Decreasing the environmental impacts of residential buildings: to renovate or to rebuild?

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Decreasing the environmental impacts of residential buildings: to renovate or to rebuild?

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Abstract

The built environment is responsible for a substantial amount of energy use and greenhouse gas emissions. To improve energy efficiency and reduce environmental impacts, buildings can be renovated or replaced with more energy-efficient alternatives. Although new buildings often cause less environmental impacts from operating energy use, the higher material requirements cause additional environmental impacts. Housing corporations own more than 25% of residences in the Netherlands and need to decide between different energy efficiency improvement methods for their building stock. Therefore, the proposed thesis has the following research question: *What are optimal building renovation or replacement solutions for housing corporations to improve energy efficiency and reduce environmental impacts in the context of the Dutch climate goals?* Environmental impacts of materials and energy have been calculated according to the MPG^+ method, which follows the life cycle assessment approach. The results show that extensively renovated porch flats and new buildings lead to similar amounts of environmental impacts if both use a collective heat pump and are insulated according to nearly-zero energy building standards. The comparison between the environmental impacts of extensive renovations and building replacement depends on the expected building life span after the intervention, the quantity of solar panels, and the use of sustainable materials. Renovations including lower energy efficiency levels or fossil energy sources cause more environmental impacts. The MPG^+ method aligns with the Dutch policy context but lacks transparency, completeness, and data certainty. The alternative scenarios in this study are compared per square meter, so the overall environmental impacts may increase if the relative apartment size per resident is greater in the new building. Considering the Climate Agreement, the housing crisis, and many uncertainties, extensive renovations are recommended as a no-regret solution for housing corporations.

Keywords: Life Cycle Assessment, energy consumption, material performance, renovation, rebuilding, housing corporations

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Abbreviations

BAU: Business as usual; current situation

BEA: Building Energy Assessments

Conv New: Conventional new building scenario

COP: Coefficient of Performance; efficiency indicator of heat pumps

DH: District heating

EOL: End Of Life

EP1: Energy Performance 1: Energy demand (kWh/m^2/year)

EP2: Energy Performance 2: Primary fossil energy use (kWh/m^2/year)

EP3: Energy Performance 3: Percentage renewable energy (%)

EPG: Energy Performance of Buildings; *Energieprestatie Gebouwen*

Ext Ren: Extensive renovation scenario

GHG: Greenhouse gas

GIS: Geographic Information Sciences

HHP: Hybrid heat pump

HP: Heat pump

HR: High efficiency boiler; *Hoog Rendement CV ketel*

IF: Impact factor

kWh: kilo Watt hour

LCA: Life Cycle Assessment

LCEA: Life Cycle Energy Assessment

Min Ren: Minimal renovation scenario

MJ: Mega Joules

MPG/MPG$^+$: Material Performance Buildings; *Milieuprestatie Gebouwen* (MPG$^+$ is the method to combine the environmental impacts of materials and energy)

NMD: National Environmental Database, *Nationale Milieu Database*

NTA 8800:2022: Dutch technical agreement for energy efficiency; *Nederlands Technische Afspraak*

nZEB: Nearly-zero Energy Building

PV: Photovoltaic; solar panels

Rc: Insulation value, representing the heat resistance of the construction

SDH: Sustainable district heating

Stand Ren: Standard renovation scenario

Sust New: Sustainable new building scenario

TO July max: Maximum temperature exceedance in July; *Temperatuuroverschrijding*

1. Introduction

The increase of the effects of heat waves, fires, cyclones, and other extreme weather conditions due to human activities, also known as climate change, calls for a drastic reduction in greenhouse gas (GHG) emissions (IPCC, 2021). An important contributor to climate change is the built environment, which is responsible for approximately 40% of energy use and 36% of CO_2 emissions in the EU (Directive (EU) 2018/844). Therefore, it is crucial to improve energy efficiency and reduce environmental impacts from the built environment on a large scale.

The operational energy consumption in a building typically consists of energy for heating, cooling, and domestic hot water (thermal energy), and electricity (Terés-Zubiaga et al., 2020). Operational energy refers to the total energy consumption during the use phase of the building. Furthermore, primary energy stands for the total amount of energy harvested from natural sources, thereby considering the entire energy chain and conversion losses. The demand for thermal energy depends for a large part on building characteristics and includes losses from transmission (energy moving through the building envelope) and ventilation, as well as internal gains (heat from people and appliances) and solar gains (heat from the sun) (Itard & Klunder, 2007). Finally, the operational energy demand also depends on the behavior and appliances of users.

European policies for reducing energy use in the built environment have been formulated to solve the issue that many buildings in for instance Western European countries such as the Netherlands do not meet current energy standards (Thomsen & Van der Vlier, 2009; Meijer & Kara, 2012). These standards will also not be achieved with the currently insufficient rates of building renovation (Terés-Zubiaga et al., 2020) or replacement (Sayce & Wilkinson, 2019). To jointly decrease greenhouse gas emissions and boost economic recovery after the COVID-19 pandemic, the EU has set forth a strategy for a Renovation Wave (European Commission, 2020). This strategy consists of plans to double the current rate of renovations and to "promote energy efficiency, building renovation and renewables deployment at building, neighborhood and district level" (European Commission, 2020, p. 4). Moreover, in line with the European Green Deal, this focus on energy efficiency, renovation, and renewables has been integrated in the Energy Performance of Buildings Directive, the strategy for the built environment (Directive (EU) 2018/844); European Commission, 2021).

Methods to increase energy efficiency in buildings are various forms of renovation (Terés-Zubiaga et al., 2020). Different renovation options include, for instance, insulation, solar shading, renewable energy sources, draught sealing, double or triple glazing, and improving heating, ventilation, and air conditioning (HVAC) systems (Nguyen, 2017; Ding & Ying, 2019). Moreover, Itard and Klunder (2007) discuss transformations, which are larger interventions that can also be implemented to improve energy performance. Transformations entail the alteration of the floor plan of a building, for which at least the load-bearing structure is preserved (Itard & Klunder, 2007).

About 49% of houses in the Netherlands were built before 1975 (CBS, 2021), when energy performance regulations were much less strict. Especially in the period from the Second World War until the 70s, there was little attention for insulation in the rapidly built houses (Meijer & Kara, 2012). Many of these buildings do not comply with renewed building standards (Ministry of BZK, 2021). In the Dutch Climate Agreement, it has been established to decrease carbon dioxide emissions from the built environment in the Netherlands with 3,4 megatons by 2030 (Ministry of EZK, 2019) to eventually achieve climate neutrality in 2050 (Regulation (EU) 2021/1119). The plans consist most importantly of increasing the speed of renovations and disconnecting houses from the natural gas grid, in which case district heating or biogas are mostly suggested as alternatives.

Energy efficiency in the built environment can be improved through renovation as well as building replacement, which both have different benefits. Ding and Ying (2019) discuss that renovation has advantages such as lower material requirements and the relatively short time span required for renovations. In addition, renovation can reduce energy poverty (Ascione, Bianco, Mauro, & Napolitano, 2019) and preserve the heritage of existing buildings (Martínez-Molina et al., 2016). Demolition is also often unpopular among occupants, because of the personal attachment they have to a house and the disruption of their lives (Power, 2008). On the other hand, a benefit of building replacement is the potential to maximize land value (Baker, Moncaster, & Al-Tabbaa, 2017). Furthermore, noise disturbances, inaccessibility, unsuitable floor plans, and mold formation in existing buildings can motivate the preference for demolition. Finally, in comparing demolition and renovation, other important factors can be costs and environmental impacts from other sources besides energy use.

Since the technological possibilities to improve energy efficiency in existing buildings are not endless, it can be more sustainable to demolish and replace dwellings. Better thermal insulation in new constructions generally results in a lower energy consumption in the use phase (Meijer & Kara, 2012). Replacing an existing building, however, leads to a higher amount of embodied energy, which can be defined as “the quantity of energy used during the lifecycle of materials, upstream or downstream of the manufacturing of building” (Gaspar & Santos, 2015, p. 387). At some point, the reduced energy consumption may compensate for the increase in embodied energy, depending on the life span of the building after the intervention. After reviewing all case studies that compared replacement with renovation, Schwartz, Raslan, and Mumovic (2018) state that it is not possible to conclusively claim that either one always has a lower environmental impact.

Because of the energy transition and increasing attention for sustainability, many different parties such as home-owners, housing corporations, and municipalities are concerned with increasing energy efficiency in the built environment in the Netherlands. Other relevant trends related to the built environment are the housing shortage and the recent explosion of natural gas prices. Next to sustainability and financial concerns, the gas phase-out is also motivated by the earthquakes caused by natural gas mining in the province Groningen and recently also by the aim to become independent of Russian gas.

Improving energy efficiency not only reduces environmental impacts, it also contributes to creating more resilient cities. Meerow, Newell, and Stults (2016) reviewed existing literature on urban resilience and formulated an integrative definition: "Urban resilience refers to the ability of an urban system […] to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity." (Meerow et al., 2016, p. 45). Urban areas become more resilient if they adopt more sustainable energy sources and reduce energy consumption, because of a decrease in fossil fuel dependency. Cities are then less affected by disturbances such as increasing gas prices, supply shortages, or geopolitical concerns about energy security related to, for instance, gas production in Russia (Bilgin, 2009). Furthermore, building resilience can be increased by renovation measures such as installing reflective triple glazing. This type of window insulates on cold days and prevents solar gains in summer, both of which mitigate indoor temperatures during extreme weather events resulting from climate change (IPCC, 2021).

Assessing the environmental impacts from building energy and materials aligns well with the principles of Industrial Ecology. These assessments require a systemic approach, as a focus on a single part of the building lifecycle can lead to misleading conclusions about optimal improvement strategies. Moreover, while behavior changes can reduce energy use, there is a lot of potential for reducing the impact of buildings in technological solutions. Considering the key elements of Industrial Ecology as summarized by Erkman (1997) - a systemic approach, emphasizing complex material and energy flows, and considering technological dynamics – the decision between renovation or rebuilding is highly relevant to this scientific discipline.

In this section, some core concepts have been defined and the relevance of increasing energy efficiency through building renovation or replacement has been established. Chapter two outlines how decisions between renovation and rebuilding are currently informed. Chapter three introduces the selected case study, chapter four defines the research gap and research questions, and in chapter five the methodology is described. The details of the developed scenarios are explained in chapter 6, and the results and sensitivity analysis of these scenarios are described in chapter 7. Finally, chapter 8 consists of a discussion of the limitations of this study and the conclusions are presented in chapter 9.

2. Renovation or rebuilding: state of the art

2.1. Methods used to compare renovation with demolition

Although it has been established that energy efficiency should be improved, more research is required to support the decision between life cycle expansion or building replacement. Goldstein, Herbøl, & Figueroa (2013) discuss six tools, namely five types of Building Environmental Assessments (BEA) in addition to Life Cycle Assessments (LCA), which are used to evaluate the sustainability of buildings. BEAs assess multiple environmental performance criteria to determine how environmentally friendly buildings are and to showcase possible ways to improve (Ng, Chen, & Wong, 2013). Examples of performance criteria, according to Ng et al., (2013), are site management, energy efficiency, air and atmosphere, materials, water efficiency, indoor environmental quality, transport, global warming, waste and pollution, and ecology. The frameworks in BEA tools provide a standardized way to compare buildings, and the certification can be used to communicate the level of sustainability to users or the public. However, BEAs focus more on operational energy compared to embodied energy in the materials (Goldstein et al., 2013).

