation 8 (see chapter 5).

6.2.3 Calculation method LCC

LCC is estimated as the sum of operational costs and embodied costs. An overview of the calculation is provided in figure 38.

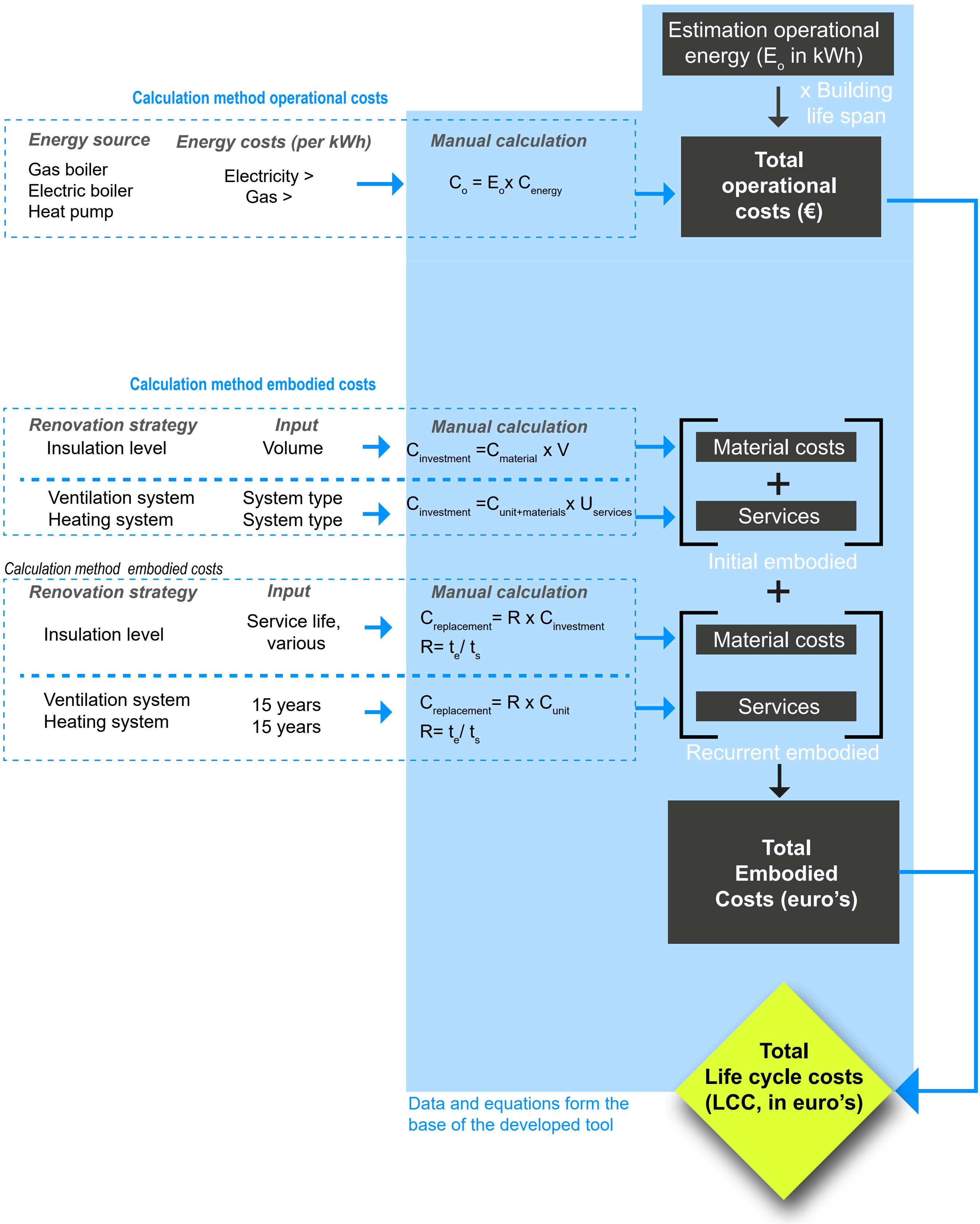


Figure 38. Calculation method life cycle costs (created by author).

Equation
The total costs are estimated with equation (14):

$$C_{total} = C_{investment} + C_{replacement} + C_{operational} \quad (14)$$

Where:

C_{total} represents the total costs of the renovation over the full life cycle of the building (€)
$C_{investment}$ represents the investment costs related to both services and materials (€)
$C_{replacement}$ represents the costs for replacement of materials and service over the remaining service life of the building (€)
$C_{Operational}$ represents the operational costs (€)

Equation (14) estimates the total costs of the renovation strategy as the sum of the investment costs and the replacement costs, related to both materials and services.

6.2.4 Life cycle costs - single go renovation

Investment and recurrent costs (embodied costs)
The embodied costs related to shallow renovation strategies are presented in figure 39. The total costs for shallow renovation strategies range from €9876,- to €17224,-. The costs for window replacement are higher than costs related to other measures. Costs related to cavity insulation and roof insulation range from €9876,- to €10998,-, of which cavity insultion is cheapest.

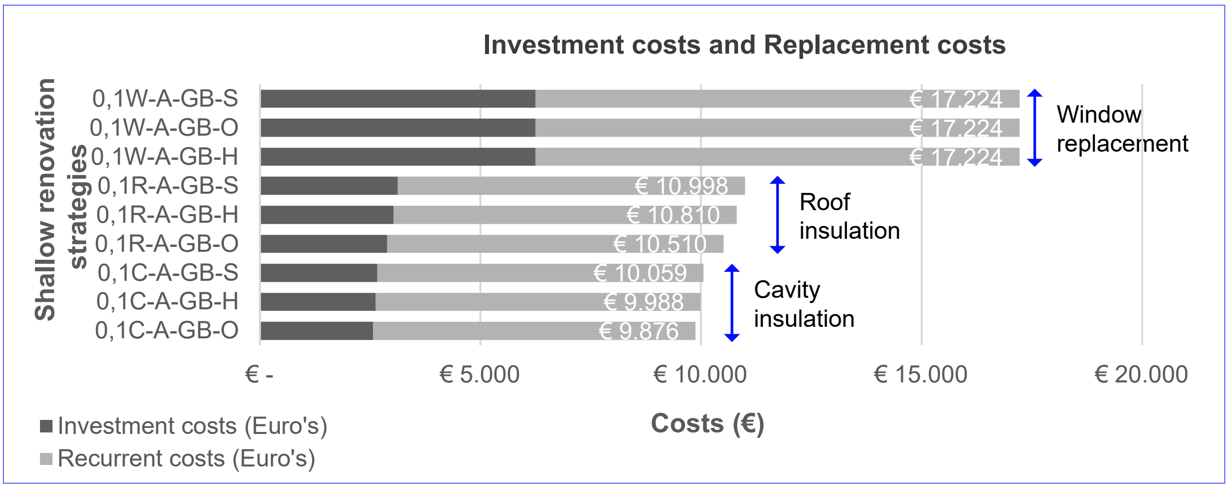


Figure 39. Investment costs and replacement costs shallow renovation strategies (created by author).

In figure 40 embodied costs for deep renovation strategies are presented. The costs consist of the cost for insulation, window replacement, ventilation system, and heating system. The costs for deep renovations vary from €23556,- to €54375,-. For the majority of strategies the costs are between €40000,- and €50000,-. Strategies with costs lower than €40000,- do not include a heat pump. Low costs are related to gas boiler strategies, due to the low investment price compared to other energy systems. Strategies with various insulation levels result in low as well as high costs, in other words the level of insulation has limited effect on the investment costs. Out of the 5 strategies with the highest costs, all strategies consider a heat pump and ventilation system D. Thus, a heat pump influences the embodied costs the most, followed by the ventilation system and insulation level. For the service life of the heating systems 15 years is considered, while for the service life of the insulation around 50 years (depending on the material) is considered. The recurrent costs therefore mainly consists of costs related to replacing either the heat pump, electric boiler or gas boiler.

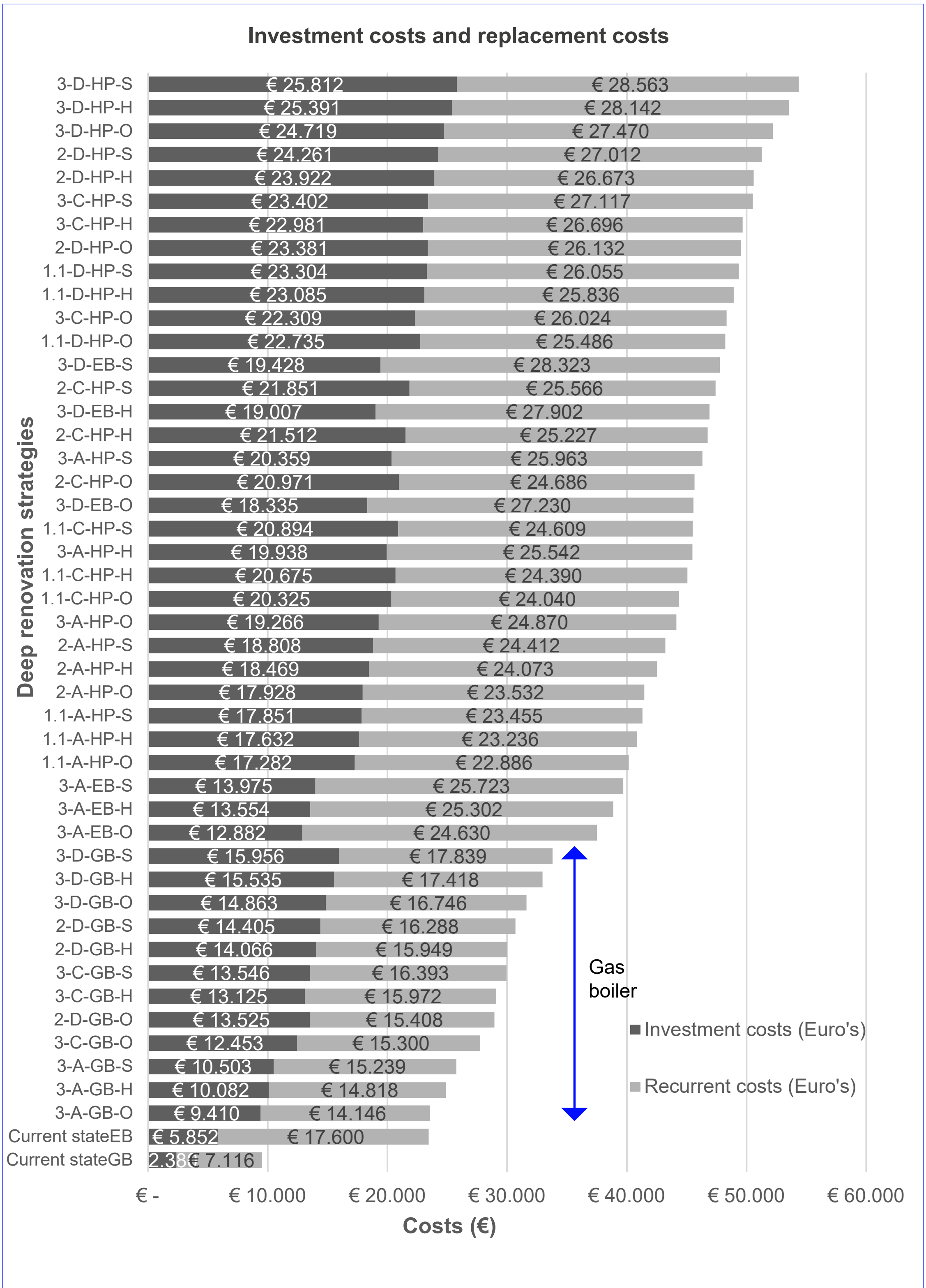


Figure 40. Investment costs and replacement costs deep renovation strategies (created by author).

Life cycle costs (embodied + operational costs)

Total life cycle costs for the current state are approximately €184.000,- (figure 41). Out of the shallow renovation strategies lowest costs over the life cycle are achieved with cavity insulation, followed by roof insulation and window replacement (figure 42). The life cycle costs mainly consist of operational costs. Out of the deep renovation strategies high life cycle costs are related to strategies that consider an electric boiler (figure 43). Due to the high energy price of electricity the startegies that consider an electric boiler have significantly high life cycle costs, even higher than the life cycle costs of the current state. Low costs are related to strategies that consider a gas boiler. As heat pumps use electricity to function, the operational costs are still relatively higher compared to natural gas. However, with a heat pump the life cycle costs are lower compared to the current state. Furthermore, life cycle costs are related to the ventilation system. Ventilation system D shows lower costs compared to C, due to lower operational costs. Ventilation system A seems optimal, but is calculated as underventilation to represent the current ventilation behaviour of building occupants. If Ventilation system A would be calculated according to the required ventilation in houses, the operational energy costs would increase. Besides the ventilation system the costs are determined by the level of insulation, high insulation (level 3) resulting in lower life cycle costs.

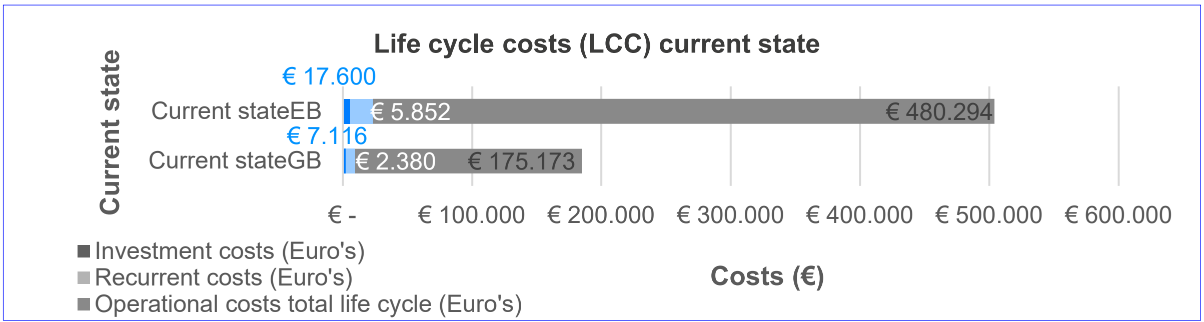


Figure 41. Life cycle costs current state (created by author).

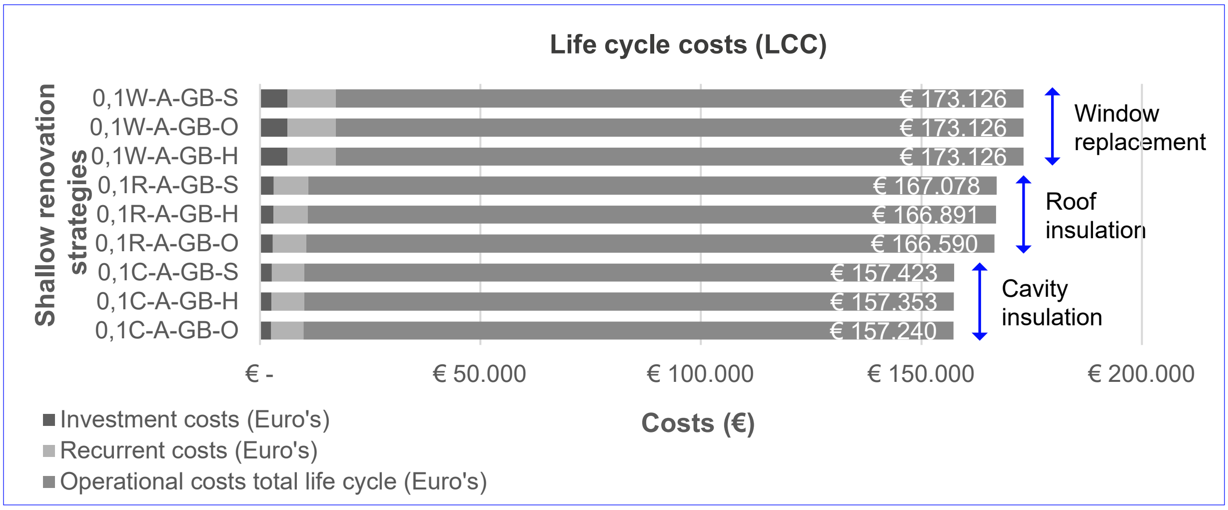


Figure 42. Life cycle costs shallow renovation strategies (created by author).