The LCA method considers the environmental burden of a product or service in all stages of its lifecycle from resource extraction, production, and transportation to the use and end-of-life (EOL) phases (Guinée et al., 2002). A total of eleven impact categories are required to be assessed according to the Dutch Building Decree, among which global warming, eutrophication, human toxicity, and ecotoxicity (Ministry of BZK, 2021). By considering the damage costs to society from the environmental impacts, the emissions per impact category can be expressed in a monetary unit and summed up to form a singular metric, namely the shadow price (Bickel & Friendrich, 2004).

With the LCA approach, the environmental impacts resulting from all building components and their production and disposal or recycling processes, as well as the impacts from the operational use of the building, can be considered. Because of the generally applicable design of LCAs and focus on all lifecycle stages, Goldstein et al. (2013) argue that they are suitable for comparing rebuilding with renovation. Furthermore, LCA results for building materials have been collected in different databases, such as the Dutch National Environmental Database (*Nationale Milieudatabase*, NMD) (Stichting NMD, 2022a). The NMD is partially connected to EcoInvent (EcoInvent, 2022), a larger and more general LCA database, but another example of such databases is IDEMAT (IDEMAT, 2022).

In addition to LCAs, energy use can be compared through a Life Cycle Energy Analysis (LCEA), in which all energy inputs of a building are considered. An LCEA includes the embodied energy, operating energy, and demolition energy (Cabeza, Rincón, Vilariño, Pérez, & Castell, 2014). Here, energy used for the construction and renovation of a building are also considered in the embodied energy.

2.2. Decision-making at larger scales

To inform policy makers on how to improve energy efficiency in buildings, it is efficient to apply this type of analysis on a broader level. Mastrucci, Marvuglia, Benetto, ad Leopold (2020) named three types of models required to compare different scenarios to reduce the environmental impacts of buildings at urban scales: energy demand models, building stock models, and LCAs. Swan and Ugursal (2009) distinguish two methods to spatially represent and analyze energy demand, namely a top-down and bottom-up approach. With the top-down approach, total energy demand data are divided over areas based on for instance macroeconomic data. In the bottom-up approach, energy demand of a set of individual buildings is extrapolated to larger scales. The bottom-up approach can consist of either statistical or engineering models. Statistical models use historical data and methods such as regressions to estimate energy use of dwellings. In contrast, Swan and Ugursal (2009) describe engineering methods as models that "explicitly account for the energy consumption of end-uses based on power ratings and use of equipment and systems and/or heat transfer and thermodynamic relationships" (p. 1822). The engineering models, in turn, can rely on a population distribution, building archetypes, or a representative sample of buildings to estimate energy use on larger scales.

Mastrucci et al. (2020) complement the framework of bottom-up energy demand models by Swan and Ugursal (2009) with building stock aggregation models and LCAs to determine the environmental performance of building components. Two ways to determine the materials used in the building stock are the archetype approach and the building-by-building approach (Mastrucci et al., 2020). The archetype approach uses data from a set of building typologies to represent other similar buildings. In the building-by-building approach, actual information about the buildings is used, which requires more data and computational load but is less sensitive to assumptions and simplifications. For instance, elevation data from Geographic Information Sciences (GIS), used to determine building height, can be combined with existing floor plans to estimate the surface of building components and calculate material contents, if these data are sufficiently detailed (Matrucci et al., 2017). Because of these limitations, the building-by-building approach is usually applied to smaller scales.

Several studies have evaluated the environmental impacts of buildings with the use of data for energy use, building materials, and environmental impacts related to both these aspects. For instance, Blom, Itard, and Meijer (2010) assessed several heating and ventilation systems and calculated the combined impacts from operational energy use, material use, and maintenance for a reference building in the Netherlands. They found that at that time, the heating technology with the most environmental impacts was the heat pump, and that environmental impacts are best reduced by decreasing energy consumption and improving the efficiency of technologies. Mastrucci et al. (2020) studied different renovation scenarios in a city in Luxemburg through a building-by-building approach and suggested that the renovation rate should improve to reduce the carbon footprint of the urban building stock.

Furthermore, De Oliveira Fernandes et al. (2021) compared the energy and material life cycle impacts of several building archetypes in the Netherlands. They conclude that there is no one-size-fits-all solution for all buildings, and that material-intensive renovations under the conditions of the Dutch energy mixes were effective. However, they state that this finding may not hold up under a more sustainable energy mix composition (De Oliveira Fernandes et al., 2021). In addition, W/E Adviseurs (2021b) explored the combined shadow costs from energy and materials in several renovation alternatives for five types of buildings. With a similar method, they also compared the environmental impacts of new buildings with nZEB standards to energy neutral and passive building standards in the same buildings (W/E Adviseurs, 2021a). In both reports they conclude that buildings with a better energy performance, meaning that energy consumption is low and sustainable energy sources are used, lead to the lowest shadow costs. However, both studies are based on different assumptions regarding for instance life span, so the shadow cost values cannot be directly compared. A suggestion for further research by Mastrucci et al. (2020) is to combine the impacts of energy and materials for renovation and demolition scenarios within the same study, to compare the full range of options.

Many other studies with similar aims use only some of the required models that Mastrucci et al. (2020) listed. Some studies within the same research group focused on only the material impacts of refurbishment options (Mastrucci et al., 2015) or end-of-life (EOL) scenarios (Mastrucci, Marvuglia, Popovici, Leopold, & Benetto, 2017), and therefore did not include energy demand. Other studies only looked at operational energy use and omitted the lifecycle impacts from materials (e.g., Mastrucci, Baume, Stazi, & Leopold, 2014; Paiho et al., 2019; Gaspari, De Giglio, Antonini, & Vodola, 2020). Also, in these studies the environmental impacts are only measured through primary energy use, greenhouse gas emissions, or a new metric such as an Urban Energy Renovation index (Gregório & Seixas, 2017). Finally, Yang et al. (2020) modelled the energy consumption for residential heating in the city of Leiden through a GIS-archetype approach but did not include an LCA to calculate environmental impacts.

2.3. Decision-making and comparisons in practice

Goldstein et al. (2013) found that both LCAs and BEAs are rarely used by decision-makers and that LCAs are mostly only used at the level of building components. According to their analysis, historical preservation is the main concern in renovation versus replacement decisions. Furthermore, while sustainability and energy use are often mentioned, it is usually unclear how exactly they informed a decision. Xu, Shen, Lui, and Martek (2019) found that the consumption of energy and resources and structural building safety are only two of the factors that determine demolition projects in China, besides many others that are often related to local development. Dissatisfaction about the quality of buildings can also be an important factor in deciding to replace a building, for instance in the case of deterioration, draught, water penetration, or structural instability (Baker et al., 2017). On the other hand, demolitions can be related to several social issues (Power, 2008). Firstly, the required displacement of current inhabitants can cause resistance, also because people are attached to their homes and need to be compensated. Moreover, demolition causes nuisance to an area, is costly and organizationally complex, and at least temporarily leads to a reduction in housing capacity (Power, 2008).

The decision-making process and resulting selections between building renovation and replacement in the Netherlands, based on a sustainability perspective, were studied by Thomsen and Van der Flier in 2009. While they cited several Dutch case studies resulting in varying preferences between demolition and life cycle extension, based on both material and energy use, they argued that life cycle extension was in most cases the best option in terms of sustainability. These case studies often focused on individual buildings or neighborhoods, such as Itard & Klunder (2007), which used an LCA approach to compare neighborhoods in Delft and the Hague. They found that transformations were the optimal solution from an LCA perspective in the case study areas. Mostly because of the reduced amount of construction waste, transformation resulted in less environmental impacts compared to demolition and new construction.

In a study on rebuilding or renovating office buildings in the Netherlands, it was found that for buildings over 20 years old or with an energy label of D or lower, drastic renovation or rebuilding was often needed to produce the lowest environmental impacts (Anink et al., 2010). According to this study, the best option between these two is very dependent on the specific situation, although renovation was optimal if demolition would be preceded by multiple years of vacancy. Moreover, Meijer and Kara (2012) performed an LCA study to assess four building renewal options and found that, if the energy consumption for heating can be drastically reduced and there is a long lifetime expectancy after the intervention, the replacement of a building would result in a better environmental performance. However, these studies did not include fossil-free heating installations and nearly-zero energy building norms. Since the publication of these studies, stricter building regulations have been developed to force renovation and construction projects to reduce environmental impacts from materials and energy use. These policies are established in the Dutch Building Decree, although materials and energy use are still evaluated separately.

2.4. The aspect of time

While operational energy use is usually measured per month or year, the embodied energy during the life cycle of a building reflects a total amount. In LCAs of building refurbishments, alternatives are often compared by their impact per square meter per year (Vilches, Garcia-Martinez, & Sanchez-Montañes, 2017). Assumptions on the total service life of a building must be made to divide the impacts over this period. Rauf and Crawford (2015) found that changing the service life of a building from 50 to 150 years reduces the annual life cycle embodied energy by 29%. They also discuss the recurrent embodied energy, related to the replacement of building components. According to their results, the annual recurrent embodied energy increases with a longer service life of buildings, but this does not nullify the reduction in life cycle embodied energy from postponing demolition. Furthermore, Miatto, Schandl, and Tanikawa (2017) show that different life span distributions assumed for a city do not have a large impact on the modelled city-wide stock accumulation but do affect the size of demolition waste flows. Finally, results from Meijer and Thomsen (2009) indicate that, due to the maintenance of many components, the lifetime expansion of a Dutch reference building from 75 to 400 years does not significantly change the ratio of impacts from materials and energy.

Klunder and Van Nunen (2003) mention several other factors in which the factor of time is important in building LCAs. These include, for instance, future materials and production technologies that may be used in the replacement of building components or waste treatment technologies that have evolved during the service life. Furthermore, conventional LCAs calculate the total environmental impacts for a building throughout its lifetime, but do not consider when these emissions occur (Mastrucci, Marvuglia, Benetto & Leopold, 2020). It is also expected that energy sources in the EU will drastically change as a result of the ongoing energy transition. This would for instance impact the future electricity mix, including associated environmental impacts, and primary energy use.

2.5. The energy performance gap

Energy performance modelling is based on theoretical calculations for the energy consumption as opposed to actual energy use and can therefore be incorrect (Van den Brom, Meijer, & Visscher, 2018). This phenomenon is also known as the performance gap. Majcen, Itard, and Visscher (2013) showed that buildings which are considered energy efficient usually consume more energy than expected. On the other hand, they found that buildings with low energy labels consume less energy than predicted but subsequently also that the expected energy reductions of renovations from low to high energy labels are often overestimated (Majcen et al., 2013). Another study revealed that the over-predictions in energy savings in Dutch non-profit housing increase with the combination of two or more different energy savings measures, such as the replacement of glazing and heating installations (Filippidou, Nieboer, and Visscher, 2019). In addition, Van den Brom et al., (2018) studied different combinations of household and building characteristics to further understand the performance gaps in the Netherlands and provide policy recommendations. For instance, they found that low-income families which receive state benefits tend to have a high energy consumption, so they could be an appropriate target group for energy-saving campaigns.

2.6. Research aim

In conclusion, buildings should be renovated or rebuilt to reduce environmental impacts and energy use in the Netherlands, as established in the Climate Agreement. Scenarios for renovations and rebuilding are best compared through LCAs, in which the impacts of energy and materials are combined. A bottom-up archetype approach is suitable to apply a building LCA to a broader scale without requiring excessive data and computing load, is, by which common building typologies are evaluated to represent a larger part of the building stock. Finally, it is crucial to use an accurate estimate of the service life of a building as well as technological developments that occur over this period. The aim of this thesis project is thus to compare renovation to building replacement, for which the life cycle impacts from energy and materials are considered as well as fossil-free energy sources and energy efficiency standards in the Dutch policy context. These results can be used by housing corporations in the Netherlands, so that environmental sustainability can be considered next to other social aspects, when deciding between renovating or rebuilding. Furthermore, the findings can help municipalities in advising and guiding housing corporations through energy performance agreements, and to define pathways to a climate neutral society in 2050.