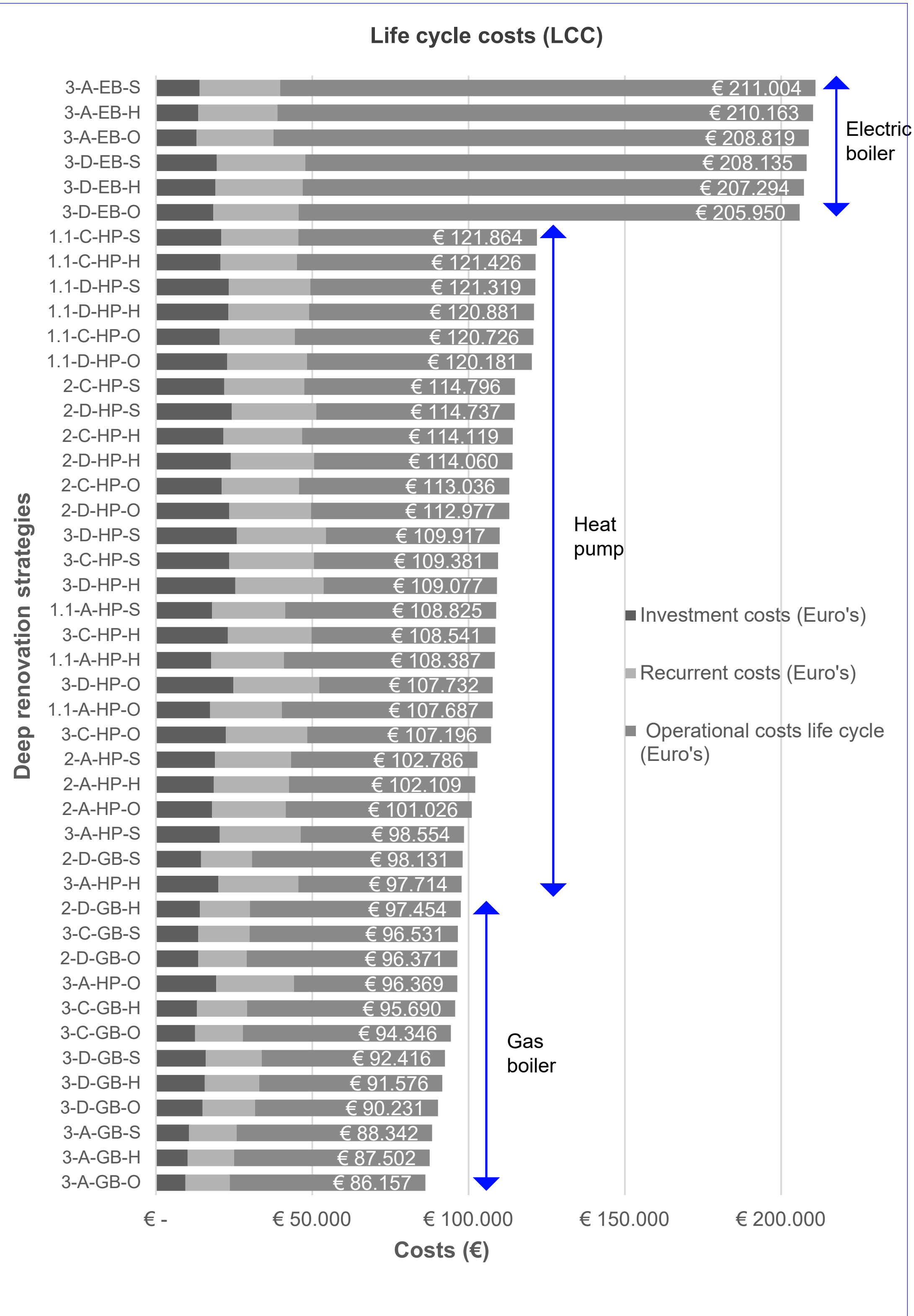


Figure 43. Life cycle costs deep renovation strategies (created by author).

6.3 LCA and LCC Comparison

Deep renovation strategies are praticularly referred to in research as cost intensive. Therefore it is important to investigate which strategies result in low costs and carbon emissions. The deep renovation strategies are analyzed with a spread chart to capture the holistic performance (figure 44).

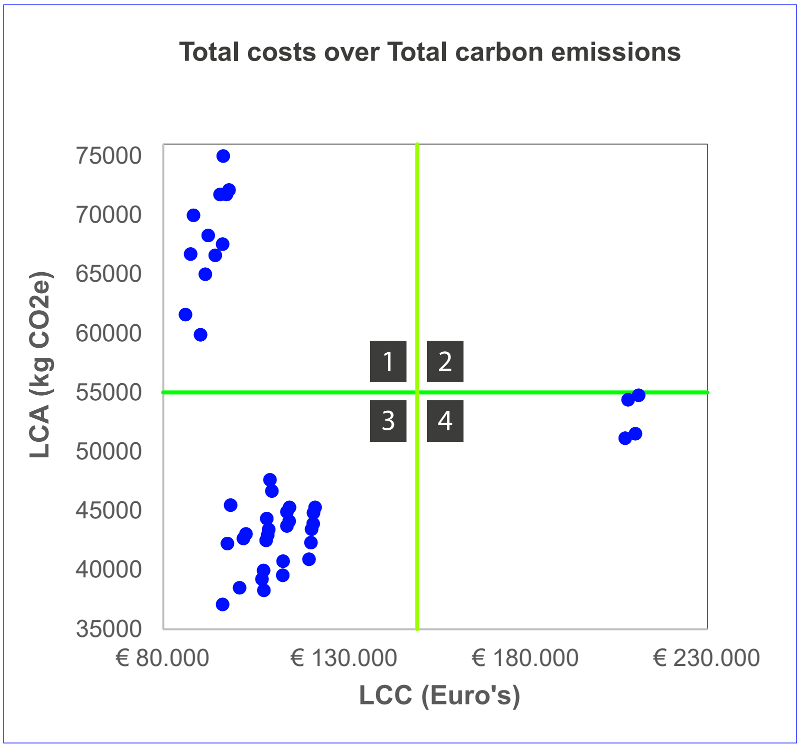


Figure 44. Comparison LCC in relation to LCA of deep renovation strategies (created by author).

The strategies can be assigned to 4 quadrants, with in quadrant 3 the strategies with lowest costs and carbon emissions. Zoomed in views of quadrants 1,3 and 4 are provided in figures 45, 46 and 47.

Quadrant 1 - High carbon emissions, low costs

Strategies related to high carbon emissions and low life cycle costs are related to strategies that consider a gas boiler as energy system. This is even the case for strategies that consider, high insulation in combination with a gas boiler. High carbon emissions and low costs are related to strategies that consider natural gas as energy source.

Quadrant 3 - Low carbon emissions, low costs

Strategies that result in low carbon emissions and low costs, al contain a heat pump. Lowest life cycle costs are achieved with strategies that consider a heat pump and moderate insulation. Lowest emissions are achieved with startegies that consider a heat pump and high insulation. On the contrary minimum insulation can also result in low carbon emissions. The costs when a heat pump is combined with minimum insulation results in an extra cost over the full life cycle of approximately €15.000,-.

Quadrant 4 - Moderate carbon emissions, high costs

Moderate carbon emissions and high costs relate to strategies that consider an electric boiler. Figure 47 does not contain all deep renovation strategies that consider an electric boiler as these had higher life cycle costs. Strategies within quadrant 4 with lowest life cycle costs, consider besides an electric boiler, high insulation and ventilation system D.

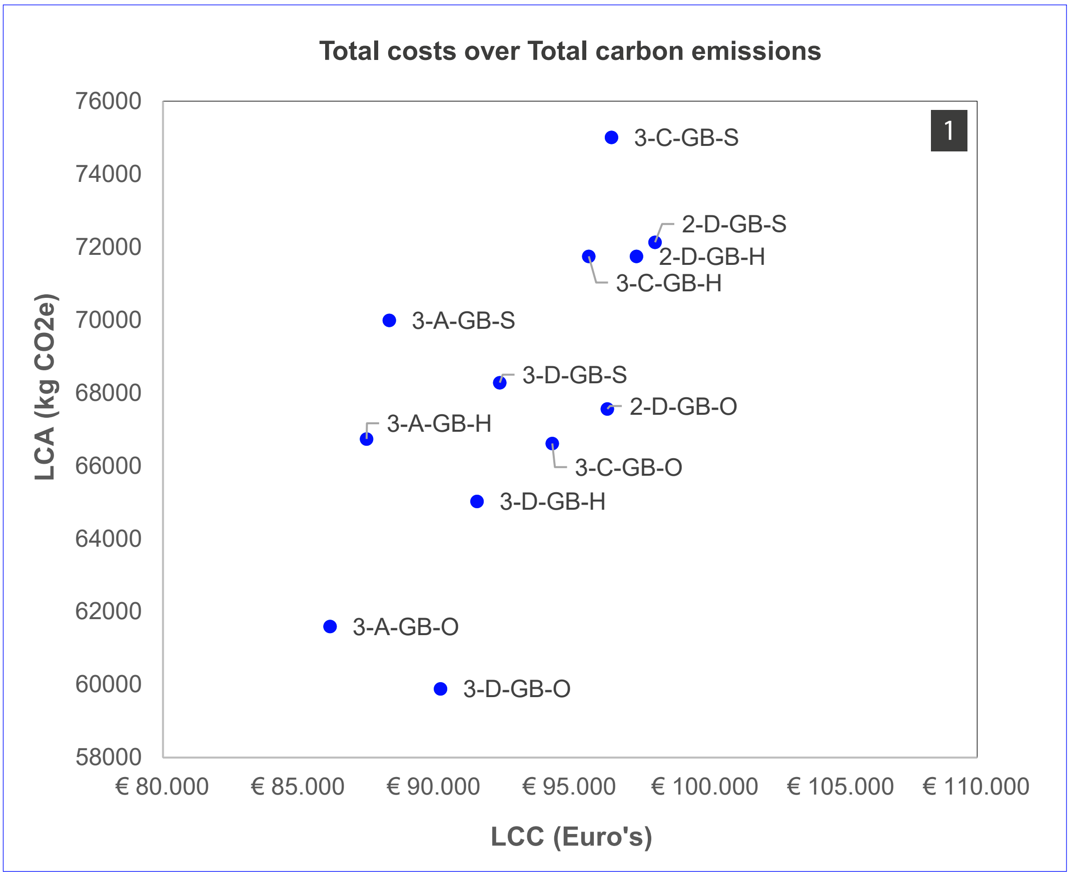


Figure 45. Spread in quadrant 1: comparison LCC in relation to LCA of deep renovation strategies (created by author).

Overall conclusion

Out of the shallow renovation strategies cavity insulation is suitable for renovation where investment budget is limited, followed by roof insulation and window replacement. Out of deep renovation strategies, strategies that consider a gas boiler are lowest in embodied costs, followed by strategies considering electric boilers, and heat pumps. Secondly, high embodied costs are related to implementation of system D. The level of insulation and the type of material has limited influence on the embodied costs over the life cycle.
Life cycle costs considering the operational and embodied costs, are mainly determined by the operational costs, which is lower voor deep renovations that cosider a heat pump. Due to the high energy price for electricity, strategies that consider an electric boiler have high life cycle costs, resulting in significantly higher costs compared to the current state. If the objective is to reduce life cycle costs, choosing a strategy that considers an energy source with a low (and stable) energy price is crucial.
Out of the assessed renovation strategies, strategies that result in low carbon emissions and low costs, al contained a heat pump. While high emissions relate and low costs relate to strategies that considered a gas boiler. High costs and moderate carbon emissions related to strategies that considered electric boilers, of which the costs is caused by the energy price.

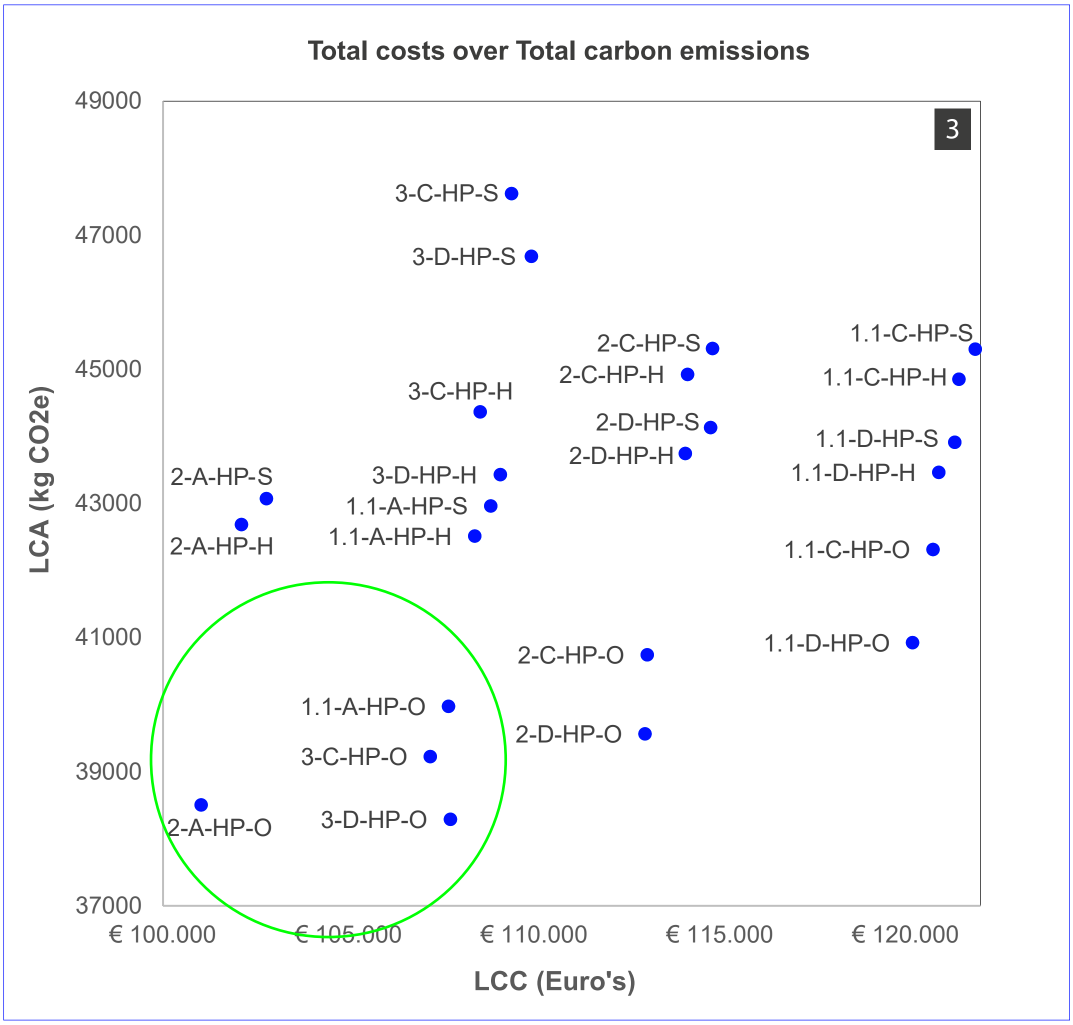


Figure 46. Spread in quadrant 3: Comparison LCC in relation to LCA of deep renovation strategies (created by author).

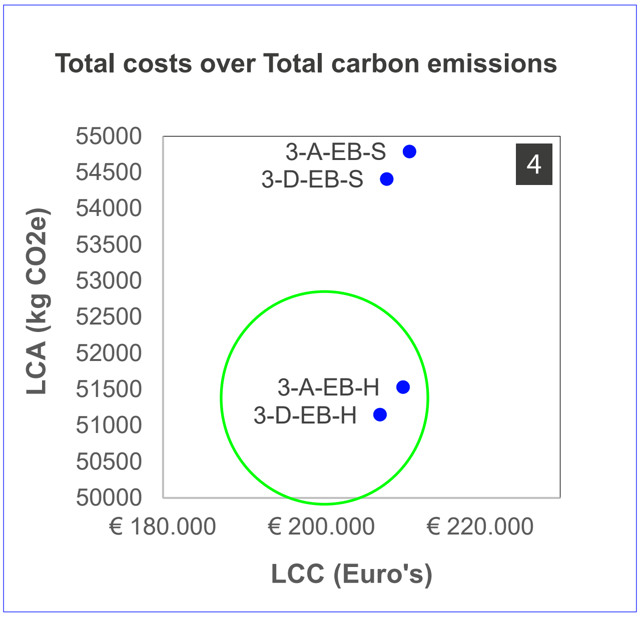


Figure 47. Spread in quadrant 4: Comparison LCC in relation to LCA of deep renovation strategies (created by author).

6.4 Zero carbon potential single step renovations

In this paragraph the potential to generate energy on a building scale is described. It specifically investigates for which ***deep*** renovation strategies the remaining energy demand can be compensated for with photovoltaic panels.

Calculation method
In the energy generation estimation only energy generation on a building level is considered. Photovoltaic panels are considered, as these are commonly used to generate electricity on a building scale. The data used for the calculation are obtained from literature. Specific data on the angle of the PV panel is derived from the building data. The case building has a specific depth, that varies from 7 to 8,5 meters, with an average roof angle of 34 degrees. The data is used in excel to enable the assessment of different amount of solar panels to influence the costs, emissions, and energy generation. The equation used to estimate the energy yield of solar panels is adapted from a lecture (S. Broersma, personal communication, October, 2022):

$$E_{yield} = A \times eff_{system} \times \eta \times c_{orientation} \times c_{tilt} \times 1000 \qquad (15)$$

Where:

E_{yield}	represents the annual energy yield (kWh)
A	represents the area of the solar panels (m^2)
eff_{system}	represents the efficiency of the photovoltaic panels
η	represents a correction factor for losses
c_{tilt}	represents a correction factor for the agle of the panel
$c_{orientatio\ n}$	represents a correction factor for a specific orientation
1000	represents the solar irradiance on the panel (kWh/m^2)

Equation (15) estimates the energy yield of photovoltaic panels as the product of area of panels, efficiency panels, correction factor for losses, correction factor for the agle of the panel, correction factor for orientation and the solar irradiance on the panel. The carbon emissions saved with carbon offsetting is estimated with equation(9):

$$CO_{offset} = (E_{demand} - E_{production}) \times CF \qquad (9)$$

Where:

CO_{offset} represents the carbon emissions for offsetting (CO_2e/kg)
E_{demand} represents the energy demand (kWh)
$E_{production}$ represents the energy produced by photovoltaic panels (kWh)
CF represents the carbon emission factor specific to the material or product (CO_2e/kg)

This formula (9) estimates the amount of carbon for carbon offsetting by multiplying the remaining energy demand or energy production with a carbon emissions factor. The specific carbon emissions factor is dependent on the energy source used in the building. For a gas boiler the emissions factor of natural gas is used while for and electric boiler or heat pump the emissions factor of electricity is used. In case the energy production is higher than the energy demand the outcome will be negative.

Energy generation potential
For energy generation only, solar panels are considered. 3 variations are assessed:

- Concept 1 ‘full capacity’: 12 PV panels on each side of the roof, oriented to east-west.
- Concept 2 ‘50% capacity’: 6 PV panels on each side of the roof, oriented to east-west.
- Concept 3 ‘50% capacity’: 12 PV panels on one side of the roof, oriented to the south.

The results are presented in figure 47, 48, and 49.

<u>Concept 1</u>
Orientation east – west, and the roof fully covered with PV-panels provides enough energy to compensate for the remaining energy that is achieved with renovation strategies that consider heat pumps, and strategies that include high insulation with natural ventilation and ventilation system D. Natural ventilation performs better due to underventilation. The costs of this concept is twice as high compared to the other concepts, specifically for the replacement of the PV panels at the end of service life.

<u>Concept 2 and 3</u>
The roof covered for 50% with PV-panels provides enough energy to compensate for the remaining energy that is achieved with renovation strategies that consider a heat pump, regardless of the orientation. Other strategies can not be compensated for with these concepts. The costs for both concepts is the same, but the energy generation is higher for panels oriented to the south.

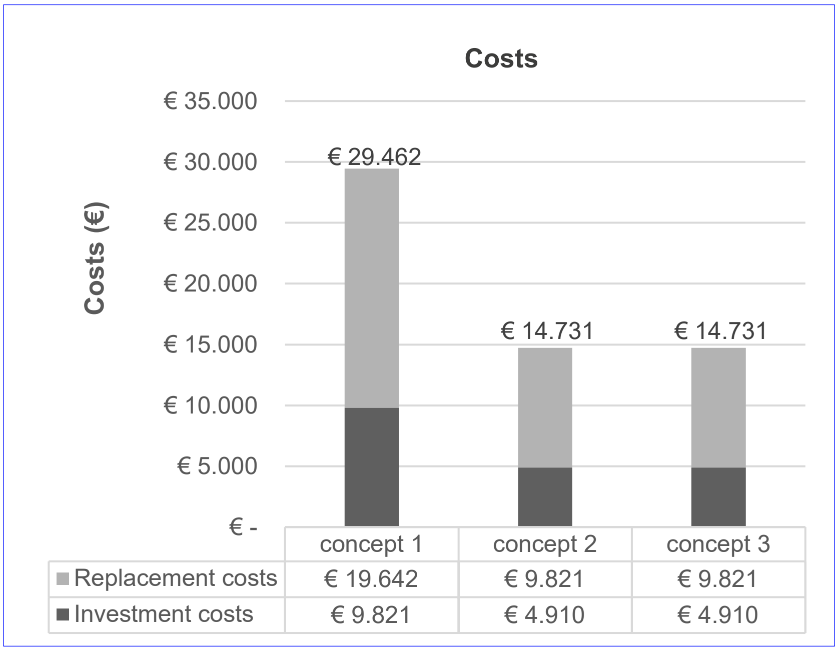


Figure 47. Material related costs for the 3 concepts (created by author).

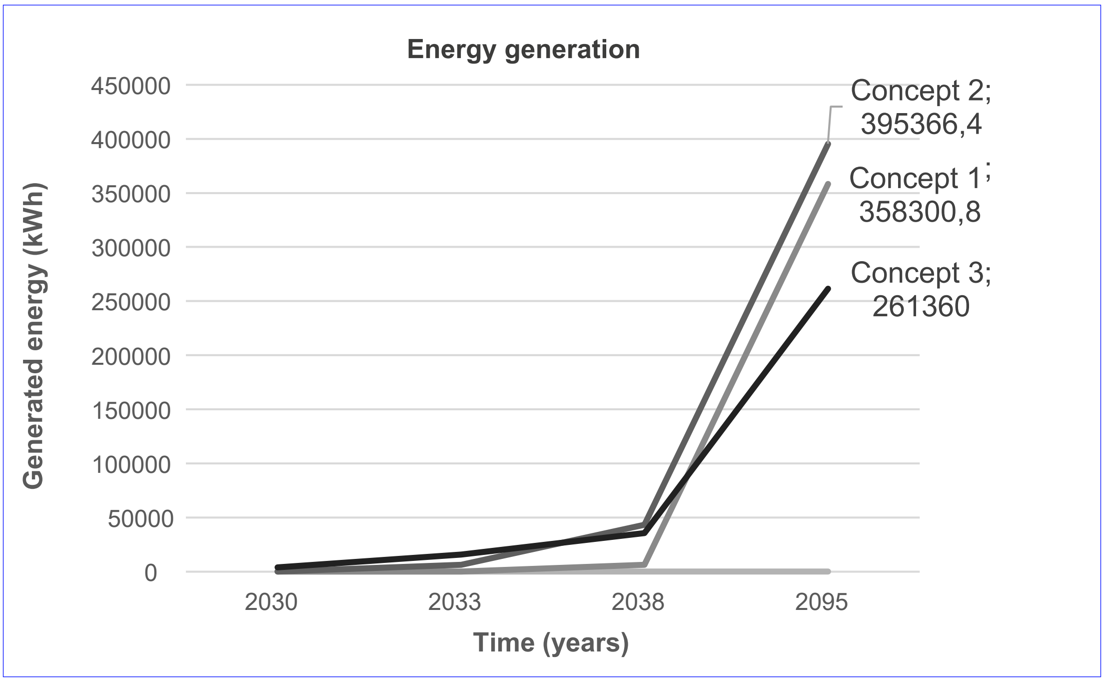


Figure 48. Energy generation for the 3 concepts (created by author).

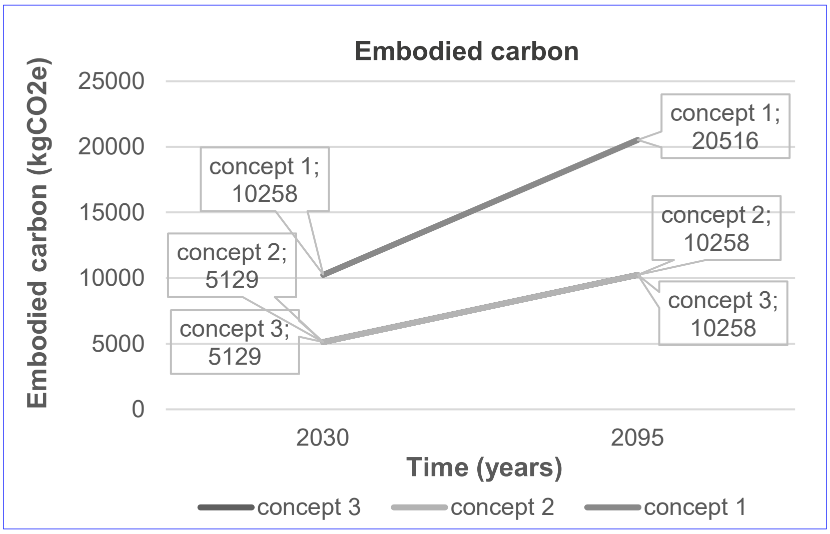


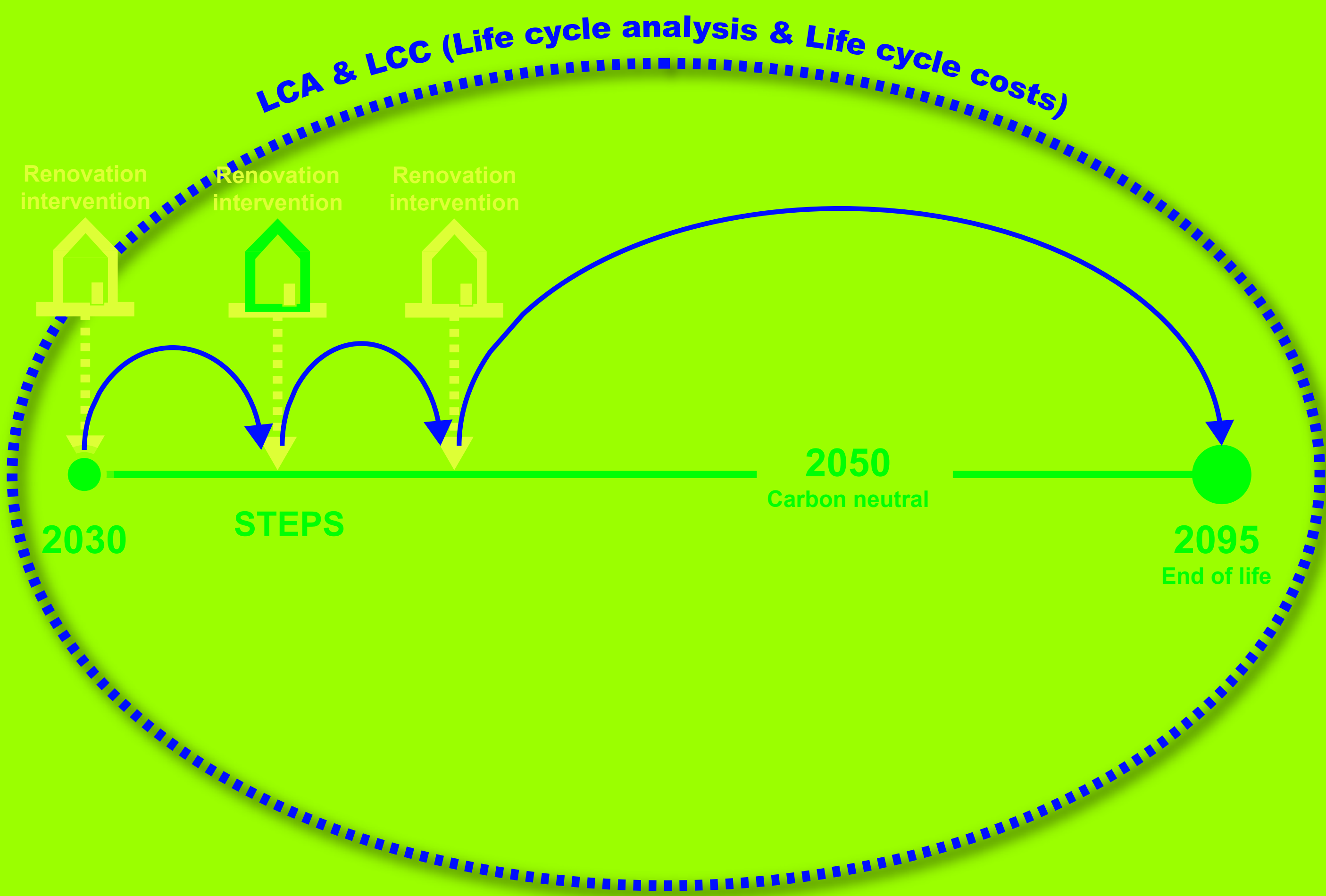
Figure 49. Embodied carbon performance for the 3 concepts (created by author).

CHAPTER 7| Deep renovation in steps

This chapter provides insight in the performance of a stepped renovation .

The chapter contributes to answering the sub question: "What renovation scenarios for a terraced house can be defined considering a buildings life cycle in the Netherlands? ".

The chapter starts with an introduction on how to assess stepped renovations. Then different renovation scenarios and the renovation strategies that are assessed are discussed. At last the results are presented and reflected on.



7.0 Introduction

The literature study revealed that a deep renovation (energy saving >60%) is related to high costs and can in most cases not be executed in one go. It is in practice therefore, executed in multiple steps over time. Assessing the performance of a renovation strategy, without taking into account the aspect time, results in less reliable outcomes on carbon emissions over the full life cycle of a building. In this chapter a selection of the deep renovation strategies of the previous chapter are assessed on their life cycle performance in case of a stepped renovation.

A methodological approach was used to answer the sub question: "What renovation scenarios for a terraced house can be defined considering a buildings life cycle in the Netherlands?". First different renovation scenarios are explained for a deep stepped renovation. To simplify the assessment only the scenario that considers 3 steps is assessed, a 2 step renovation is not included in the assessment (figure 50). To the renovation scenarios selected renovation interventions are assigned based on literature. Then 3 renovation strategies selected out of the deep renovation strategies are used as input for the scenarios. And at last the results are discussed.