3. Case study

3.1. Requirements for renovations and new buildings in the Netherlands

3.1.1. Energy use

Existing buildings

The national building code in the Netherlands, the Building Decree, lists several requirements for drastic renovations, meaning that at least 25% of the building envelope is adapted (Ministry of BZK, 2021). These standards require minimum insulation levels of respectively 1,4, 2,1, and 2,6 m^2K/W for façades, roofs, and floors, in addition to a small amount of renewable energy generation and HVAC systems with up-to-date efficiency levels. Following the Climate Agreement, more ambitious target values have been formulated for the recommended heat demand and insulation in existing buildings, which would also allow buildings to be disconnected from the natural gas network (RVO, 2021). AEDES, the national association of housing corporations, has settled upon energy performance agreements with the Ministry of the Interior and Kingdom Relations (Ministry of BZK, 2022). In addition to availability, affordability, and livability, several targets have been formulated for the sustainability of dwellings owned by housing corporations with the goal of a climate neutral building stock in 2050. Some of the interventions entailed the accelerated renovation of houses with energy labels E, F, and G, phasing out natural gas, and extensive renovations towards the aforementioned target values (RVO, 2021).

New buildings

New buildings in the Netherlands are also required to comply to energy performance norms. The indicator of energy performance used to be the energy performance coefficient, representing the fraction of energy a building uses compared to a standard building in 1990 (NEN, 2017). The method to calculate the energy performance coefficient was called the Energy Performance of Buildings (EPG).

Since 2021, new buildings are required to be nearly-zero energy buildings (nZEB) (Ministry of BZK, 2021). The nZEB norms consist of three indicators: energy demand (EP1, in $kWh/m^2/year$), primary fossil energy use (EP2, in $kWh/m^2/year$), and percentage renewable energy (EP3, in %). The maximum allowed EP1 value is dependent on the ratio of usable floor area in a building compared to the surfaces in the building envelope through which heat is lost to the environment, also known as the compactness. Furthermore, there are regulations about the insulation levels.

See table 1 for an overview of the nZEB standards for energy efficiency and insulation, including the EP1 calculated for a reference building for post-war porch flats based on Agentschap NL (2011a). The determination methods for these indicators of energy performance have been outlined in the NTA8800:2022 norms (NEN, 2022). While the nZEB standards apply to an entire building, for individual houses it is required to register the energy label, which is based on the EP2, and the chances of temperature exceedance in July (TO July, max) (Vabi Support, 2022c). In figure 1 the division of EP2 values and the corresponding energy labels are shown.

Table 1: nZEB norms in the Netherlands (Ministry of BZK, 2021)

Energy efficiency		**Insulation**	
Energy demand	< 65 kWh/m^2/year (situation dependent)	Façade	4,7 m^2K/W
Primary fossil energy use	< 50 kWh/m^2/year	Roof	6,3 m^2K/W
Renewable energy percentage	> 40 %	Floor	3,7 m^2K/W

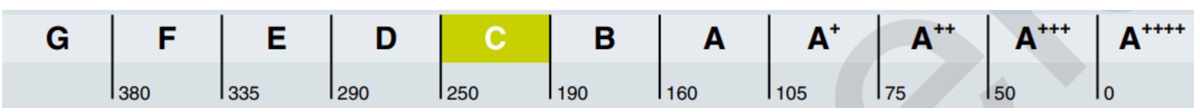


Figure 1: Energy labels corresponding to EP2 values in kWh/m2/year (Energie Label, 2021)

3.1.2. Material use

The indicator of the environmental impact of a building's materials, which needs to be calculated to obtain a building permit, is the MPG (environmental performance of buildings; *MilieuPrestatie Gebouwen*) (Stichting Bouwkwaliteit, 2017). The MPG stands for the shadow price of all materials in the building divided by the gross floor area and the life span of a building. The shadow price represents the sum of the costs of the different environmental impacts to society, based on the LCA methodology. In 2021, the maximum value of the MPG was changed from 1,0 to 0,8 €/m^2/year, and it is expected to decrease further until a value of 0,5 in 2030 (RVO, 2017). The shadow costs have been standardized because of the practical advantage of a single value, but it is important to consider that this is an anthropocentric, economic value which only indirectly reflects environmental impacts (De Oliveira Fernandes et al., 2021). Furthermore, De Oliveira Fernandes et al. (2021) state that there is no international consensus on the height and use of these shadow costs. Additionally, Van Haagen et al. (2022) mention that the standardized shadow prices in the

Netherlands are being reevaluated and they expect the environmental costs to become at least three times as high.

3.1.3. Combined environmental impacts from energy and materials

Koezjakov, Urge-Vorsatz, Crijns-Graus, and Van den Broek (2018) state that operational energy has historically had a larger emphasis in Dutch building regulations. For renovations, the Building Decree mostly has requirements regarding the insulation levels, which relates to energy efficiency but only indirectly to material use. For new buildings, there are limits to the allowed energy use and material shadow costs, but these are not combined to incorporate the tradeoffs between energy and material consumption. Furthermore, the policies of some municipalities favor renovation in general, such as Amsterdam (Gemeente Amsterdam, 2016).

In several sources, it has been acknowledged that the impacts from energy and material use should be combined into a single measure to accurately represent trade-offs between energy and material performance in the Netherlands (Alsema, Anink, Meijer, Straub, & Donze, 2016b; Koezjakov et al., 2018; Anink, Donze, & Niyongabo-Paulussen, 2022). Anink et al. (2022) therefore formulated the MPG^{+}, which consists of the sum of the MPG and the EPG*. EPG* is an adapted form of the EPG, in which the amounts of heat, natural gas, and electricity consumption have also been multiplied by environmental impact factors. Afterwards, the impacts can be combined with those from material use. One downside of the MPG^{+} is that there is not yet any distinction for different types of district heating (Anink et al., 2022). The environmental impacts of district heating networks can vary a lot based on energy sources and transport distances. Moreover, it must be made sure that the impacts of the infrastructure are not double counted, as they are also part of the MPG (Anink et al., 2022).

3.2. Housing corporations in Leiden

The municipality of Leiden has ambitious plans to increase the sustainability of heating systems (Municipality of Leiden, 2021) and to become climate neutral in 2050 (Over Morgen, n.d.). In the transition vision for heating, it is mentioned that about 80% of the houses in Leiden are built before 1990, of which a large share has a low energy efficiency. Both renovation and new construction are mentioned as possible interventions. Since it is more difficult to influence individual homeowners, which cover 50% of the building stock on Leiden, a large role is given to housing corporations (Municipality of Leiden, 2021). The four biggest corporations – Ons Doel, De Sleutels, Portaal, and DUWO – own 30% of houses in the city. Since housing corporations work with more collective and strategic plans for renovating or replacing buildings, the municipality considers them to be an important stakeholder for increasing energy efficiency. Furthermore, Leiden has an extensive database regarding building types and energy consumption (Municipality of Leiden, 2022). These factors make housing corporations in Leiden an interesting case study for comparing building renovation and replacement.

3.3. Porch flats

Energy and material performance calculations are dependent on a building design due to differences in material use, installations, and size. A recurrent building typology can be used for calculating the environmental impacts of different interventions to be able to generalize findings to as many buildings as possible, as described as the archetype approach in section 2.2. Furthermore, by renovating multi-family buildings, the energy performance can be efficiently improved for a lot of households at the same time. Common types of multi-story buildings in the Netherlands are porch flats and gallery flats (EPISCOPE, 2016a; EPISCOPE, 2016b). Porch flats were built mostly during the reconstruction period, the years after World War II until 1965, while in the period afterwards gallery flats became more conventional (Garritzmann, Poiesz, & Snijders, 2015).

Porch flats (a.k.a. porch apartments, garden apartments, *portiekflats*) usually consist of a common entrance and staircase, four stories, and two relatively small apartments per floor on each side of the staircase. According to an assessment from 2006, at that time 3.9% of the Dutch housing stock consisted of porch flats built between 1946 and 1964 (Agentschap NL, 2011b). The majority of these buildings were built by housing corporations (Van Vlaenderen, 2011). Van Vlaenderen and Singelenberg (2007) describe porch flats as affordable and relatively containing a lot of bedrooms. However, they are especially being criticized for being too small, noisy, and inaccessible for people with comprised mobility (Van Vlaenderen & Singelenberg, 2007). Since there were no standards for energy efficiency yet, many of these buildings were not insulated and still contained single glazing, although later double glazing has become more prevalent (Agentschap NL, 2011a). Besides, usually there is quite some green space around the buildings (Van Vlaenderen & Singelenberg, 2007), which would allow for densification if the flats were to be demolished to make room for new constructions. All in all, these characteristics make post-war porch flats relevant for comparing renovation or rebuilding options to increase energy efficiency and reduce environmental impacts.

4. Research gap and research questions

4.1. Research gap

Based on the literature review, a comparison of renovation and rebuilding alternatives to decrease total building impacts on an urban scale has been identified as a research gap (e.g., Mastrucci et al., 2020). Most other studies only focus on individual aspects, such as the environmental impacts of material use (e.g., Mastrucci et al., 2015; Mastrucci, Marvuglia, Popovici, Leopold, & Benetto, 2017), or operational energy consumption (Paiho et al., 2019; Gaspari et al., 2020). Other studies combined the impacts from both materials and energy to assess the performance of certain installations (e.g., Blom et al., 2010) or renovation options (e.g., De Olivera Fernandes et al., 2021), but did not make a comparison to building replacement. Furthermore, previous studies which compared renovation and rebuilding for multi-story apartments in the Netherlands assumed natural gas heating and did not include the new, stricter energy efficiency standards for new buildings and drastic renovations (e.g., Itard & Klunder, 2007; Meijer & Kara, 2012). Therefore, the combination of environmental impacts from energy and materials to compare renovation with building replacement in the context of the Dutch Climate Agreement is currently understudied. Finally, in many previous studies the environmental impacts are not weighted. While this avoids potential biases, using shadow costs to summarize all environmental impacts into one value makes the results of the different scenarios easy to compare.

4.2. Research approach

The aim of this study is to compare alternative scenarios for renovations or building replacement to decrease the environmental impacts of buildings, with a focus on housing corporations. A case study approach has been adopted, addressing a common building typology which also has undesirable characteristics, so that demolition is considered as a serious option. Therefore, this study has been conducted for porch flats, a common building archetype of housing corporations in the city of Leiden and the Netherlands in general.

Next to comparing different scenarios of renovation and building replacement to determine the most environmentally friendly alternatives, the most important factors determining the differences are analyzed to inform decisions about building renovation or replacement. Furthermore, this study aimed to advise decision-makers such as the municipality of Leiden or housing corporations about possible ways to locally improve energy efficiency and decrease environmental impacts. This advice is also illustrated in the form of a decision tree.

4.3. Research questions

To address the established research gap and approach, the following research questions have been formulated:

How do the environmental impacts of different renovation scenarios for typical buildings owned by housing corporations compare to demolishing and rebuilding in the context of the Dutch climate goals?

This research question is divided into the following sub-questions:

1. What are realistic building renovation or replacement scenarios for housing corporations in the Netherlands?
2. What are the environmental impacts of different scenarios for renovating a post-war porch flat or constructing a new multi-family building?
3. What key parameters have a large impact on the comparison between the environmental impacts of renovating or replacing buildings owned by housing corporations?

5. Methodology

5.1. Energy modelling

5.1.1. NTA8800:2022

The NTA8800:2022 is the national standard for calculating the energy performance of buildings in the Netherlands (NEN, 2022). The energy performance is based on building-related energy use, and therefore excludes the electricity used by lighting and appliances. The main framework for the calculations is the Building Decree. This leads to the use of the three indicators needed for the nZEB standards: energy demand (kWh/m^2/year), primary fossil energy use (kWh/m^2/year), and renewable energy percentage (%). The number of square meters refers to the usable floor area, which for instance would include the apartments in a building but not the shared corridors. In the NTA8800:2022 method, a benchmark is assumed for the energy-related behavior of inhabitants, which includes monthly variations due to seasonal changes of temperature and sun intensity. This allows for an equal comparison of buildings, but the actual energy demand may therefore be different as illustrated by the energy performance gap. Depending on the efficiency of installations, energy loss surfaces, insulation levels, energy sources, and potential onsite energy generation, the energy demand leads to a modelled primary and non-primary energy consumption.

The total primary fossil energy consumption (EP2) is an important indicator of energy performance, as it reflects the impacts on the environment and is the value used to determine the energy label of a building. The EP2 includes the primary fossil energy use for heating, cooling, ventilation, and domestic hot water for buildings with a residential function. In the case of utility buildings, essential lighting, humidification, and dehumidification are also included into the energy performance calculations. The primary energy use is calculated with a standard factor applied to the non-primary energy consumption and incorporates energy losses from energy generation and transportation (NEN, 2022). The primary energy factor of electricity is 1,45. Since natural gas is incinerated indoors and condensing boilers are very efficient, this primary energy factor is 1,0. District heating has a primary energy factor of 0,9, which means that the primary energy use is considered lower than the consumption. This is because often district heating systems are partially fueled with waste heat, for which the primary energy is not or only partially allocated to the heat consumer, or renewable sources such as geothermal energy.

5.1.2. EPA-W

The operational energy consumption of the buildings has been modelled in the software EPA-W, owned by Vabi Development B.V. (2022). This program follows the NTA8800:2022 method and can therefore be used to award building permits. The software requires inputs regarding the building dimensions, insulation levels, and installations. The resulting consumption is given following the nZEB indicators as well as more specific primary and non-primary consumption values per energy carrier, solar energy generation, the energy label, the TOjuly value, and CO_2 emissions. Furthermore, the energy use per application is given, including heating, hot water, ventilation, and auxiliary electricity. Auxiliary electricity is required to operate other installations, such as district heating and ventilation systems. Finally, the heating demand is given and compared to the target value for heating demand (RVO, 2021), calculated for the dimensions of the modelled building.

5.2. Material impacts modelling

5.2.1. Life Cycle Assessment

Life Cycle Assessment (LCA) is a method used to assess the environmental impacts of a product, process, or service throughout its entire life cycle. It involves identifying and quantifying the inputs and outputs of a system, including raw materials, energy, water, and waste, as well as any emissions to air, water, and soil. The purpose of LCAs is to understand the environmental impacts of a product or process, and to identify opportunities for improvement.

Performing a full LCA requires several steps (Guinée et al., 2002). The goal and scope definition involves outlining the studied product or process as well as the life cycle stages and environmental impacts that are included in the assessment. For an overview of all possible life cycle stages, see table 2. In the inventory analysis, all environmental inputs and outputs – such as raw materials, energy, water, and waste – are quantified per process in the life cycle. With the impact assessment, the environmental impacts are derived from the inputs and outputs identified in the inventory analysis, using a set of impact categories and a specific assessment method. An optional step is then to apply weighting factors to the impact categories, so that the impacts can be summed up into a single unit. An example of weighting factors are shadow costs. In the final interpretation step, the results of the impact assessment and/or weighting are assessed and used to inform, compare alternatives for the same product or service, if applicable, or to identify opportunities for improvement.

Table 2: Life cycle stages included in the NMD

Life Cycle Stages	
A1 + A2 + A3: Production	B5: Refurbishment
A4: Transport to construction site	C1: Deconstruction / demolition
A5: Building phase	C2: Transport to waste processing site
B1: Use of product	C3: Waste processing
B2: Maintenance	C4: Waste removal
B3: Repair	D: Miscellaneous costs and benefits outside of the system boundaries
B4: Replacement	

5.2.2. Material Performance of Buildings

The Material Performance of Buildings (MPG) is the standardized method in the Netherlands for evaluating the environmental impacts of materials used in buildings throughout their entire life cycle (Stichting Bouwkwaliteit, 2017). For the MPG score, a specified selection of building components needs to be incorporated, which can be found in appendix A.1. Furthermore, the MPG is based on the LCA method and uses data from the Dutch Environmental Database (NMD). This database is managed by an independent organization and includes both producer-specific and generic data for building materials and related products (Alsema et al., 2016b). The MPG method prescribes certain standard values, such as an expected service live of 75 and 50 years for residential and non-residential buildings, respectively. Moreover, for the product EOL phases, standards have been determined by the NMD regarding the recycling rates per material (Stichting NMD, 2022c).

In the MPG method, the use of the CML method for lifecycle impact assessments has been determined (CML, 2016), which includes the 11 impact categories listed in table 3. These impact categories are measured by a unit indicator. For example, all emissions that contribute to global warming are represented as kilograms of CO_2-equivalents measured over a time horizon of 100 years (CML, 2016). The impact scores for each category are then combined into a single score using weighting factors, based on the shadow price for each impact category. The shadow price represents the virtual cost to avoid or reverse the damage of an environmental impact (Alsema et al., 2016b). The shadow costs per impact category are also shown in table 3.

Table 3: LCA Impact categories, unit indicators, and shadow costs included in the NMD and CML method

Impact Categories	Unit indicator	Shadow costs (S€)
Depletion of abiotic resources (excluding fossil energy carriers)	kg antimony equivalent (eq.)	0,16
Depletion of fossil energy carriers	kg antimony eq.	0,16
Global warming	kg CO_2 eq.	0,05
Ozone layer depletion	kg CFK-11 eq.	30
Photochemical oxidation	kg ethylene eq.	2
Human toxicity	kg 1,4-dichlorobenzene eq.	0,09
Fresh water aquatic eco-toxicity	kg 1,4-dichlorobenzene eq.	0,03
Marine aquatic eco-toxicity	kg 1,4-dichlorobenzene eq.	0,0001
Terrestrial eco-toxicity	kg 1,4-dichlorobenzene eq.	0,06
Acidification	kg SO_2 eq.	4
Eutrophication	kg PO_4^- eq.	9

The NMD lists a large collection of LCA data for building components in the Netherlands. Three categories of product information exist in the NMD: (1) producer-specific data; (2) producer-unspecific data which are tested by a qualified, independent party; and (3) untested, producer-unspecific data (Stichting NMD, 2022b). Only for category 3 data, the environmental emissions per impact category of every life cycle stage are public. These impacts are informed as much as possible by the most recent version of the EcoInvent database, which currently is version 3.6. Furthermore, because the data are not verified, the environmental impacts are increased with a surcharge factor of 30% because experience showed that untested impacts are often underestimated (Stichting NMD, 2022b). Accessible data from products and services in the other categories entail the expected service life and total shadow costs per unit.

The final MPG score of the building is calculated by adding up the shadow costs in every impact category of each product, adjusted to the life spans of the building and the individual components. If the life span of a product is shorter than the expected building life span, the environmental impacts of the full life span of a product are attributed to the shorter building life span. If the building life span exceeds that of the product, the shadow costs increase incrementally, based on the additional fraction of its life span. This way of calculating is referred to as the fraction method (*breukenmethode*) and it is used because the life span prediction in the end only represents a generic suggestion (Stichting NMD, 2021). The total shadow costs are then divided over the building life span and the gross surface area of the building. Thereby, the MPG score is expressed in euros per square meter per year so it can also be used to compare different buildings on their environmental impacts.

5.2.3. GPR Gebouw

GPR Gebouw (*GPR Building*) is a software for calculating the environmental performance of buildings (W/E Adviseurs, 2023). It follows the MPG method and is licensed to provide building permits. Next to materials, there are also modules to measure energy performance, health impacts, living quality, and future value. In this study, only the material performance section has been used. The software firstly requires the inputs of main building characteristics, such as the usable and gross floor area and the life span. Next, the materials have been selected for each building component, separated into the following main categories: foundation, floor, load-bearing structure, façade, roof, installations, and indoor elements such as kitchens and bathrooms. Most materials amounts are defined per surface area in square meters, sometimes complemented by additional dimensions, but others are specified per item, length (m), or volume (m^3).

5.3. MPG^+

To assess the environmental impacts of the complete building life cycle and the tradeoffs between energy and material use of renovations and rebuilding, the environmental impacts of energy and materials need to be combined. A method developed for this purpose in the Dutch context is MPG^+ (W/E Adviseurs, 2021a, W/E Adviseurs, 2021b). To calculate the MPG^+, energy consumption is also transformed into the units required for the MPG. This transformation involves several steps, as outlined by Alsema et al. (2016b). Firstly, the environmental impacts of different energy carriers in the Netherlands should be determined. For sources such as electricity and district heating, all impacts are produced during external energy generation and transportation. However, for natural gas, external emissions are related to the infrastructure and transportation, while the emissions from combustion occur indoors. The shadow costs of these emissions have been reflected in impact factors in terms of euros per kWh or MJ of energy consumption. The impact factors per energy carrier and the corresponding environmental impact of a building are calculated as follows (Alsema et al., 2016b):

(1) $IF_i = IF_{external} + IF_{internal}$

(2) $EPG_i = IF_i * E_i$

where:

IF_i	=	Environmental impact factor for energy carrier *i* (€/kWh or €/MJ)
EPG_i	=	Environmental impact for energy carrier *i* (€/kWh)

E_i = Final non-primary energy consumption for energy carrier i (kWh/m²/year)

The resulting impact factors are listed in table 4. Because of the wide variety of sources for district heating, by default, the impact is calculated as 150% of the shadow costs of natural gas (W/E Adviseurs, 2016). For the impact factors per environmental impact category, see section 7.1.1.

Afterwards, the energy performance (EPG) and MPG^+ are calculated according to the following formulas (Alsema et al., 2016b):

(3) $EPG = \sum_i EPG_i$

(4) $MPG^+ = MPG + EPG$

Table 4: Impact factors for energy carriers in the Netherlands

Energy carrier	**Unit**	**$IF_{external}$**	**$IF_{internal}$**	**IF**
Electricity	€/kWh	$6{,}09 * 10^{-2}$	0	$6{,}09 * 10^{-2}$
Natural gas	€/MJ	$3{,}45 * 10^{-3}$	$1{,}60 * 10^{-3}$	$5{,}05 * 10^{-3}$
External heat supply from district heating	€/MJ	*situation dependent*	0	$7{,}55 * 10^{-3}$

With the combination of EPG and MPG, the indicators have been adapted in three different ways to avoid double counting and to ensure consistency. First, the MPG requires the energy consumption to be entered to calculate the environmental impacts from the energy infrastructure and associated material use. Since the infrastructure is already included in the energy impact factors, these impacts are left out of the MPG in this study. Secondly, because the MPG is calculated per year, the yearly energy consumption should be used to calculate the EPG and subsequently the MPG^+. Lastly, the nZEB indicators measure energy use per usable floor area while the MPG looks at total building floor area, or gross surface area. Thus, for the MPG^+ the energy consumption of the entire building has been divided by the gross surface area as well to calculate the EPG and MPG^+.

In conclusion, the shadow costs have been calculated by combining the material performance and energy performance of the building. The material performance, or MPG, has been altered by leaving out the impacts related to energy generation. The environmental impacts from energy are reflected by the energy consumption multiplied by a standardized impact factor per energy carrier. The sum of the shadow costs from the total yearly energy consumption per energy carrier of the building have been divided by the total floor area. As a result, the MPG^+ gives the shadow costs per scenario in €/m²/year, by which the environmental impacts can be easily compared.