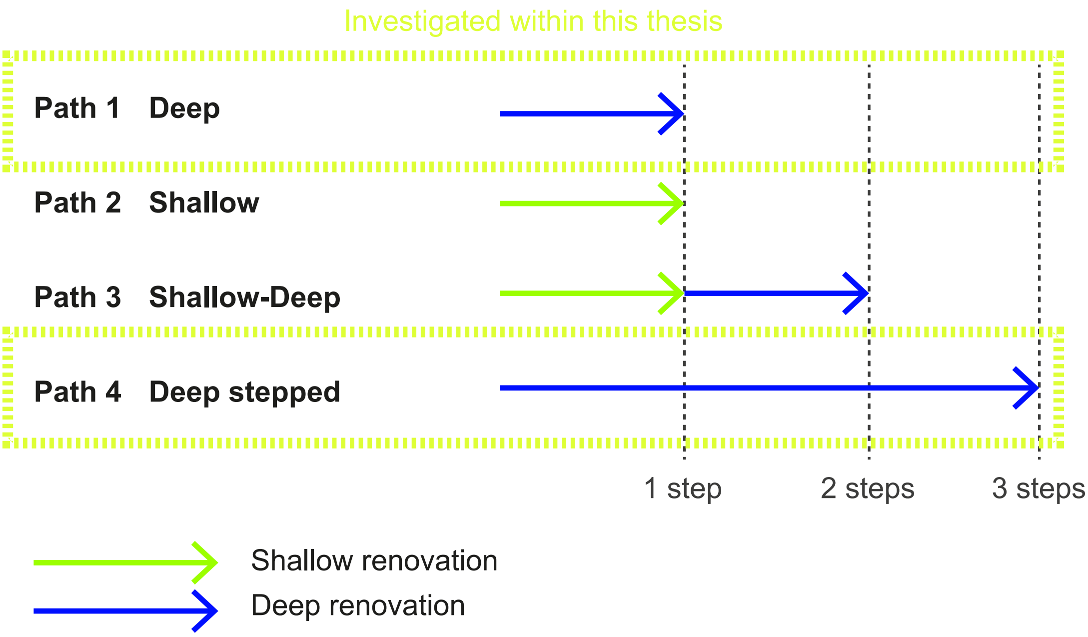


Figure 50. Assessed renovation scenarios (created by author).

7.1 Assessment method

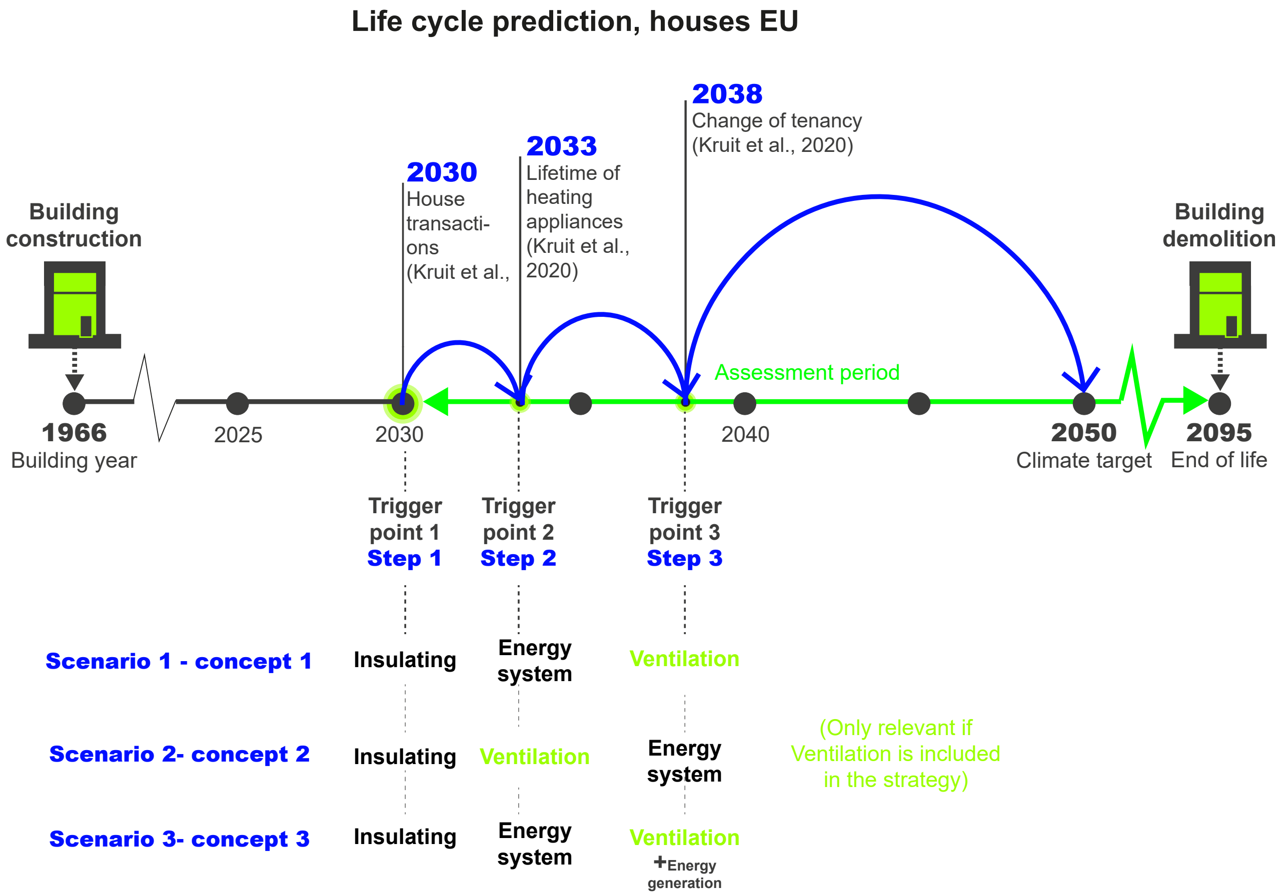


Figure 51. Created renovation scenarios and the corresponding trigger points (created by author).

Trigger points as moments for renovation intervention

According to the literature study trigger points, such as house transaction, change of heating appliances and change of tenancy, can be used to identify moments when renovation will likely take place. When trigger points may occur depends on the context. The assessment of mutliple scenarios could help to gain insight in how the spread of renovation interventions influences the performance over a buildings life cycle. As a starting point for the assessment the trigger points predicted for the EU buildings stock are used. Based on these trigger points the timeline in figure 51 was established.

Order of renovation measures at renovation interventions

The order in which renovation measures are executed is important to determine the long term effects of renovation strategies performed in steps. Although there are no guidelines on this matter, literature indirectly refers to the order of renovation. Ferreira et al. (2023) states that deep renovation interventions should only be performed when the end of service life of a building element is reached. In this perspective the order of renovation is dependent on the life span of building elements. In the study of Østergaard (2018) the order of renovation is dependent on the low heating supply temperature of the heating source resulting in less power to heat the building and the necessity to reduce the heating demand through insulating first. Maia et al. (2021) mentions the risk of over dimensioned

heating appliances when changing the heating appliances before insulating the building. Milieucentraal (n.d.) states that a logical order to renovate is to insulate first and change the heating system second, this way less power is needed to heat the building, and thus more energy is saved. Sibileau et al. (2021) states that the first step needs to be the most impactful in terms of energy saving, and should be insulating.
The approach of Ferreira et al. (2023) has the potential to avoid excess costs and carbon as it prevents replacement costs and encourages direct investment into measures that upgrade the performance. However, the façade and structure of old terraced buildings in the Netherlands often consist of bricks (table 3), which has a long service life approximately 100 years (Brand, 1994) and will probably extend the service life of the heating system (20-30years) (Brand 1994). This suggests that the heating system should be replaced before replacement of the façade, which is contradicting with the other approaches that suggest to insulate the façade before replacing the heating system. Therefore, this approach still contains the risk of over dimensioning the heating system and an uncomfortable indoor climate, which is a downside to this approach. In summary, the following can be stated about the order of renovation:

- Insulating should be the first step, and changing the heating system should come after;
- Second, match the execution of renovation intervention as much as possible with the end of service life of building components (to avoid excess costs and carbon emissions).

Assessed renovation scenarios

The thesis focuses on insulating first and changing the heating system second, as it saves energy, avoids investments in over dimensioned heating appliances and secures thermal comfort at lower heating supply temperatures. From this the following scenarios can be created:

- Scenario 1 (8 years between insulating and replacing the heating system) :

Insulating – doing nothing or changing the ventilation system – replacing the energy system

- Scenario 2 (3 years between insulating and replacing the heating system):

Insulating – replacing the energy system -doing nothing or changing the ventilation system

Additionally a scenario is included that considerd energy generation in the last step:

- Scenario 3 (towards zero carbon):

Insulating – doing nothing or changing the ventilation system – replacing the energy system + integrating pv panels

Assessed strategies

From the previous chapter, 3 deep renovation strategies were selected for further investigation. The selection consists of 2 strategies (containing a heat pump) with low carbon emissions and low life cycle costs, and 1 strategy that considers an electric boiler. The strategies are briefly discussed here.

<u>1.1 - A - HP -O</u>

This deep renovation strategy shows low carbon emissions and low costs over its life cycle (figure 46). It contains minimum cellulose insulation, ventilation system A, and a heat pump. The calculation inputs related to the renovation measures are presented in table 11. Results of the assessment are presented in figures 52-55.

3 - D - HP - O
This deep renovation strategy shows low carbon emissions and low costs over its life cycle (figure 46). It contains high cellulose insulation, ventilation system D, and a heat pump. The calculation inputs related to the renovation measures are presented in table 11. Results of the assessment are presented in figures 56-59.

3 - D - EB - H
This deep renovation strategy shows low carbon emissions and high costs over its life cycle (figure 46). However, as the share of electricity increase the life cycle costs might decrease in the future. It is therefore included in the assessment. It contains high cellulose insulation, ventilation system D, and an electric boiler. The calculation inputs related to the renovation measures are presented in table 11. Results of the assessment are presented in figures 60-63.

Energy generation
For the scenarios that consider energy generation, orientation to the south, including 12 monocrystalline photovoltaic panels were assumed.

Output
As the goal of a stepped renovation is to spread the investment costs, the output consides the investment and recurrent costs. Further more energy saving and carbon emissions are generated. The assessment period considers the first trigger point (2030) until the end of service life of the building (2095).

Results
The in figure 52-63 presented results show the results for deep renovation strategies performed in steps for the 3 scenarios presented in figure 51. The results show that when the strategy is performed in steps the operational energy use and carbon emissions over the life cycle are higher compared to when the renovation is performed in a single step (single go results are presented in previous chapters).

The graphs also shows that scenario 1, insulating first and changing the energy system second performs best in terms of energy performance and carbon emissions. On the contrary, scenario 3 including photovoltaics, shows higher carbon emissions, compared to the other scenarios. The high carbon emissions are related to the use of photovoltaic panels. However the energy generated by the panels compensates for the carbon emissions (carbon offset). Scenario 3 is therefore most effective in reducing carbon emissions.

7.2 Performance deep renovation strategies - step by step

Results 1.1-A-HP-O

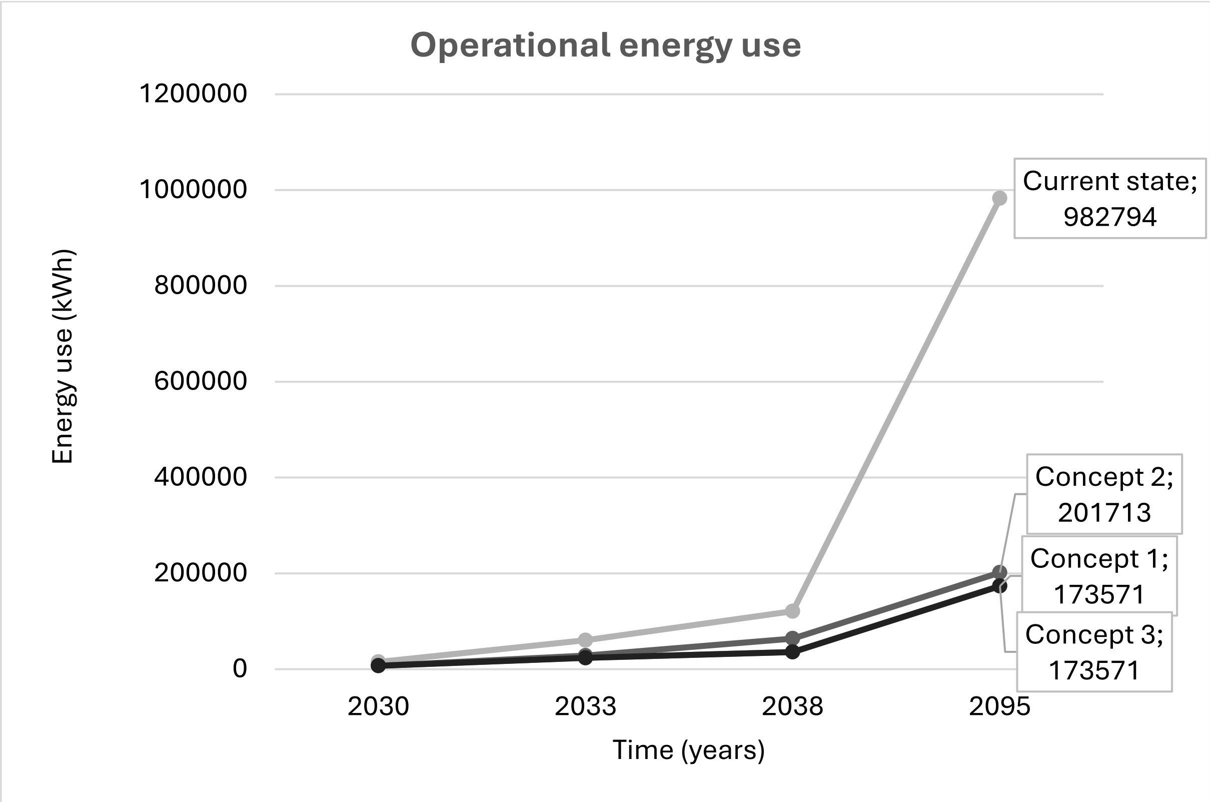


Figure 52. Life cycle operational energy performance strategy 1.1-A-HP-O, based on trigger points (created by author).

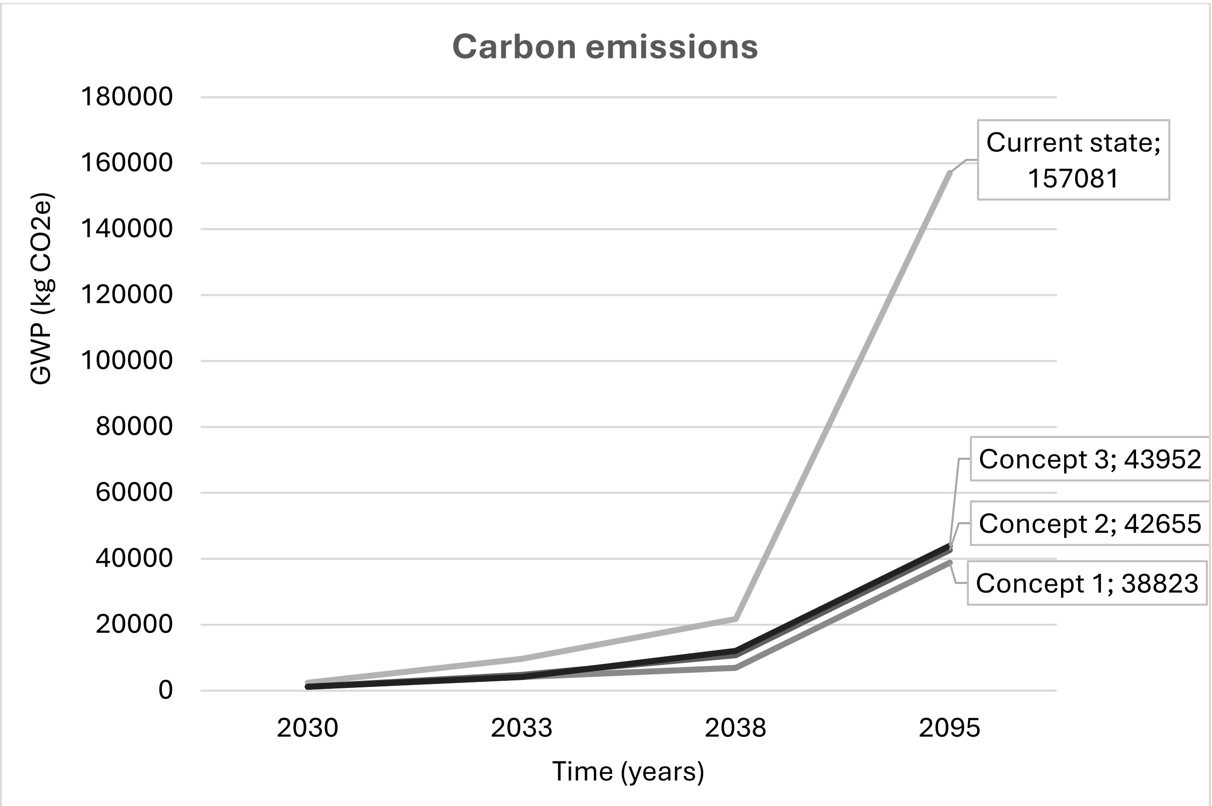


Figure 53. Life cycle carbon emissions, strategy 1.1-A-HP-O, based on trigger points (created by author).

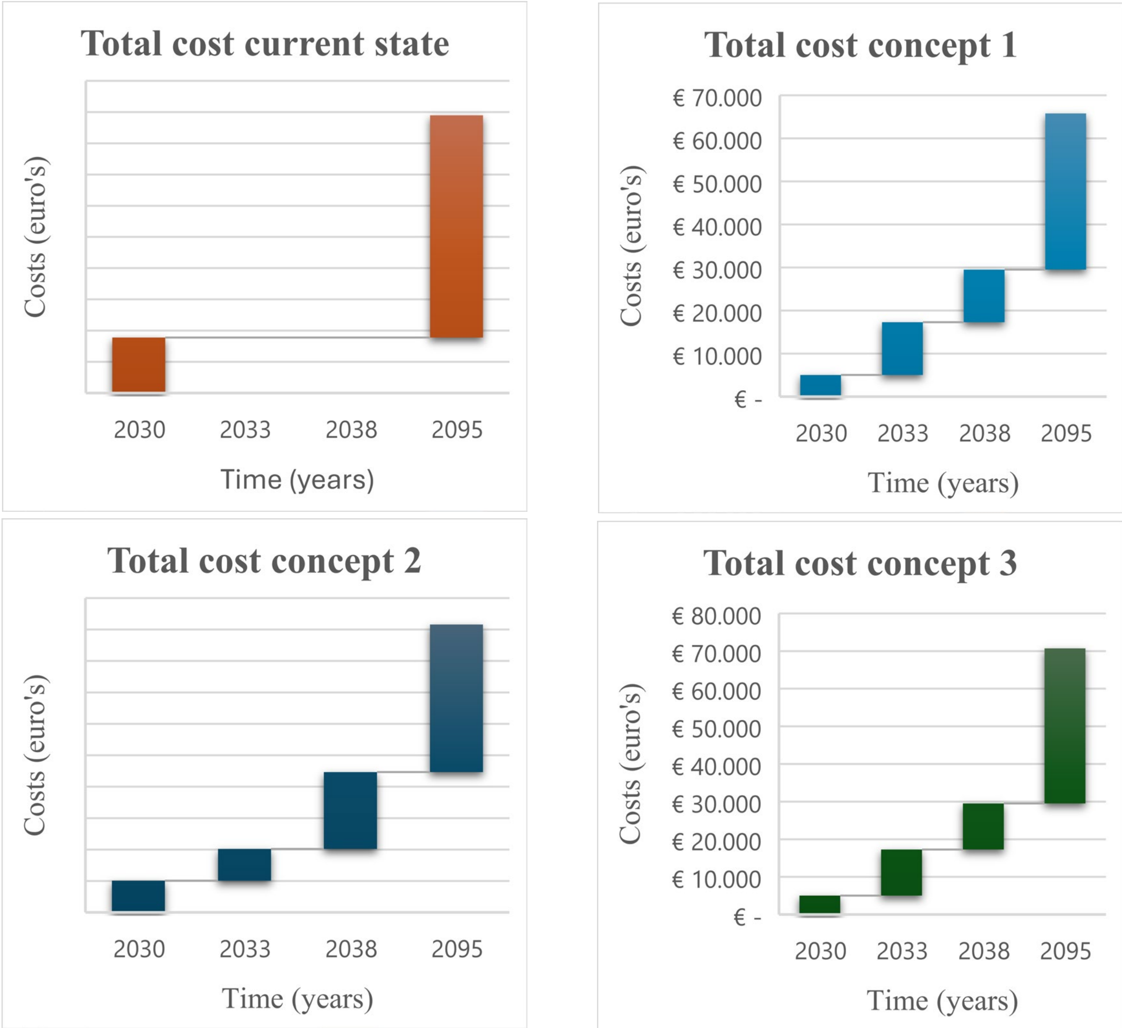


Figure 54. Total investment and recurrent costs strategy 1.1-A-HP-O, based on trigger points (created by author).

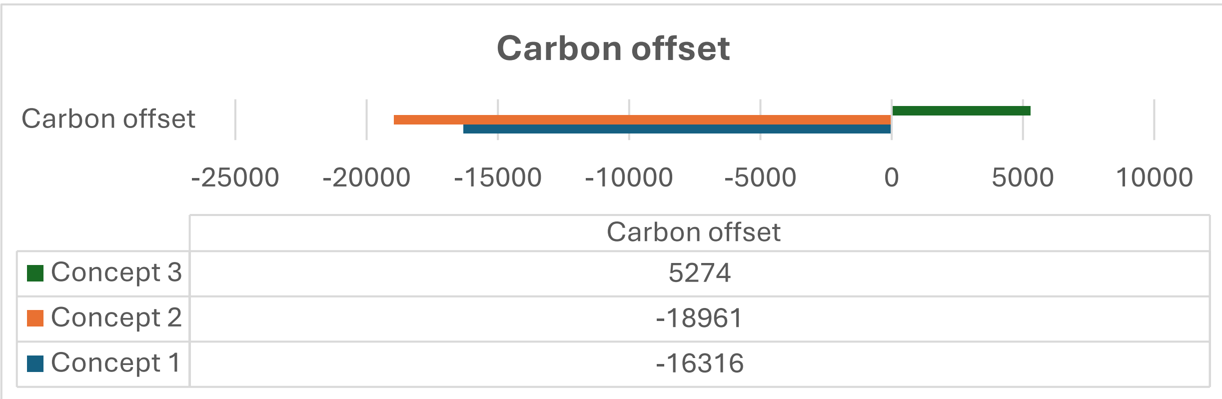


Figure 55. Carbon offsetting strategy 1.1-A-HP-O, based on trigger points (created by author).

Results 3-D-HP-O

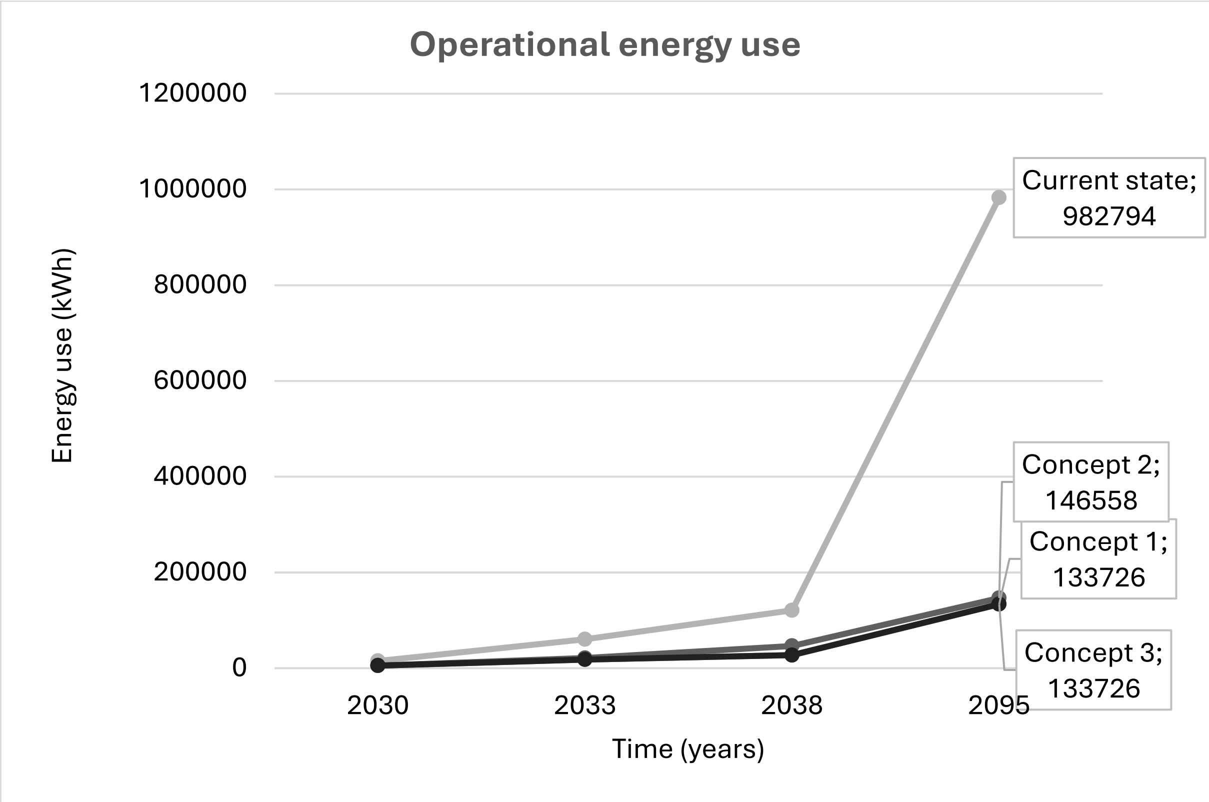


Figure 56. Life cycle operational energy performance strategy 3-D-HP-O, based on trigger points (created by author).

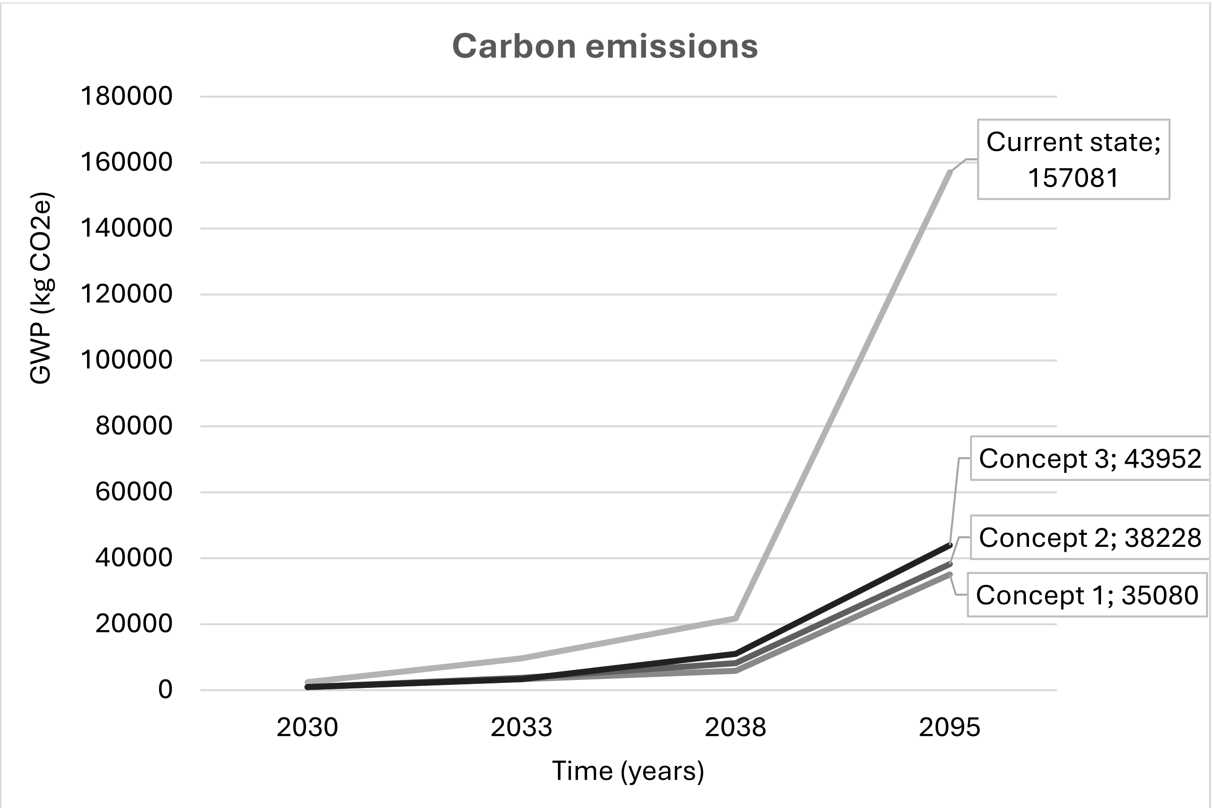


Figure 57. Life cycle carbon emissions, strategy 3-D-HP-O, based on trigger points (created by author).