5.4. Calculations for reduced electricity and district heating impacts

5.4.1. Electricity impact reduction

The goal of the Dutch Climate Agreement is to be climate neutral in 2050 (Ministry of EZK, 2019). This would also entail that the generation of electricity does not cause net CO_2-emissions. Electricity consumption used to be responsible for a lot of shadow costs (Alsema et al., 2016a), so it is important to accurately represent this reduction pathway in the scenarios, since all life spans last nearly up to or beyond 2050.

Baumgärtner et al. (2021) performed an LCA of the environmental impacts of electricity in Germany, among other energy sectors, until 2050. They state that the impacts in the environmental impact categories which are expected to increase with more renewable energy sources, such as non-fuel abiotic depletion, are very uncertain and that therefore more research is required. In a Danish case study, it was calculated that the climate change impacts will be reduced to 25% (Turconi, Tonini, Nielsen, Simonsen, & Astrup, 2014). Since this study did not use the same impact assessment method as the Dutch impact factors, the environmental impacts are difficult to compare. However, in the impact categories for which the same units were used by Turconi et al. (2014) and the CML method (CML, 2016), the impacts reduced by around 50%, on average. Since global warming is responsible for a large part of the shadow costs (Alsema et al., 2016a), it has been assumed that the environmental impacts of carbon-neutral electricity will be 25% of the shadow costs of electricity in the data by Alsema et al. (2016a), calculated per impact category.

The shadow costs used by Alsema et al. (2016a) are based on EcoInvent data from 2004 and 2008 for natural gas and electricity, respectively. According to Rijksoverheid (2022), the emissions of greenhouse gases in the Netherlands were approximately similar in 2005 and 2010, namely 52,0 or 52,1 Megatons of CO_2 equivalents. The emissions in 2021 were estimated to be 32,7 Mton CO_2-eq. (Rijksoverheid, 2022). Furthermore, the EU-wide target, adopted in the Climate Agreement, is to have reduced the greenhouse gas emissions in 2030 to 45% (Ministry of EZK, 2019). Based on linear reductions between these checkpoints, the percentage of GHG emissions compared to those in 2008 has been calculated for the years 2025 and 2045, which are part of the scenarios in the current study.

The expected reduction percentage of the overall shadow costs compared to original values has been calculated by considering the same linear reductions pathways of CO_2-eq. impacts, but then the shadow costs decrease to 25% instead of 0%. For the resulting percentages of both greenhouse gas emissions and overall environmental impacts, see table 5. Next, based on the average values between the checkpoints, the reduced electricity impact percentages throughout the entire period of the different life spans considered in this study have been calculated, which can be found in table 6. For a complete overview of the calculations, see appendix C. The scenarios are explained in full in chapter 6.

Table 5: Forecasted greenhouse gas emissions and environmental impacts in the years until 2050

Reduction Year	Source	Greenhouse gases	Shadow costs
2016	Rijksoverheid (2022)	100%	100%
2021	Rijksoverheid (2022)	63%	72%
2025	Based on 2021 data and 2030 target	55%	66%
2030	EU-wide target: 55% reduction (Ministry of EZK, 2019)	45%	59%
2045	Based on 2030 and 2050 targets	11%	33%
2050	Climate Agreement: carbon neutral (Ministry of EZK, 2019)	0%	25%

Table 6: Reduced electricity impact percentages for the different life spans

Life span	End year	Percentage in end year	Assumed number of years with climate neutral electricity	Reduced percentage of electricity impacts
20 years	2045	33%	0	50,2%
40 years	2065	25%	15	38,1%
75 years	2100	25%	50	32,0%
125 years	2150	25%	100	29,2%

5.4.2. District heating impact reduction

Because there is a wide variety of energy sources for district heating and the associated environmental impacts are very uncertain, the default values used by W/E Adviseurs (2016) entail 150% of the shadow costs of natural gas. This percentage applies to each impact category, leading to the same relative contribution of each impact category to the total shadow costs.

With renewable energy sources in the future, also related to the Climate Agreement and climate neutrality targets in 2050 (Ministry of EZK, 2019), the environmental impacts of district heating are expected to be lower than the default values given by Alsema (2016a) (Wijngaart et al., 2014). However, the construction and operation of the network and infrastructure as well as the production of renewable sources such as biomass still require energy and materials. Bartolozzi, Rizzi, and Frey (2017) compared the impacts of individual natural gas boilers to a district heating network based on natural gas, a district heating network using geothermal energy, and one using biomass as fuel. Because of different units and impact categories, the LCA impacts are not one-on-one comparable to the shadow costs of natural gas in the Netherlands.

In the current study, the results from Bartolozzi et al. (2017) have been used to roughly estimate the difference in shadow costs that could result from the district heating options. This has been done by looking at the ratio of emissions per impact category in the results of Bartolozzi et al. (2017). The increase or decrease compared to natural gas boilers in that study has been applied to the shadow costs of natural gas in the Dutch context for the impact categories that overlapped between Bartolozzi et al. (2017) and the CML method. This resulted in fractions of the shadow costs related to natural gas ranging from 0,64 (for geothermal district heating) and 0,78 (for biomass-based district heating). Although the list of impact categories is incomplete, it does include global warming potential and human toxicity, which have the highest shadow costs per kWh for electricity and natural gas (Alsema et al., 2016a). The intention of this alternative shadow cost calculation is to include an optimistic option that represents district heating based on renewable energy. Therefore, a fraction of 0,7 compared to natural gas shadow costs has been selected for the district heating alternative with reduced environmental impacts. The resulting shadow costs per energy carrier can be found in table 12 in section 7.1.1. For more details on the impacts calculated by Bartolozzi et al. (2017) and the calculations, see appendix C.

5.5. Sensitivity analysis

To assess how different assumptions and data inputs have influenced the results, a sensitivity analysis has been performed. Building life span has been incorporated into the main analysis. In the sensitivity analysis, firstly the effects of a 20% increase and decrease in energy and material inputs have been illustrated. The results have also been recalculated with changes to the assumed reduction of the impacts of electricity, as described in section 5.4.1. The three alternative pathways for the reduction of electricity impacts that have been assessed are:

- No reduction since the shadow costs by Alsema et al. (2016a)
- No reduction since the estimated impacts in 2021 (see table 5)
- A reduction to 50% instead of 25% of the shadow costs by Alsema et al. (2016a)

Next, the impacts of the selected heating technology have been analyzed by applying the different energy carriers to an otherwise identical building. In addition, the main scenarios are compared to the shadow costs with installed solar panels, which leads to a reduction of environmental impacts from electricity use but also an increase in material impacts because of the solar panels. Furthermore, the possible effect of the energy performance gap on the actual energy consumption, as explained in section 2.5, has been applied to the main results. Finally, the shadow costs have been calculated per apartment instead of per square meter, which exposes possible underestimations of environmental impacts due to an increase in apartment size per resident.

6. Inventory

The results by which the different scenarios are compared heavily rely on many modelling assumptions. The following section discusses important inputs and assumptions for the building dimensions and the variables in the EPA-W and GPR programs. For a complete overview of all inputs, see appendix C.

6.1. Scenario selection

The scenarios for this study have been selected based on the perspective of housing corporations in Leiden and rest of the Netherlands. Firstly, for housing corporations it is essential that the interventions are not disproportionally expensive. This ensures that the rent remains affordable for tenants with low incomes. Because of this requirement, renovations towards energy neutral or passive house standards or more expensive insulation options with ecological materials such as cork or sheep wool are not considered. Furthermore, it has been the aim to create scenarios that are applicable to as many buildings as possible. Therefore, mostly conventional insulation techniques and materials are included. Finally, collective heating solutions are probably efficient in terms of costs and time and cause less disturbance from activities within individual apartments. In addition to these aspects, the scenario selection has been informed by conversations with housing corporations in Leiden and experts in the field of building energy.

Six main scenarios, of which two have an extra variant, have been created for this thesis project. The scenarios are listed in table 7. In the municipality of Leiden, among other areas in the Netherlands, there are plans to expand its district heating network (Municipality of Leiden, 2021). Since this will be a system with medium temperatures (~70°C), the additional insulation needed for the existing porch flats in this scenario is minimal. The Minimal Renovation scenario (1.1) uses this type of district heating. For the insulation levels, the minimum requirements in the Building Decree for drastic renovations are used and the windows are replaced with HR++ glazing. Scenario 1.1b uses a sustainable alternative for district heating, as explained in section 5.4.2, but all other specifications are identical to scenario 1.1. Because of the minimal insulation levels, these scenarios have the lowest energy labels of the renovation scenarios.

In terms of operational energy use, the remaining scenarios for existing buildings are based on the selection of heating technologies and standardized renovation scenarios created for porch flats by EPISCOPE (EPISCOPE, 2016a). The current situation and basic renovation scenarios by EPISCOPE coincide largely with the current scenario and the energy savings package suggested for porch apartments in the report of exemplary buildings by Agentschap NL (2011a). In the current situation, the Rc values (the heat resistance of the construction) without insulation are listed as well as the most common types of windows and heating. The basic renovation scenario includes the insulation of façades, roof, and floor, as well as new windows and heating by a condensing boiler based on natural gas. The Business as Usual (BAU; scenario 0) and Standard Renovation (1.2) scenarios in the current report mostly align with the current situation and the basic renovation scenario by Agentschap NL (2011a) and EPISCOPE (2016a). In addition to the Standard Renovation scenario, variation 1.2b uses a hybrid heat pump instead of the condensing boiler but is otherwise identical.

The advanced refurbishment scenario from EPISCOPE (2016a) uses an individual heat pump and follows previous new building standards. This scenario forms the basis of the Extensive Renovation scenario (1.3) in the current study, although a collective air-sourced heat pump with an electric boiler for domestic hot water has been selected instead of an individual heat pump with a solar boiler. Furthermore, the insulation levels have been updated to current nZEB guidelines. The new building scenarios (2.1 and 2.2) also follow nZEB standards but use a ground-sourced heat pump. The energy specifications of the new building scenarios are the same, they only differ in terms of material selection.

The created scenarios are summarized in the following table:

Table 7: Scenarios for calculating environmental impacts of the renovation or replacement of post-war porch flats

Category	Scenario	Energy Label
0. Baseline	**0. Business as Usual**: No intervention	E
1. Renovation	**1.1a Minimal Renovation** to required level for medium temperature district heating network with conventional sources (minimal renovation standards Building Decree) **1.1b Minimal Renovation** with district heating with renewable sources	B
	1.2a Standard Renovation with a condensing boiler **1.2b Standard Renovation** with a hybrid heat pump	A
	1.3 Extensive Renovation to required level for collective heat pump (nZEB standards)	A++
2. Demolition and new construction	**2.1 New Conventional:** residential building with conventional materials (nZEB standards)	A++
	2.2 New Sustainable: residential building with sustainable materials (prefabricated, biobased; nZEB standards)	A++

6.2. Building dimensions

The dimensions of the porch flats, listed in table 8, are based on the reference building typologies for post-war porch flats as outlined by Agentschap NL (2011a) and EPISCOPE (2016a). EPISCOPE uses the same reference building but includes more details. Furthermore, Vringer and Blok (1993) created a list of materials for post-war porch flats, derived from an older edition of the reference buildings report by Agentschap NL (2011a). They assumed 28 apartments in a four-floor building with four different porches, which has been copied for the current study. The three sources only describe dimensions relevant for the calculations of energy or material use, such as the floor area, closed and open parts of the façade, or the volume of concrete. The complete list of dimensions for the reference porch flat has been created through experimentation until the modelled surfaces were approximately the same as the dimensions in the existing sources. Some details, such as the dimensions of the balcony and stairwell are based on measurements in a porch flat in Amsterdam Slotervaart with similarly sized apartments. Figure 2 illustrates the layout of the apartments within the porch flat and figure 3 contains an example picture of a porch flat in Leiden.