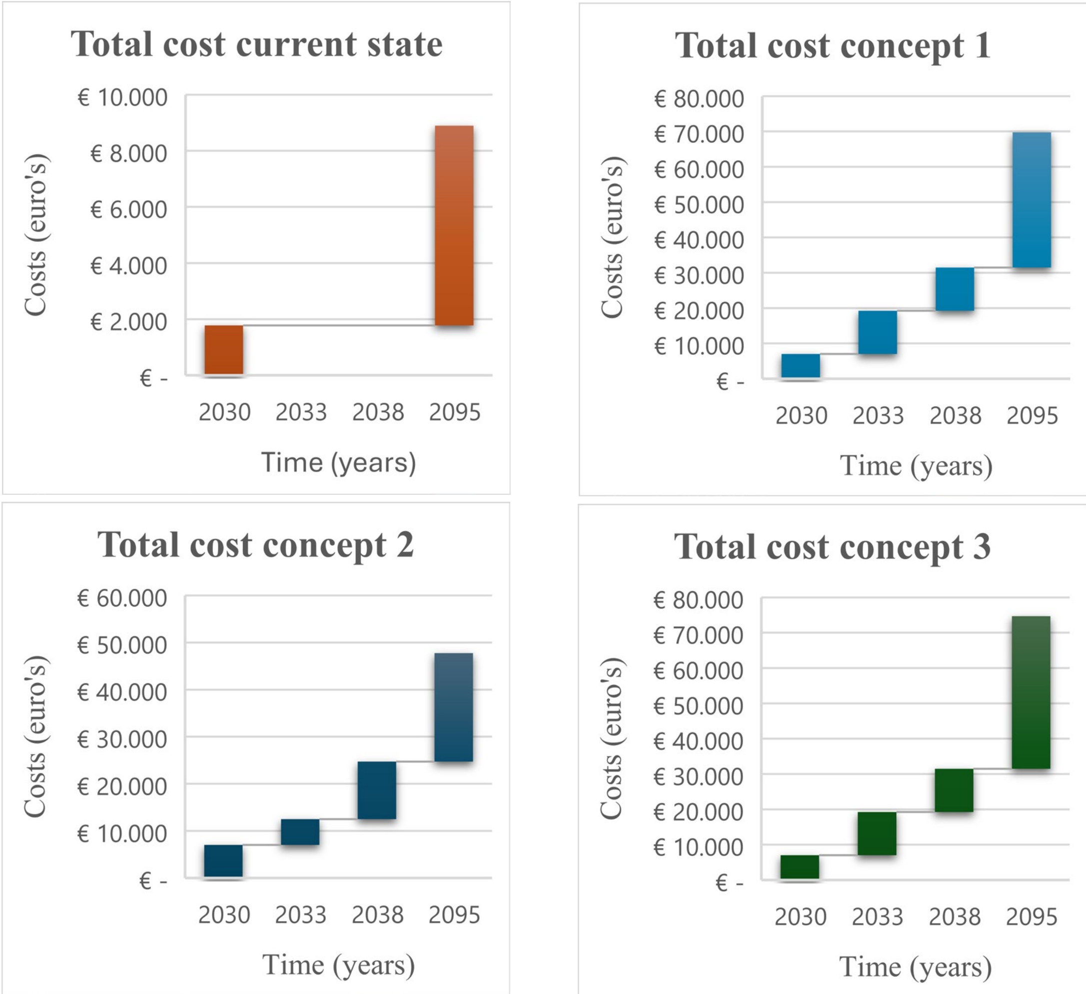
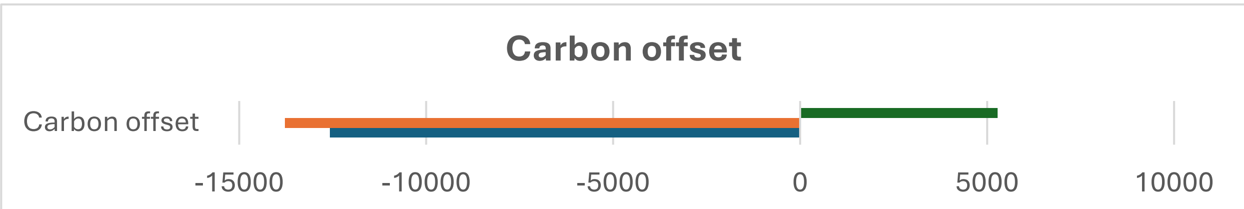


Figure 58. Total investment and recurrent costs strategy 3-D-HP-O, based on trigger points (created by author).



	Carbon offset
Concept 3	5274
Concept 2	-13776
Concept 1	-12570

Figure 59. Total investment and recurrent costs strategy 3-D-HP-O, based on trigger points (created by author).

Results 3-D-EB-O

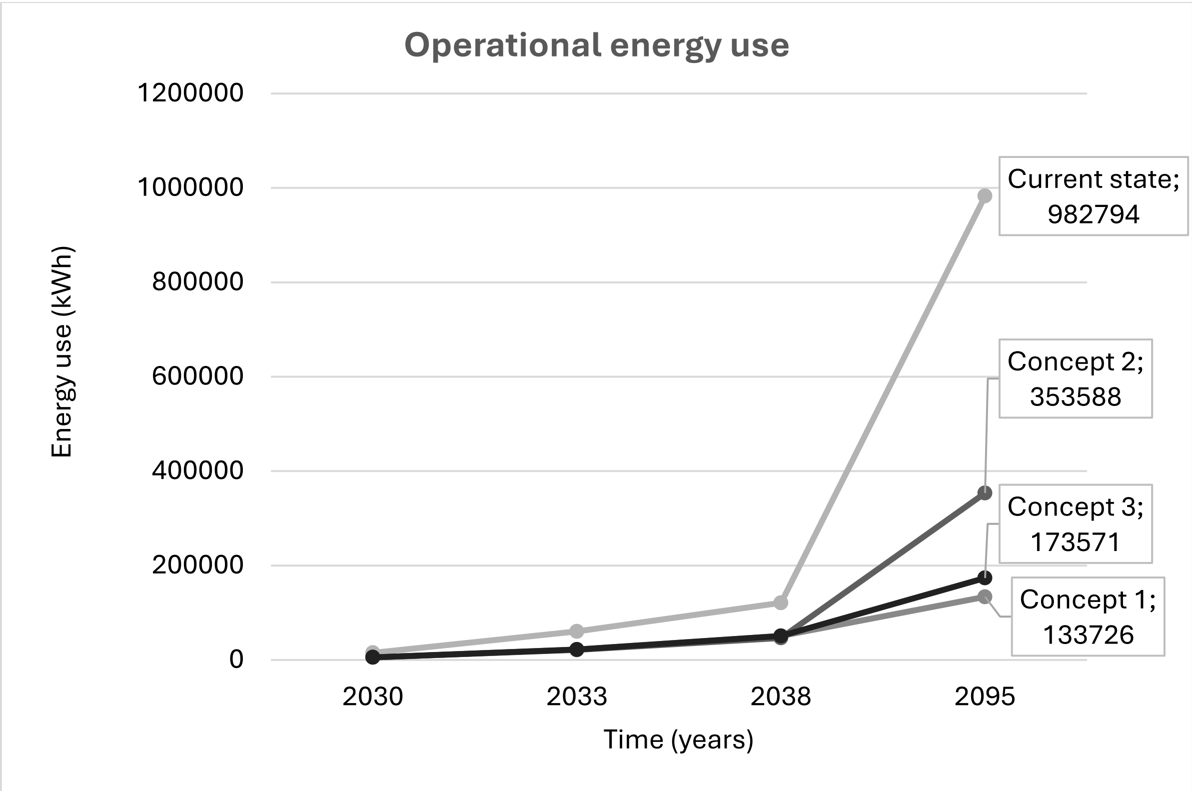


Figure 60. Life cycle operational energy performance strategy 3-D-EB-O, based on trigger points (created by author).

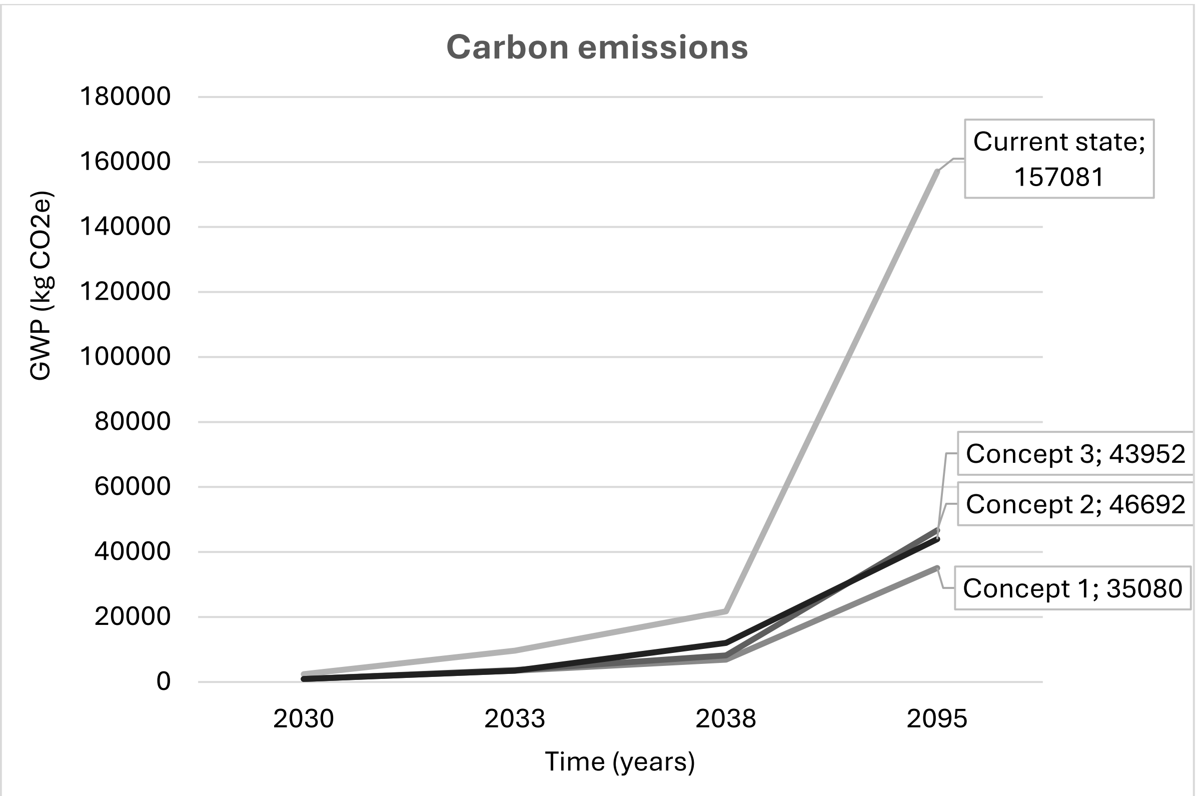


Figure 61. Life cycle carbon emissions, strategy 3-D-EB-O, based on trigger points (created by author).

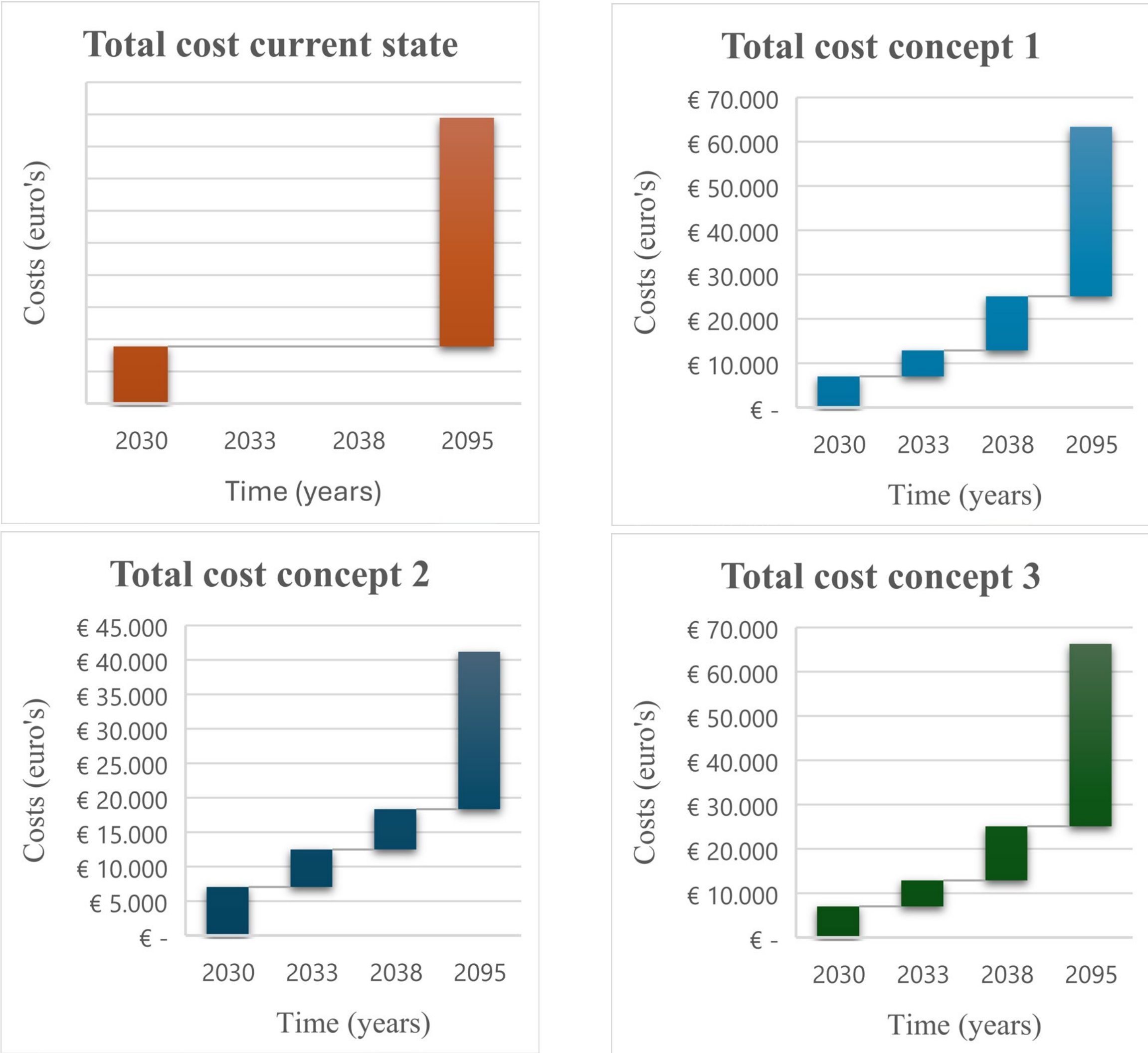


Figure 62. Total investment and recurrent costs strategy 3-D-EB-O, based on trigger points (created by author).

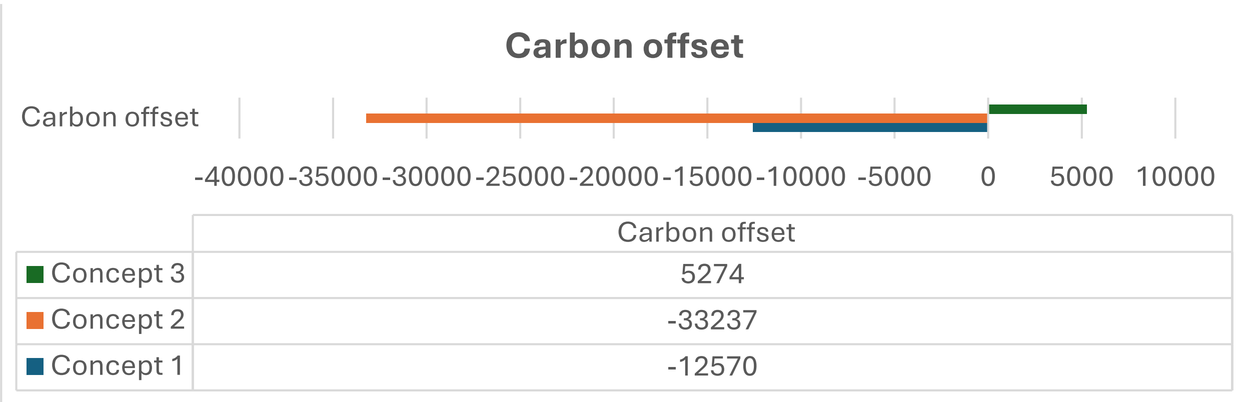


Figure 63. Carbon offsetting strategy 3-D-EB-O, based on trigger points (created by author).

Conclusion

Overall executing a renovation strategy in steps, causes an increase in carbon emissions and energy use on the long term. From the shape of the graphs can be concluded that the energy use and carbon emissions do not behave linearly. By executing the steps in a shorter time interval, the energy reduction is achieved earlier, resulting in less energy use and carbon emissions. As the time interval increases the energy reduction is achieved later and therefore results on higher carbon emissions and energy use in the long run. This phenomenon is presented in figure 64.

Spreading a deep renovation strategy, in steps with differemt intervals

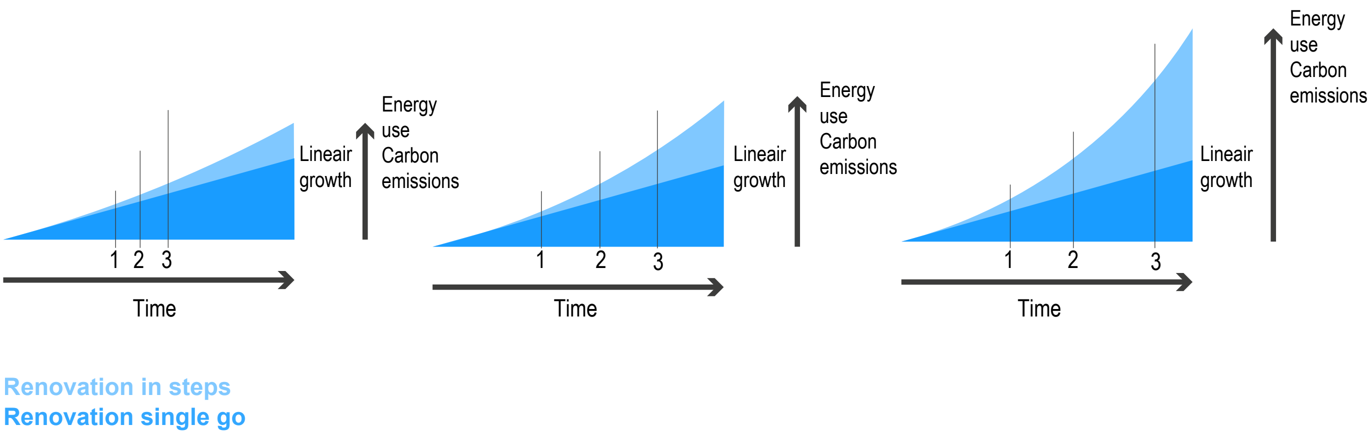


Figure 64. Energy use and carbon emissions in relation to steps and time (created by author).

CHAPTER 8| TOOL design

This chapter discusses the tool designed to support decision making for renovation strategies.

This chapter contributes to answering the research question : "How can decision making be supported with the results, through a design?"

First the problem in decision making is defined, along with the requirements for the solution. Then the design of the tool is explained and at last, the limitations of the tools are discussed.

8.0 Introduction

This chapter focusses on answering the sub question: ‘how can decision making be supported with the results, through a design?’ The chapter describes how the results of the literature review, and the assessment of strategies can contribute to the research question through a design. The main insights obtained from literature to create a design are summarized below:

- There is a need for decision support tools regarding renovation, that provides insight in the performance of a renovation regarding energy use, carbon emissions and costs;
- Decision makers with large portfolios especially could benefit from such tool. In order to do so, the tool should provide insight in the costs over time to support financial planning;
- Support tools for decision making should not be time consuming;
- Data on carbon emissions and costs fluctuates.

This let to the following problem definition:
There is a lack of support tools for decision making regarding renovation, that provide insight in the performance of renovations on multiple criteria. Therefore, the performance of varying renovation strategies remains complex to compare. The assessment of renovation strategies is time consuming, which limits the renovation strategies explored. A simplified method is needed to increase the assessment rate of renovation strategies. And lastly, the main limitation in decision making regarding renovation are costs, as a consequence renovation is performed in steps. Tools developed for renovation should therefore pay extra attention to financial planning, and the performance achieved over time.

Design objective
The objective of the design is to create a tool that addresses the challenges as described in the problem definition. It should at least take into account long term performance, provide insight in the costs over time and create an interface that is simple and user friendly. The tool should consists of various renovation measures to increase the assessment of strategies.

User requirements informing design decisions
Through the perspective of a decision maker the tool should be easy to use and assess the performance of a strategy in a quick manner. The level of technical knowledge on buildings should not be a constraint when using the tool, as decision makers could have different levels of knowledge about buildings.

8.1 Tool design

Workflow
The workflow of the tool is based on the equations as presented in the calculation method of previous chapters. By using reference codes for renovation strategies the tool is able to find the related performance of the renovation strategy. It then applies the found strategy on the set time period, and calculates the performance until the end of service life of the building, which represents the endurance of the renovation strategy.

Limitations
The tool is limited to 110 renovation strategies, that all imply that envelope measure (such as insulation the roof, external walls, and ground floor and replacing the windows) are performed in one go (within a year). In other words it does not offer the possibility to assess the performance of renovations performed in steps that consider the envelope measures to be executed in steps. Although the data for this is obtained through the research, due to time constraints it could not be integrated in the tool. A simplified assessment method is used which allows for the exploration of a wide range of strategies, but does not represent the exact costs or carbon emissions, therefore the tool should not be used to assess strategies, but rather be used for the comparison of strategies in the early design stage. Another limitation of the tool is that is uses the

8.1.1 User interface design

This section provides an overview of the design of the tool and its elements. The tool consists of tabs that are assigned a Letter, the letters stand for (figure 65):

R results
O overview
S simulation
D data

Figure 65. Worksheets in the tool (by author).

Input tab
The input tab offers the possibility to insert case specific data on energy generation, life cycle data, the measures to investigate for a single and/or step by step approach (see figure 66). The CO_2- emissions factor input fields allow for case, or context specific data to be entered, and otherwise uses the default data inserted in the tool. This way data uncertainty can be mitigated. The input tab is accompanied by a graphical representation of the input values, that shows the pathway towards the end of service life of the building, the trigger points and related renovation measures assessed within the buildings service life and the years at which these trigger points occur. The input fields are limited to one sheet to enable quick assessment.

Based on the input values provided the tool generates the operational energy use, investment costs, recurrent costs, (initial and recurrent) embodied and operational carbon emissions and generated energy (according to the equations provided in previous chapters, calculation schemes). Furthermore it provides insight into carbon offsetting.

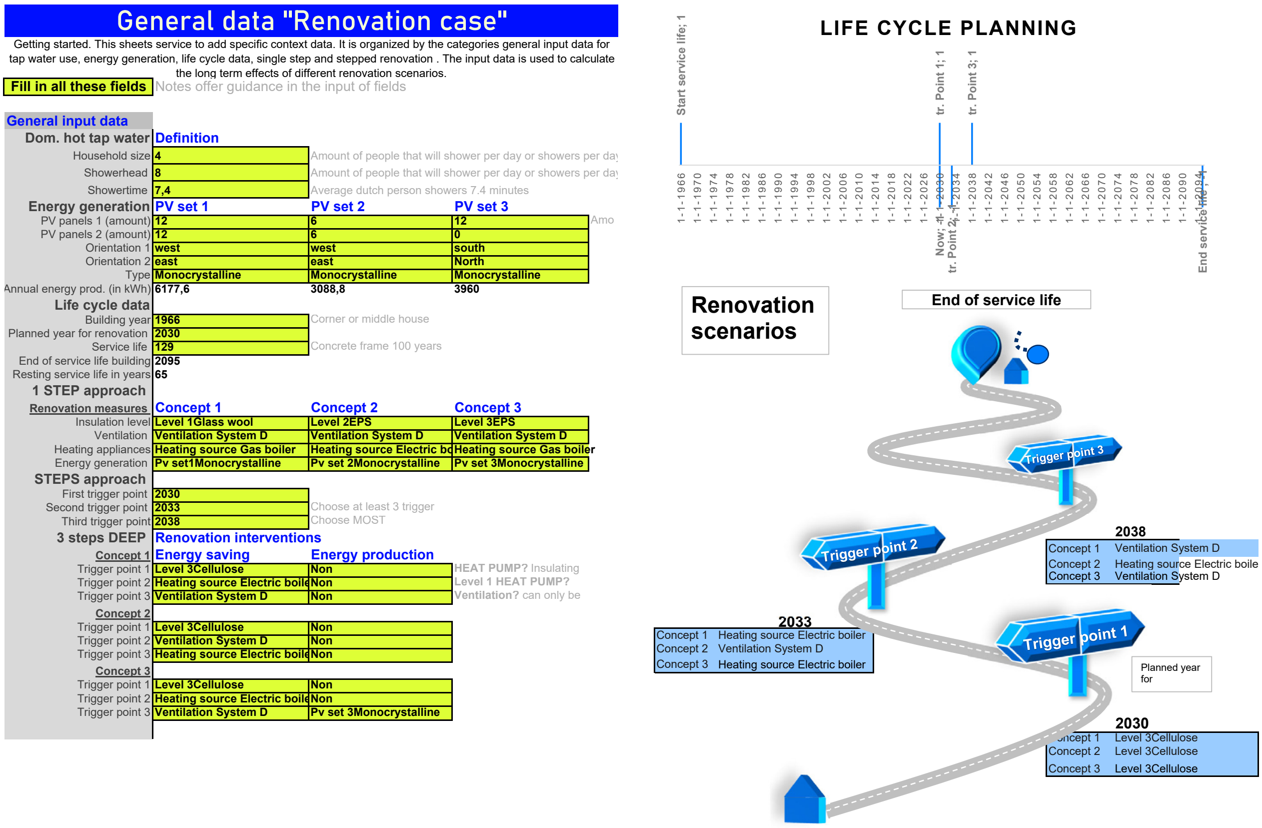


Figure 66. Input worksheet tool (by author).

Uncertainty tab

The uncertainty tab is integrated to reduce uncertainties. The research revealed that the main uncertainties influencing the results are carbon emissions related to services, the operational carbon emissions factor, and the costs for materials and services. To reduce uncertainties, and increase accuracy of the tool in the long run, the tool offers to insert specific data on carbon emissions related to materials and energy. Additionally it allows to use case specific costs, providing a more accurate outcome. The default settings are based on the input values described in previous chapters and provides generic outcomes for a typical terraced house.

The results tabs

The results tab provides and overview of the generated results for single go and step by step renovations. Overall it provides insight in the carbon emissions, energy use, costs and carbon offsetting potential in the form of graphs (figure 68).

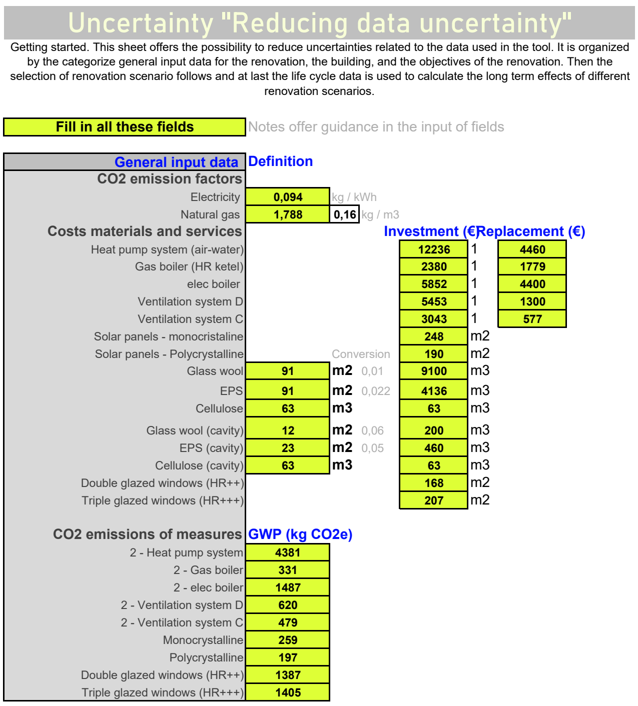


Figure 67. Input worksheet tool (by author).

Figure 68. Results sheet tool, 3 step comparison, based on input data (created by author in excel).

Simulation recurrent costs tab

The tab S-recurrent cost reveals for a 3 step renovation when investment and recurrent costs will occure in time, to support budget planning. The calculation takes into account the measure assigned to the trigger points and calculates the investment costs and recurrent costs for each measure. The results are provided in graphs, where graph trigger point 1 refers to the renovation measures assigned to trigger point 1, and so on.

Data tabs

The data tabs provide insight in the calculation and data use to estimate DHW, the energy yield of photovoltaic panels and the costs.

Report

To support decision making in a practical matter the tool generates a report on the performance of the investigated renovation strategies (figure 68), which can be printed to discuss the results with others involved in the decision making process.

Concept 1

Year	T 1	Year	T2	Year	T3
2030	€ 7.030	2033	€ 17.600	2038	€ 13.380
2080	€ 7.030	2048	€ 17.600	2053	€ 13.380
0	€ -	2063	€ 17.600	2068	€ 13.380
0	€ -	2078	€ 17.600	2083	€ 13.380
0	€ -	2093	€ 17.600	0	€ -
0	€ -	0	€ -	0	€ -
0	€ -	0	€ -	0	€ -
0	€ -	0	€ -	0	€ -
0	€ -	0	€ -	0	€ -

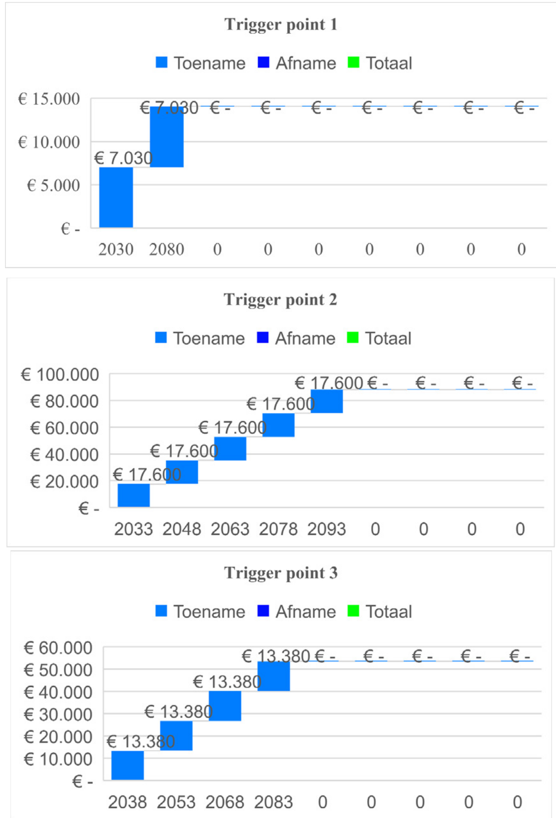


Figure 69. Recurrent costs sheet tool (created by author in excel).

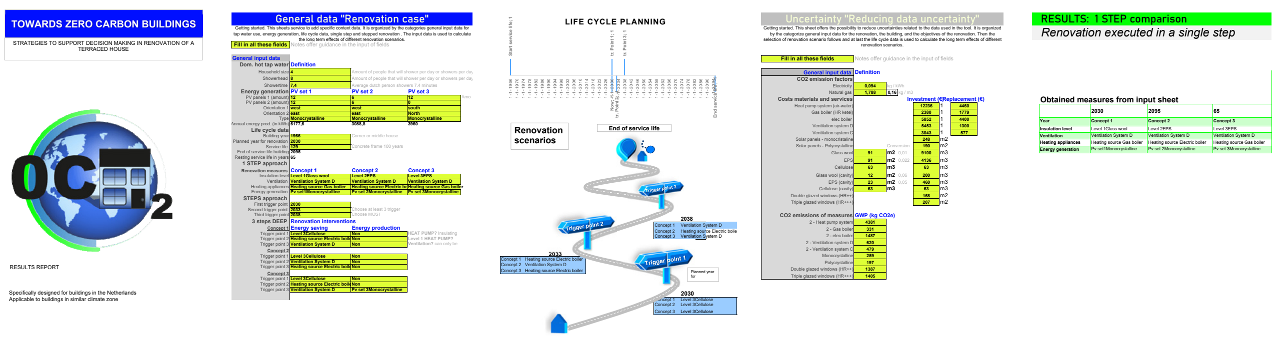


Figure 69. Report generated by tool (created by author in excel).

Discussion

The thesis provides insight on how to reduce carbon emissions over the full life cycle of a terraced house. It contributes to research in the field of renovation by specifically focussing on the influence of a buildings life cycle on total carbon emissions. As most studies focus on the energy performance of a building, this research addresses how renovation interventions are influenced by the existing life cycle and its importance to be included in decision-making. Furthermore, the study replies to the need for transparant tools for decision making in renovation.

Although the research provided many insights, the study could have gained more depth by investigating the budget for renovation and investigating which set of steps in terms of time provide the best results. As deep renovations are performed in steps due to limited budget for renovation, this is an important aspect, and should gain more attention in research. Furthermore research is specifically lacking in defining scenarios when trigger points will take place and which renovation interventions to match with the trigger points.

Secondly, the research is limited by uncertainty in data. Especially the data on operational costs and carbon emissions and the related long term changes, are difficult to predict, but important to investigate as these influenced the outcomes significantly. A high amount of data is needed to provide outcomes on energy, costs and carbon emissions, and is difficult to gather and process, which limits the amount of renovation strategies assessed. Digitalization could help in this matter, and might provide more advanced tools, that could take into account frequently updated data.