Table 8: Main dimensions and specifications of the Porch flat and Woongebouw

		Porch flat	Woongebouw
Number of apartments	#	28	33
Surface area per apartment	m²	66,6	Apartment A: 89 Apartment B: 83
Total usable floor area	m²	1865	2834
Gross surface area	m²	2304	3828
Building height	m	12	18
Ground floor dimensions	m	L: 64 B: 9	L: 29 B: 22

CR-W	IR	IR	IR	IR	IR	IR	CR-E
CM-W	IM	IM	IM	IM	IM	IM	CM-E
CM-W	IB	IM	IB	IM	IB	IM	CB
CG	B	IG	B	IG	B	IG	B

Figure 2: Layout of reference porch flat. Orange cells stand for the basements, furthermore, the apartments are organized by their differences in surfaces through which energy is lost. Abbreviations: B: Basement, CR-W/E: Corner Roof (West/East), IR: Intermediate Roof, CM-W/E: Corner Middle (West/East), IM: Intermediate Middle, IB: Intermediate Basement, CB: Corner Basement, CG: Corner Ground floor, IG: Intermediate Ground floor. The front of the building faces north.

Figure 3: Image of porch flat in Leiden, constructed in 1958 (Arndt, 2021)

Van der Loos (2017) created 33 types of reference buildings as an example of how different types of buildings could comply to the nZEB norms. Out of these buildings, *Woongebouw M* (medium-sized apartment block) is most similar to porch flats and appropriate for the tenants of housing corporations that currently live in porch flats. The apartments in the new building are larger, contain an elevator, and contain some insulation between floors. Therefore, some of the disadvantages of porch flat, as described by Van Vlaenderen and Singelenberg (2007), are tackled with the selection of this building. Figure 4 contains a picture of the three-dimensional model of *Woongebouw M* (Vabi Support, 2022a). The document by Van der Loos (2017) focuses on energy-related specifications for three different heating alternatives: natural gas, district heating, and all-electric. Vabi also published files in which the alternatives for *Woongebouw M* by Van der Loos (2017) have been elaborated in terms of energy use (Vabi Support, 2022a) in EPA-W. These have been used to verify the calculated dimensions. Furthermore, Klaver (2018) has expanded *Woongebouw M* into a complete list of materials for several scenarios in order to calculate the MPG. For this, a floor plan of the building has been created, which has been used in the current study to define the internal building dimensions. Figure 5 shows the floor plan of all floors except the ground floor, in which the area of the front half of the apartments is used for storage and the common entrance. The 3D-model and floor plan have been used to determine the external dimensions of the building. Although Klaver (2018) also describes dimensions used in the research project, the building dimensions have been recalculated to ensure consistency between all elements of the current study.

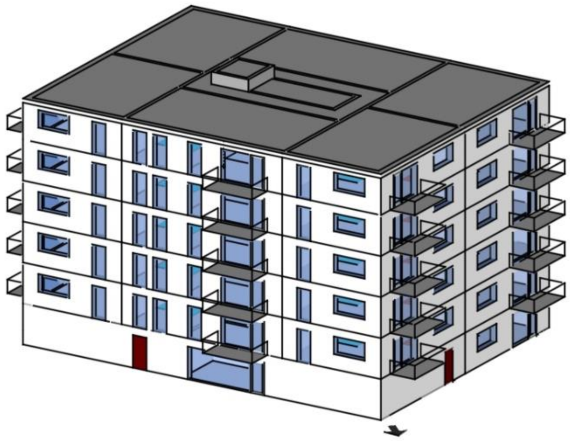


Figure 4: 3D drawing of Woongebouw M (Vabi Support, 2022a)

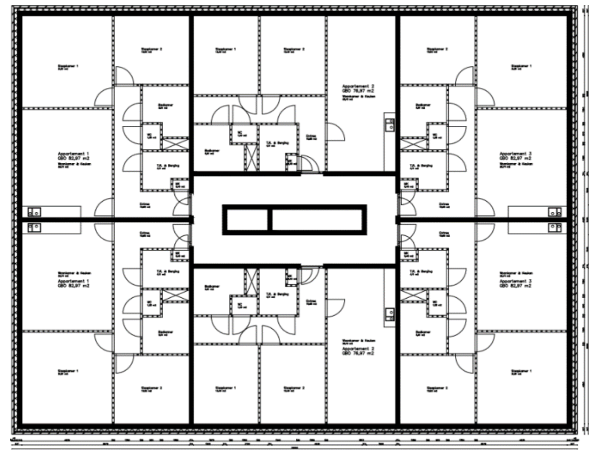


Figure 5: Floor plan Woongebouw M, floors 2-6. Corners: Apartment A; Middle: Apartment B (Klaver, 2018)

6.3. Energy inputs

6.3.1. Porch flats

In existing buildings, the insulation levels given by Agentschap NL (2011a) and EPISCOPE (2016a) or the minimum insulation values in the Building Decree have been followed. In addition, increasingly efficient installations for ventilation have been selected. Furthermore, it is assumed that during all renovations some additional improvements are made to the heating system for which the materials are not modelled, such as the insulation of pipelines, shackles, and fittings. The COP values of the air-water heat pumps is 3,7, based on the upper bound of conventional values according to Mijzen (n.d., a).

By selecting *unknown* for several inputs for ventilation, heating, cooling, and hot water in EPA-W, the program selected conservative values that are still representative for the building, for instance based on construction year. This reduced the need to select arbitrary values if average numbers for post-war porch flats were not available. The use of conservative values ensures that the results are in any case not too optimistic for most porch flats. In appendix C, all input values can be found.

Inputs for which it was difficult to obtain realistic values were the required power and/or number of heat pumps required to fulfill peak demand, as well as the size of storage tanks used for the electric boilers. A rough estimate for these values is selected, as it was seen that the results in EPA-W were barely influenced by these inputs.

6.3.2. Woongebouw M

For *Woongebouw M,* the all-electric alternative created by Van der Loos (2017) has been selected, because it is in line with the intention to phase out natural gas in the Netherlands and independent of the availability of district heating networks. For this reason, it is considered a no-regret alternative.

Since it is more difficult and expensive to change energy systems in existing buildings compared to implementing it immediately in new buildings, some measures have only been selected in scenarios 2.1 and 2.2. Only new buildings include showers with heat recovery and use underfloor heating, which also allows for a lower water supply temperature for heating. In addition, the porch flats use air-water heat pumps which require less nuisance during construction, while new buildings use ground water as source for the heat pumps. The ground-sourced heat pump has a COP value of 4,4 (Mijzen, n.d., a). In combination with all collective heat pumps, an electric boiler is used for domestic hot water supply. Moreover, new buildings use free cooling. This is a form of cooling possible with ground-sourced heat pumps, in which the cold from the ground is used to cool the building during summer (Mijzen, n.d., b). Only the circulation pump is required for the cooling process, the heat pump itself is not active. Furthermore, some additional heat is stored in the ground through this process, which can in turn be used in the winter for heating.

Table 9 gives a summary of the energy inputs selected for the different scenarios.

Table 9: Main energy specifications of the different scenarios

	Scenarios	**Baseline**	**Renovations**			**New building**
Section	**Values**	0. BAU	1.1 Minimal renovation	1.2 Standard renovation	1.3 Extensive renovation	2. New residential building
Sub-scenarios		x	1.1a: Default district heating 1.1b: Renewable district heating (not modelled in EPA-W)	1.2a: Standard renovation with HR boiler 1.2b: Hybrid heat pump	x	2.1 Conventional materials 2.2 Sustainable materials (not modelled in EPA-W)
Description		Current situation, uninsulated porch flats	Minimum insulation with medium-temperature district heating	Standard insulation with	Renovation based on nZEB with collective heat pump	New nZEB building with collective heat pump

Building envelope: closed	Sourcess:	*Agentschap NL (2011a): Current*	*Building Decree (2022), Article 5.6.2*	*Agentschap NL (2011a): Energy saving package, floor: Building Decree*	*Minimum values Building Decree (2022), Table 5.1A+B*	*Minimum values Building Decree (2022), Rc for floor insulation based on ribbed floor in GPR Gebouw*
Façade	Rc value (m2K/W)	0,36	1,4	2,53	4,7	4,7
Roof	Rc value (m2K/W)	0,39	2,1	2,53	6,3	6,3
Floor	Rc value (m2K/W)	0,32	2,6	2,6	3,7	4,0
Building envelope: open	Sources:	*EPISCOPE (2016): Existing state*	*Same as EPISCOPE (2016): Usual* Renovation	*EPISCOPE (2016): Usual* Renovation	*EPISCOPE (2016): Advanced* Renovation	*RVO (2017): Woongebouw M, all-electric, same g-value as EPISCOPE (2016): Advanced* Renovation
Window single	U-value (W/m2K)	5,2	x	x	x	x
	g-value	0,72	x	x	x	x
Window double glazing	U-value (W/m2K)	2,9	x	x	x	x
	g-value	0,72	x	x	x	x
Window HR++	U-value (W/m2K)	x	1,8	1,8	x	x
	g-value	x	0,6	0,6	x	x
Windows triple glazing	U-value (W/m2K)	x	x	x	1,0	1,0
	g-value	x	x	x	0,6	0,6
Door	U-value (W/m2K)	3,5	3,5	3,5	1,4	1,4
	Rc value (m2K/W)	x	x	x	x	x
Installations	Sources:	*EPISCOPE (2016): Existing state*	*Assumptions for minimal renovation with medium-temp. district heating*	*EPISCOPE (2016): Usual* Renovation	*EPISCOPE (2016): Advanced* Renovation *COP: based on Mijzen (n.d., a)*	*Ground HP + free cooling: RVO (2017): Woongebouw M, all-electric COP: based on Mijzen (n.d., a) Ventilation: same as EPISCOPE (2016): Advanced* Renovation *Electric boiler: availability in GPR Gebouw*
Ventilation	Type of ventilation	C. Mechanical exhaust	C. Mechanical exhaust	C. Mechanical exhaust	D2. Balanced, heat recovery 95%	D2. Balanced, heat recovery 95%
	Current	Alternating	Alternating	Direct	Direct	Direct

Heating		HR gas combination boiler	Medium-temperature district heating	HR gas combination boiler / Hybrid heat pump, COP=3,7	Air / water heat pump, collective, COP=3,7	Ground water / water heat pump, collective, COP=4,4
Domestic hot water	Type of installation	HR gas combination boiler	Medium-temperature district heating	HR gas combination boiler / electric boiler	Electric boiler, individual	Electric boiler, individual
	Shower heat recovery	x	x	x	x	Yes
Cooling		x	x	x	x	Free cooling
PV Panels	m2	*460*	*460*	*460*	*460*	*510*

6.4. Material inputs

6.4.1. Porch flats

The materials used for renovations included the relevant heating technologies and insulation, as well as the replacement of window frames, shared outer doors, water pipelines, radiators, water barriers, and roof covers, as these are common maintenance measures to combine with renovation. Apart from this, no other replacements or maintenance are included in the material assessment. This leads to an underestimation of material use, for which the extent has been assessed in the sensitivity analysis.

The type of insulation varies among the renovation scenarios, which leads to a difference in material selection. Scenario 1.1 uses cavity wall insulation, but these are often too slim for the required Rc values of scenarios 1.2 and 1.3. Scenario 1.2 uses an indoor wall system for insulation because of lower environmental impacts per square meter (Stichting NMD, 2022a). However, the indoor insulation alternative would result in an excessive loss in floor space in scenario 1.3, so for this reason external façade insulation is implemented in this scenario. This can lead to a different appearance of the building.

The types of materials used for renovation have been made consistent with the conventional materials scenario by Klaver (2018) as much as possible, which is explained in the next section. Furthermore, in scenario 1.3, the electrical wiring is replaced because of the reliance on electricity for all energy consumption. Moreover, the front doors of apartments are also assumed to be replaced in scenario to increase airtightness. See table 10 for a summary of the materials and appendix C for the full list. Finally, it was not possible to select collective heat pumps in GPR. Therefore, 13 individual heat pumps have been included to cover the power required for the collective heat pump, based on a comparison to the floor area and the power required per square meter in an example calculation by Aerts (n.d.) (see appendix C for the full explanation).

Table 10: Materials and properties of porch flats. Rc-values are given in m^2K/W and U-values are given in W/m^2K.

	Scenario	**1.1: Minimal renovation (1.1a + b)**	**1.2: Standard renovation (1.2a + b)**	**1.3: Extensive renovation**
Components	**Amount**			
Insulation façade	1239 m^2	Glass wool (dry fill), cavity wall (Rc = 1,4)	Glass wool (plates), timber frame insulation (Rc = 2,53)	IsoBouw Polystuc (polystyrene), external façade insulation (Rc = 4,7)
Insulation roof	576 m^2	EPS (Rc = 2,1)	EPS (Rc = 2,53)	EPS (Rc = 6,3)
Replacement of roof cover layers	576 m^2	Yes (bitumen, gravel, polyethene)	Yes (bitumen, gravel, polyethene)	Yes (bitumen, gravel, polyethene)
Insulation floor	576 m^2	Glass wool (Rc = 2,6)	Glass wool (Rc = 2,6)	Glass wool (Rc = 3,7)
Replacement of shared doors	4	Wood with glass opening 0,85 m^2	Wood with glass opening 0,85 m^2	Wood with glass opening 0,85 m^2
Replacement of apartment doors	28	No	No	Painted wood (U = 1,4)
Window frames	513 m^2	European coniferous wood; sustainable, painted	European coniferous wood; sustainable, painted	European coniferous wood; sustainable, painted
Glazing	345 m^2	HR++ glazing (U-value = 1,8; g-value = 0,6)	HR++ glazing (U-value = 1,8; g-value = 0,6)	Triple glazing (U = 1,0; g-value = 0,6)
Sunscreens	503 m^2	No	No	Solidscreen, white
Installations				
Ventilation	1865 m^2gbo	C: Mechanical exhaust	C: Mechanical exhaust	D: Balanced, heat recovery
Heating	28 / 28/ 13	External heat supply	1.2a: Combined HR boiler 1.2b Hybrid heat pump	Collective heat pump air/water (entered as 13 individual hybrid heat pumps)
Domestic Hot Water	28	Addition to external heat supply	Addition to heating installation	Electric boiler

6.4.2. Woongebouw M

The selection of materials included in the MPG calculations is based on the list by Stichting Bouwkwaliteit (2017). The lists of components to include and exclude can be found in appendix A.1. During a bachelor's thesis project for the University of Applied Sciences in Utrecht, Klaver (2018) created several material scenarios for *Woongebouw M*. The materials used for scenarios 2.1 and 2.2 in the current study are based on the scenarios *Basis* (Basic) *and Duurzaam 2* (Sustainable 2) (Klaver, 2018). These represent a standard material selection and an alternative with sustainable and/or bio-based materials, respectively. Moreover, all selected materials are available in the NMD so that they can be selected in GPR Gebouw for calculating the MPG. Although the surfaces or volumes per material have been calculated by Klaver (2018) as well, this has been redone to ensure consistency with EPA-W and the other building types. For some materials, the amounts were roughly estimated, but in these cases is has been ensured in GPR that the materials only cause a small fraction of the material shadow costs. Finally, based on Aerts (n.d.), the number of required individual heat pumps for the power of a collective system is 20.

The materials in the sustainable building variant differ from the conventional building in terms of insulation type, façade materials, the type of concrete floors, roof cover, and the indoor finish layers. In some cases, this entails biobased materials. For instance, wood fiber has been selected instead of EPS in the roof and façade and the internal cavity wall in the sustainable alternative is a timber frame construction instead of sand-lime bricks. The use of concrete also has been reduced, most importantly by using prefabricated, hollow-core slabs for the floors in between stories and the roof, instead of ribbed concrete which also requires a concrete pressure layer. For other materials, alternatives with lower shadow costs have been selected for the sustainable building. For instance, porous brick replaces the regular brick masonry, more sustainable types of floor cover are used, and the roof cover only consists of PVC instead of bitumen and gravel.

The main scenarios do not include PV. Because of different roof surfaces, reduced electricity use, and the increase of material shadow costs, the impacts of other materials and energy specifications would have been concealed by including solar panels. In the sensitivity analysis, the scenarios are compared with and without PV, for which 80% of roof surface coverage has been assumed to account for sufficient distance between panels and the edges of the roof. The solar panels have a peak Watt power of 200 Wp/m^2 (RVO, 2016) and are made from monocrystalline silicon, which is the most efficient type but also the most expensive and unsustainable (Planas, 2018).

A summary of important materials and amounts can be seen in table 11, for the complete list of materials and amounts see appendix C.

Table 11: Materials and specifications of *Woongebouw M*.

	Scenario	2.1 Conventional	2.2 Sustainable
Components	**Amount**		
Façade: external cavity wall	1269,38 m²	Brick masonry	Porous brick
Façade: internal cavity wall	1269 m²	Sand-lime brick elements	Timber frame construction
Façade: load-bearing walls	1229 m²	Sand-lime brick masonry	Sand-lime brick masonry
Insulation façade	1249 m²	Rock wool (Rc = 4,7)	Glass wool (Rc = 4,7)
Roof	638 m²	Wide slab floor, reinforced concrete C20/25	Wide slab floor, reinforced concrete C20/25
Insulation roof	638 m²	EPS (Rc = 6,3)	Wood fiber (Rc = 6,3)
Flat roof cover layers	638 m²	Bitumen (cover), gravel (ballast), polyethene (water seal)	PVC (cover), polyethene (water seal)
Ground floor	558 m²	Ribbed floor, prefab concrete	Ribbed floor, prefab concrete
Insulation ground floor	(included in ribbed floor)	EPS (Rc = 4,0)	EPS (Rc = 4,0)
Floor story	3190 m²	Wide slab floor, reinforced concrete C20/25 + pressure layer	Hollow-core slab, prefab concrete
Internal load-bearing walls	1405 m²	Sand-lime brick masonry	Sand-lime brick masonry
Shared doors	3	Wood with glass opening 0,85 m²	Wood with glass opening 0,85 m²
Front doors and shared doors	49	Painted wood (U = 1,4)	Painted wood (U = 1,4)
Internal doors in apartments	231	Honeycomb core doors, painted	Wooden doors, sustainably sourced honeycomb core
Window frames	567 m²	European coniferous wood; sustainable, painted	European coniferous wood; sustainable, painted
Glazing	383 m²	Triple glazing (U = 1,0; g-value = 0,6)	Triple glazing (U = 1,0; g-value = 0,6)
Sunscreens	559 m²	Solidscreen, white	Solidscreen, white
Installations			
Ventilation	2870 m²gbo	D: Balanced, heat recovery	D: Balanced, heat recovery
Heating	20	Collective heat pump ground/water (entered as 20 individual hybrid heat pumps)	Collective heat pump ground/water (entered as 20 individual hybrid heat pumps)
Domestic Hot Water	33	Electric boiler	Electric boiler

7. Results

In this section, the shadow costs are presented for the base scenarios. First, the results are shown for energy and material use separately and afterwards the two are combined. Moreover, the shadow costs for different life spans are illustrated to visualize tipping points and subsequently the shadow costs are analyzed per environmental impact category. Afterwards, in the sensitivity analysis the impacts of energy and material inputs, unsustainable electricity, heating technology, solar panels, the energy performance gap, and apartment size per resident are tested.

7.1. Energy use

7.1.1. Shadow costs of energy carriers in the Netherlands

Table 12 shows the shadow costs of the different energy carriers per kWh and per impact category. Because of the wide variety of sources for district heating, by default, the impact is estimated as 150% of the shadow costs of natural gas (W/E Adviseurs, 2016). In section 5.4.2, the method of calculating an alternative impact factor with reduced environmental impacts due to more renewable sources is explained. The improved district heating shadow costs thus represent 70% of the shadow costs of natural gas.

The impact of electricity per kWh is almost 3,4 times higher than natural gas, due to the shadow costs of electricity being based on the electricity mix from 2008 (Alsema et al, 2016a). The Dutch electricity production mix in 2008 only consisted of 8,8% renewable sources and 85% fossil fuels (CBS, 2022). Furthermore, energy losses during electricity do not occur for natural gas as it is incinerated onsite. Because of the recent increase in the use of renewable energy sources, the overall shadow costs with reduced electricity impacts have been calculated as well, following the method described in section 5.4.1. Since these reduced impacts vary per life building life span, they are not represented in table 12.

The shadow costs from global warming and afterwards human toxicity have the largest share of the total shadow costs for all energy carriers. For natural gas and district heating, marine water ecotoxicity is the next impact category with the highest shadow costs, while the shares of acidification and eutrophication are larger for electricity use. Finally, electricity relatively causes much more shadow costs in the category of terrestrial ecotoxicity compared to the other energy carriers.

Table 12: Shadow costs S€ of different energy carriers per kWh consumption, per environmental impact category and in total (based on Alsema et al., 2016a). Color scheme of relative values per energy carrier, green = low, red = high.

	Natural gas	District heating	Electricity	District heating (reduced impact)
Based on EcoInvent data from	2004	2004	2008	2004
Unit	S€/kWh	S€/kWh	S€/kWh	S€/kWh
Abiotic depletion, non-fuel	1,24E-09	1,86E-09	1,49E-07	5,78E-10
abiotic depletion, fuel	3,25E-04	4,87E-04	8,09E-04	1,52E-04
Global warming	1,13E-02	1,70E-02	3,42E-02	5,28E-03
Ozone layer depletion	3,71E-07	5,56E-07	6,78E-07	1,73E-07
Photochemical oxidation	4,28E-05	6,43E-05	1,52E-04	2,00E-05
Acidification	2,12E-04	3,19E-04	4,26E-03	9,91E-05
Eutrophication	1,15E-04	1,72E-04	2,53E-03	5,36E-05
Human toxicity	3,78E-03	5,67E-03	1,45E-02	1,76E-03
Ecotoxicity, fresh water	1,99E-06	2,99E-06	6,25E-05	9,31E-07
Ecotoxicity, marine water	2,34E-03	3,52E-03	3,84E-03	1,09E-03
Ecotoxicity, terrestrial	1,75E-06	2,62E-06	5,60E-04	8,15E-07
Total shadow costs	0,018	0,027	0,061	0,008

7.1.2. Energy consumption and shadow costs of scenarios

In table 13, the energy use results from EPA-W are listed as well as the energy shadow costs per scenario. In this case, the energy use results have been divided by the usable floor area as this is required for energy performance calculations (NEN, 2022). However, the shadow costs are based on the gross surface area according to the MPG and MPG+ method (W/E Adviseurs, 2016; Stichting Bouwkwaliteit, 2017). It is shown that the energy demand (EP1) in the business-as-usual scenario is about two to three times higher than all other scenarios, and that the energy use decreases among the scenarios. For primary fossil energy use, the differences between the scenarios are even more extreme, with EP2 value ranging from 313 kWh/m2/year in scenario 0 to 60 kWh/m2/year in the new buildings. A similar pattern is reflected in the energy labels and shadow costs, for which it has been assumed that electricity becomes more sustainable in the future according to the calculations in section 5.4.1.