Thirdly the study focused only on terraced houses. The methodology to assess other typologies might differ. Also the outcomes could vary. Further research is needed to determine how stepped renovations can be effectively applied in other building typologies.

And at last the assessment was done in a simplified way. Carbon emissions related to the building life cycle stages construction, and end of service life were not assessed. Therefore insight in the total emissions, is still limited.

Conclusion

The research question "How can renovation strategies support decision-making, in reducing the total carbon emissions over a building's life cycle, in the Netherlands?" is answered by answering the sub questions.

1. **How can renovation strategies be created and which renovation measures should be included in the strategies regarding carbon emissions?**

To create renovation strategies for the renovation scenarios, the approach needs to be determined. The stepped approach is a strategy for carbon neutral buildings, and could be used to find measures that effectively target carbon emissions, for deep renovation strategies. The most influential building parameters (regarding the operational energy) obtained by applying this approach were envelope measures related to the roof, external wall, windows, ground floor and infiltration, and technical system measures, regarding domestic hot tap water, heating system and mechanical ventilation system. These parameters are further defined into renovation measures, by investigating different insulation levels, ventilation systems and heating systems. For the shallow renovation strategies a different approach was needed, as these are not selected on environmental performance but rather on cost effectiveness. The shallow renovation measure obtained from research are window replacement, cavity insulation, and roof insulation. Lastly measures that influence the embodied carbon are investigated. From the literature can be concluded that mainly insulation material, and services in renovation contribute the most to the embodied carbon emissions, if structural elements are not included. Conventional insulation materials such as EPS, glass wool and cellulose are considered as measures, to obtain varying results in renovation performance. The found measures are combined in different ways to obtain multiple renovation strategies, that all perform different in energy use, carbon emissions and costs.

2. ***How do the renovation strategies influence the operational performance of a building?***

The operational performance is mainly influenced by the energy system, such as heat pumps, electric boilers and gas boilers. Deep renovation strategies with an energy saving of 60% in a terraced house is achieved by incorporating a heatpump, or high insulation combined with a gas boiler, or high insulation with an electric boiler and ventilation system A or D, or moderate insulation with a gas boiler and ventilation system D. Of which strategies that consider a heat pump result in the highest (83%-88%) energy saving. A shallow renovation is achieved by executing a single measure or two measures, consisting of cavity insulation, roof inculation or window replacement. From all measures cavity insulation results in the highest energy reduction (13% energy saving).

The energy source determines mainly the operational carbon emissions, electricity resulting in lower operational carbon emisisons and gas in higer emissions. The addition of a heat pump results in higher energy saving compared to the other strategies and therefore also results in lower operational carbon emissions.

Overall high insulation, a heat pump and ventilation system D, has the best operational performance out of the deep renovation strategies. Within the shallow renovation strategies, cavity insulation has the best operational performance.

3. ***How do the renovation strategies influence the buildings embodied perfor-***

mance?

The embodied carbon consist of the initial and recurrent embodied carbon. The recurrent embodied carbon is the cause for most of the emissions. The embodied carbon of heatpump strategies is significantly high. Within the shallow renovation strategies lowest emissions are related to cavity insulation and also related to highest operational carbon saving. Overall the embodied carbon is particularly high voor services, which is caused by the short life span and high emissions related to services. Selecting services on their embodied carbon en life span is crucial to reduce embodied carbon emissions.

4. ***How do the renovation strategies influence the buildings life cycle performance?***

The LCA assessment on carbon emissions revealed that total emissions are mainly related to the heating system, and are lowest for a heat pump and highest for a gas boiler. On the contrary a heat pump has the highest embodied carbon emissions, and a gas boiler the lowest. The embodied carbon within strategies that consider a heat pump is significantly larger in proportion compared to the operational carbon. The embodied carbon could be reduced, if a heat pump is selected with lower embedded emissions or by selecting a heat pump with a longer life span. Regarding the costs for shallow renovation strategies, replacing the windows resulted in significantly higher costs, compared to roof insulation and cavity insulation. Within the deep renovation strategies a heat pump influences the total costs the most, followed by the ventilation system and insulation level. The recurrent costs are mainly related to replacing the heating system.

To compensate for the remaining emissions PV panels were considered. Orientation east-west, and south with 50% of the roof covered with PV panels, could compensate for the energy use of all strategies that consider a heat pump, regardless of the insulation level and ventilation system. Orientation east-west with the roof fully covered with PV panels, generated enough energy to compensate for the remaining energy use of strategies that considered heat pumps and strategies that considered high insulation combined with either ventilation system D or A. Ventilation system A performed better than ventilation system C, due to the low AC/h value used in the assessment. However this value resembles the underventilation in terraced houses and should therefore not be used as a starting point.

5. ***What renovation scenarios for a terraced house can be defined considering a buildings life cycle in the Netherlands?***

Renovation scenarios for a residential building in the Netherlands can be defined through defining the level of renovation, how renovation is executed and the service life the building/ the renovation. The level of renovation is in this thesis defined through the terms deep and shallow renovation. Where a deep renovation refers to an energy saving of 60% or more, while a shallow renovation is related to an energy saving of 3-30%. The level of renovation is important is it influences the renovation measures needed to achieve the energy saving. According to the climate targets, buildings should be zero carbon by 2050. In order to achieve this deep renovation should account for the majority of renovations performed. However, budget for renovation is often limited, which suggests that most deep renovations will be executed in steps, of which three steps is often found as an optimum in research, in terms of energy performance. Trigger points for renovation such as house transactions and changing the heating appliances can be used to predict at which moment it’s likely that renovation interventions will be undertaken. According to the literature review for the majority of buildings in Europe 2030, 2033, and 2038 are years that trigger points will occur. This led to the following scenarios: a deep renovation in one step (1), a deep renovation in 3 steps (2), a shallow renovation in one step (3), and a shallow renovation that transitions in a deep renovation (4). Additionally, carbon emissions are related to the service life of the building, as this determines how long a renovation strategy will endure. For a terraced house a life span of 129 years was obtained from research.

Furthermore, the assessment of deep renovation strategies performed in 3 steps, revealed that in general executing a renovation strategy in steps, causes an increase in carbon emissions and energy use on the long term. From the results can be concluded that the energy use and carbon emissions do not behave linearly over the life cycle, when renovation is performed in steps. Therefore, by executing the steps in a shorter time interval, the energy reduction is achieved earlier, resulting in less energy use and carbon emissions. As the time interval increases the energy reduction is achieved later and therefore results in higher carbon emissions and energy use in the long run.

6. ***How can decision making be supported with the results, through a design?***

The results of the literature study revealed that there is a need for decision support tools that are transparent, accessible, and support decision making regarding large portfolios. In order to do this the tool should support financial planning, provide insight in energy performance and environmental performance, to enable simplified assessment of different renovation options in the concept strategy design phase. Secondly, as deep renovations are slowly becoming the aim, the need for tools that help establishing a deep renovation becomes more important. However, costs remain a limiting factor in renovation, a stepped approach, executing renovation measures separately over a longer span of time spreads the initial high costs related to specifically deep renovations. Making it possible to achieve a deep renovation in the end. However, it also delays the energy reduction and carbon reduction achieved over time. From this perspective the tool should also take into account different scenarios for the service life of the building and provide insight into the performance achieved over the full service life for different renovation scenarios. This outcome resulted in the design of a tool, that requires limited data, to assess the performance of a terraced house, provides insight in carbon emissions, energy performance and the investment moments. A limitation of the tool is the uncertainty in data related to specifically costs and carbon emissions, as this fluctuates. To mitigate this affect the tool provides the possibility to change the data, so context specific data can be used, and make the tool useful over a longer span of time.

7. ***How can renovation strategies support decision-making, in reducing the total carbon emissions over a building's life cycle, in the Netherlands?***

Renovation strategies can support decision-making in reducing total carbon emissions over a building's life cycle, by making the performance of renovation strategies on multiple criteria in the Netherlands accessible for decision makers, and providing a method to obtain renovation scenarios that fit the renovation case. This can be done by providing guidance on renovation planning that takes into account the service life of the building, and providing a simplified assessment method of renovation strategies, that provides insight in total carbon emissions related to strategies. Due to data uncertainty, the method should provide flexibility to adapt to new data, without losing its simplicity.

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Appendices

Appendix A| Data 60s terraced house

Areas with buildings from the 60s, in South-Holland are selected in figure 1.

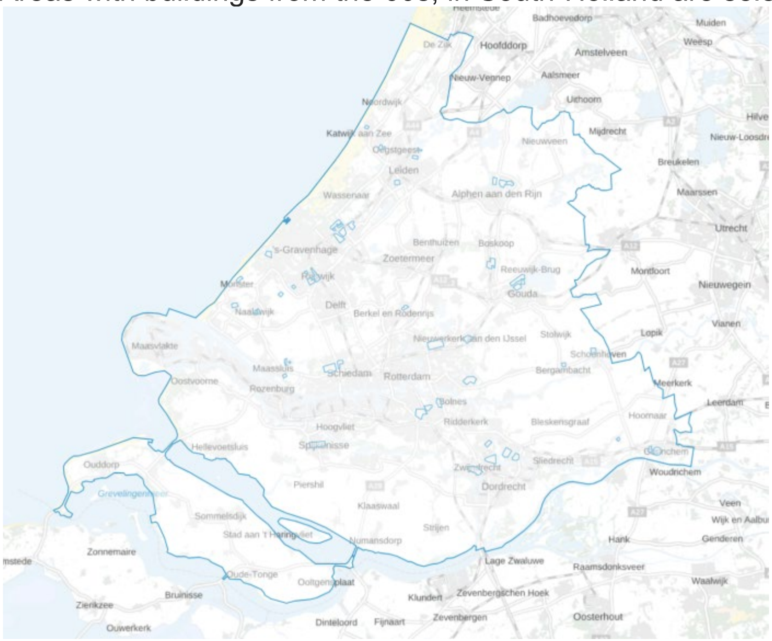
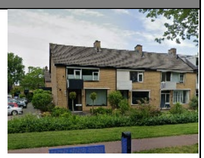
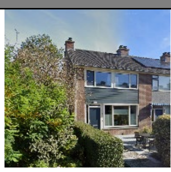


Figure 1. Areas that contain buildings from the 60s in South Holland are selected in blue (Source: https://www.atlasleefomgeving.nl/kaarten?config=3ef897de-127f-471a-959b-93b7597de188&gm-x=155604.8558361423&gm-y=462016.56250558776&gm-z=9&gm-b=1544180834512,true,1;1544724925856,true,0.8;&activateOnStart=info&deactivateOnStart=layercollection)

Table 1. ***A couple of terraced houses from a variety of areas that are selected in figure X are presented, to showcase similarities and differences between terraced houses (pictures from Google maps and building year from*** **https://huispedia.nl/krimpen-aan-den-ijssel/2922cl/heemraadsingel/2)**

1973	1971	1967	1970	1971
				
Breebaartlaan Rijswijk	RavellaanNaaldwijk	RoerdompstraatZwijndrecht	Sterrenkwartier Spijkenisse	Rembrandtlaan Papendrecht
1961	**1969**	**1968**	**1971**	**1965**
				
Akselkreek Groot Ijselmonde	Heemraadsingel, Krimpen aan den Ijssel	Fakkelgras Rotterdam	Denneweg Gouda	Vondellaan Waddinxveen

Appendix A| (continued)

1969	1960	1964	1966	1955
				
Rosinnihof, Alphen aan den Rijn	Mozartlaan, Leiden	Zilvermeeuwlaan Leidschendam	Prins Bernhardlaan Voorburg	Pr. Beatrixlaan Maassluis

Table 2. Overview building years and current state/characteristics (WoonWijzerWinkel, 2023).

			Jaren 60 woning build after world war 2, housing need 1				
Characteristics	**Before 1930**	**1930-1945**	**1946-1964**	**1965-1974**	**1975-1982**	**1983-1991**	**1992-2005**
Roof	Not insulated	Not insulated	Not insulated	Not insulated	Limited insulation	Limited insulation	Sufficient insulation
External walls	Brick wall without cavity	Cavity wall bricks	Cavity wall bricks	Cavity wall bricks	Cavity wall bricks Limited insulation	Cavity wall bricks Moderate insulated	Cavity wall bricks Sufficient insulation
Windows	Single or double glass	Single or double glass	Single or double glass	Single or double glass	Double glass	Double glass	Double glass
Groundfloor	Wooden floor, not insulated	Wooden floor, not insulated	Wooden floor or concrete, not insulated	Wooden floor or concrete, not insulated	Concrete floor, Limited insulation	Concrete floor, Moderate insulation	Concrete floor, Sufficient insulation
Ventilation	A	A	A	A	A or C	C	C
Heating	Central heating, not always present	Central heating, not always present	Central heating, not always present	Central heating,	Central heating	Central heating	Central heating
Energy label	G	G	F	E	D	C	C

Appendix A| (continued)

Building code requirements					Roof and Facade Rc= 1,3 m2K/W	Groundfloor: Rc= 1,3 m2K/W Roof and Facade 1983: Rc= 1,3 m2K/W 1988: Rc= 2,0 m2K/W	Roof, façade and groundfloor Rc= 2,5 m2K/W
Upgrades (Most buildings contain the following upgrades)	HR-combiketel Double glass and Air tight joints	HR-combiketel Double glass and Air tight joints	HR-combiketel Double glass and Air tight joints	HR-combiketel Double glass and Air tight joints	HR-combiketel	HR-combiketel	
Not upgraded	External wall	External wall	External wall				
Streefwaarden minimale isolatie voor specifieke aanvoer temperatuur	Minimal insulation value Energy label B, **70 graden Celsius** supply temperature: Vloer Rc = 3,5 Dak Rc = 3,5 Gevel Rc = 1,7 Glas U = 1,2 (HR++) Verbeterde kierdichting Mechanische ventilatie		Minimal insulation value Energy label B, **50 graden** Celsius supply temperature: Vloer Rc = 3,5 Dak Rc = 3,5 Gevel Rc = 1,7 Glas U = 1,2 (HR++) Verbeterde kierdichting Mechanische ventilatie				
0	https://www.woonwijzerwinkel.nl/oplossingen-per-bouwjaar/						
1.	https://watismijnhuiswaard.com/jaren-60-woning/#:~:text=Wat%20is%20een%20jaren%2060%20woning%3F&text=Woningen%20die%20gebouwd%20zijn%20tussen,ging%20voor%20goed%20en%20duurzaam.						

Appendix A| (continued)

Table 3. Raw data case building.

Building parameters	Values	Source
Surface	129 m2	https://huispedia.nl/krimpen-aan-den-ijssel/2922cl/heemraadsingel/2
Volume	438 m3	https://huispedia.nl/krimpen-aan-den-ijssel/2922cl/heemraadsingel/2
Soortwoonhuis	Eengezinswoning, tussewoning	https://huispedia.nl/krimpen-aan-den-ijssel/2922cl/heemraadsingel/2
Bouwjaar	1966	https://huispedia.nl/krimpen-aan-den-ijssel/2922cl/heemraadsingel/2
Rooms	5, 4 bedrooms and a living room	https://www.funda.nl/koop/verkocht/krimpen-aan-den-ijssel/huis-42917779-heemraadsingel-2/ (retrieved: 25-9-2023)
Building layers	3 layers	https://www.funda.nl/koop/verkocht/krimpen-aan-den-ijssel/huis-42917779-heemraadsingel-2/ (retrieved: 25-9-2023)
Envelope parameters	Roof insulation Double glas partially CV-ketel Energylabel C	https://www.funda.nl/koop/verkocht/krimpen-aan-den-ijssel/huis-42917779-heemraadsingel-2/ (retrieved: 25-9-2023)