Although the results in table 13 are based on the main scenarios without solar panels, the renewable energy percentage increases in the scenarios with a heat pump (scenarios 1.2b, 1.3, 2.1, and 2.2). This percentage represents the energy retrieved from the air or ground through, which is lower with a hybrid heat pump (1.2b). Furthermore, the temperature exceedance in July (TO July max) increases with the renovation scenarios, except for the extensive renovation which incorporated sunscreens. With improved insulation, more heat from sunlight is trapped in the building. Important to note here is that the TO July max value is an average for the building. Measured per apartment, the values will be different based on the location within the building and the direction towards the sun.

The shadow costs in the last row are calculated with for a life span of 75 years and with the assumption of reducing electricity impacts according to the calculations in section 5.4.1. The shadow costs decrease incrementally among the scenarios, similar to the EP2 values. For the two variants of the minimal renovation scenario with district heating, the use of renewable sources decreases the shadow costs from 3,31 to 1,96 €/m²/year. The shadow costs of an extensive renovation with a collective heat pump (scenario 1.3; 0,79 €/m²/year) are much lower than the standard renovation alternatives. Furthermore, even though the insulation levels and ventilation system in scenario 1.3 are comparable to new building scenarios 2.1 and 2.2, the new buildings use a ground-sourced heat pump with a higher efficiency, and they relatively have less surfaces through which energy is lost compared to the floor area, as reflected in the compactness value. The compactness represents the ratio of energy loss surfaces and usable floor area. Still, the energy labels are the same because of the small differences.

Finally, the target values for new and existing buildings are listed as a reference in the column on the right in table 13. Because of a different compactness value, two different target values are mentioned for heating demand. Because the scenarios do not have solar panels, none of them reaches the targets, but with a full roof of solar panels the extensively renovated porch flats and new buildings would reach all the target values.

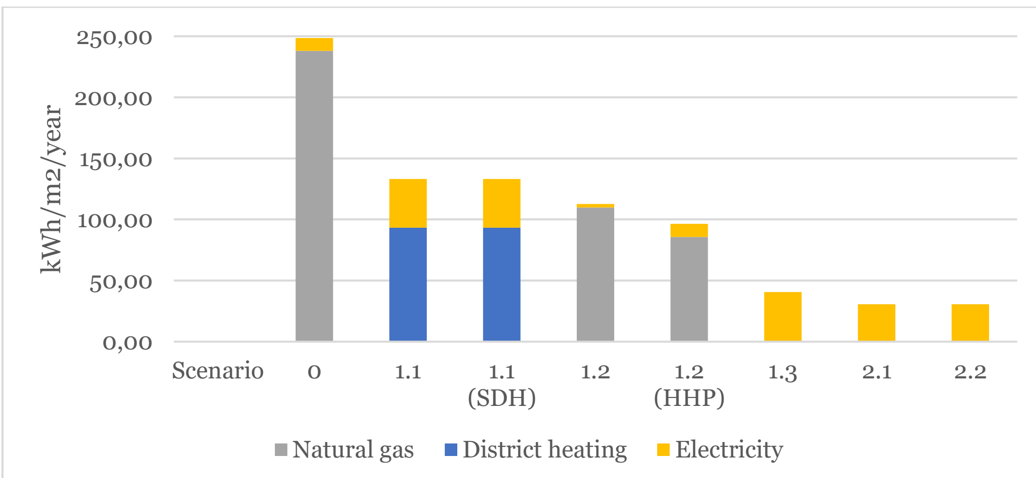
Table 13: EPA-W results per scenario and shadow costs, without PV

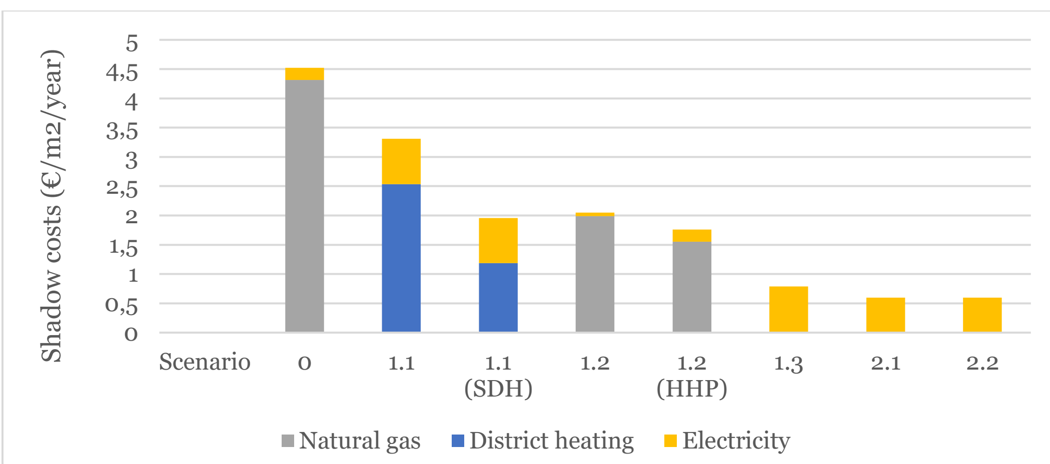
Results	Scenario Unit	0: Current situation	1.1: Minimal Renovation (1.1a & b)	1.2a: Standard renovation	1.2b: Standard Renovation hybrid HP)	1.3: Extensive Renovation	2 New building (2.1 & 2.2)	Target values
Compactness	A_{ls}/A_g	1,52	1,52	1,52	1,52	1,52	1,06	
EP 1 (Energy demand)	kWh/m²/year (usable surface area)	165	80	74	74	64	50	< 65 (nZEB)
EP 2 (primary fossil energy consumption)	kWh/m²/year (usable surface area)	313	175	141	126	73	60	< 50 (nZEB)
EP 3 (Renewable energy share)	%	0	0	0	15	31	32	> 40 (nZEB)
Energy label	-	E	B	A	A	A++	A++	
TO July max	-	1,29	2,48	2,59	2,59	1,72	*N/A (1,30 without cooling)*	< 1,20 (nZEB)
Heating demand	kWh/m²/year (usable surface area)	161	74	67	67	42	28	< 68 (ren.) / < 65 (new)
Shadow costs from energy	euro/m²/year (gross surface area)	**4,52**	**a: 3,31** **b: 1,96**	**2,05**	**1,76**	**0,79**	**0,60**	

7.1.3. Contribution analysis energy use

Figure 6 shows the energy consumption per carrier and the total energy consumption per square meter of gross building floor area. The minimal renovation scenarios use a lot of electricity, due to the operation of the district heating system and the ventilation system with alternating current. The extensive renovation and new building scenarios also have a high electricity use as this source is also used for heating. In the case of the heat pumps, the electricity use stands for the actual consumption of grid electricity. Heat pumps deliver more heat than the amount of electricity they use, so the energy demand of the buildings is higher than this. The energy use for heating as well as the total energy use decreases with increasing insulation levels in the renovation scenarios. The total energy use is higher in the new buildings but divided over the number of square meters this is not the case anymore. The two district heating scenarios have the same energy consumption, as the improvements are calculated by decreasing the impact factors of the energy carriers.

The energy consumption values are multiplied with the respective impact factors to calculate the shadow costs, shown in figure 7. In this figure the electricity shadow costs are reduced, based on a life span of 75 years. For the shadow costs without reduced electricity impacts, see appendix B.1. When the shadow costs of district heating are reduced in the minimal renovation scenario with renewable energy, the required electricity used to operate the district heating system leads to shadow costs similar to the standard renovation scenarios, despite the improved energy efficiency in the standard renovations.





Figures 6 and 7: Energy use and shadow costs from different energy carriers per scenario per square meter per year, with reduced electricity impacts for a life span of 75 years. 0: Business as Usual; 1.1: Minimal Renovation; 1.1 (SDH): Minimal Renovation with reduced DH impact; 1.2: Standard Renovation (condensing boiler); 1.2 Standard Renovation (HHP): hybrid heat pump; 1.3: Extensive Renovation; 2.1: New Conventional; 2.2: New Sustainable

Figure 8 shows the energy shadow costs distinguished by application. Heating is responsible for most of the energy use in the current scenario, but this drastically decreases with insulation and a new condensing boiler. Furthermore, with a collective heat pump and a lot of insulation, the energy use for heating becomes very small. Next, domestic hot water is responsible for the largest share of energy use for each scenario except for those with a natural gas boiler. Despite the use of more efficient technology, it makes sense that the use of DHW does not decrease as much as heating, because the consumer demand is not reduced by energy efficiency improvements such as insulation. Also, only in combination with district heating the auxiliary electricity consumption is high.

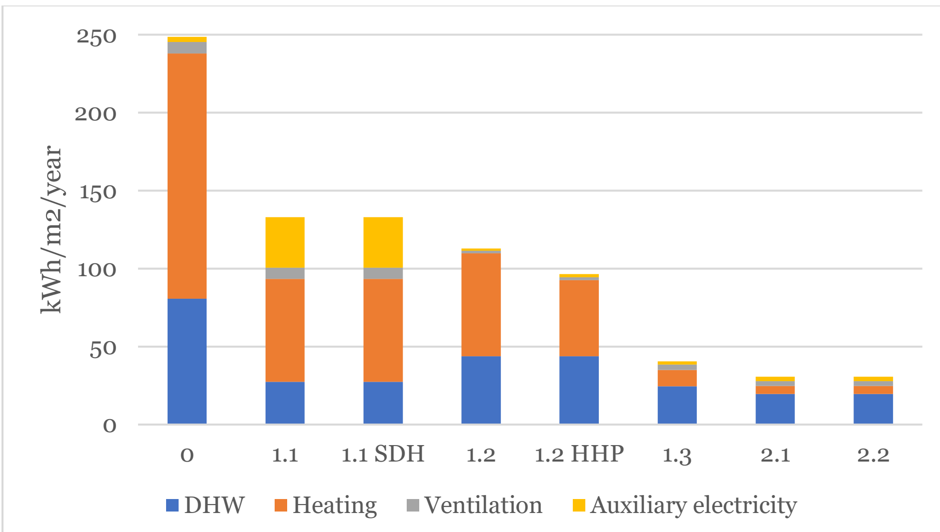


Figure 8: Energy demand per application in kWh per square meter per year. 0: BAU; 1.1: Minimal Renovation; 1.1 SDH: Minimal renovation with reduced district heating impact; 1.2: Standard renovation (condensing boiler); 1.2 HHP: Standard renovation (hybrid heat pump); 1.3: Extensive Renovation; 2.1 New Conventional; 2.2 New Sustainable

7.2. Material use

7.2.1. Shadow costs material use

Figure 9 shows the material impact per m² per year of the different scenarios. In the current situation, it is assumed that no materials are replaced, so the impact is 0 euros. The impact of the building increases with a shorter life span because some of the materials are used for less years while the initial impacts remain the same. Almost all materials used during the renovations have life spans shorter than 75 or even 40 years (Stichting NMD, 2022a). Therefore, with the use of the fraction method (see section 5.3), there is no difference in the shadow costs with life spans of 75 and 125 years for renovations.

The impact of the new building scenarios is much higher than the renovations in almost all cases, only after 125 years the sustainable building's impact is lower than the impact of the extensive renovation with a life span of 20 years. Concrete for instance has a large share of the impact and since this has a service life of 1000 years (Stichting NMD, 2022a), the impact is significantly decreases when the building life span is increased. Lastly, both new building scenarios have shadow costs below 0,50 €/m2/year for a life span of 75 years. This life span is the standard assumption for new buildings, and 0,50 is the expected maximum value for the MPG in 2030.

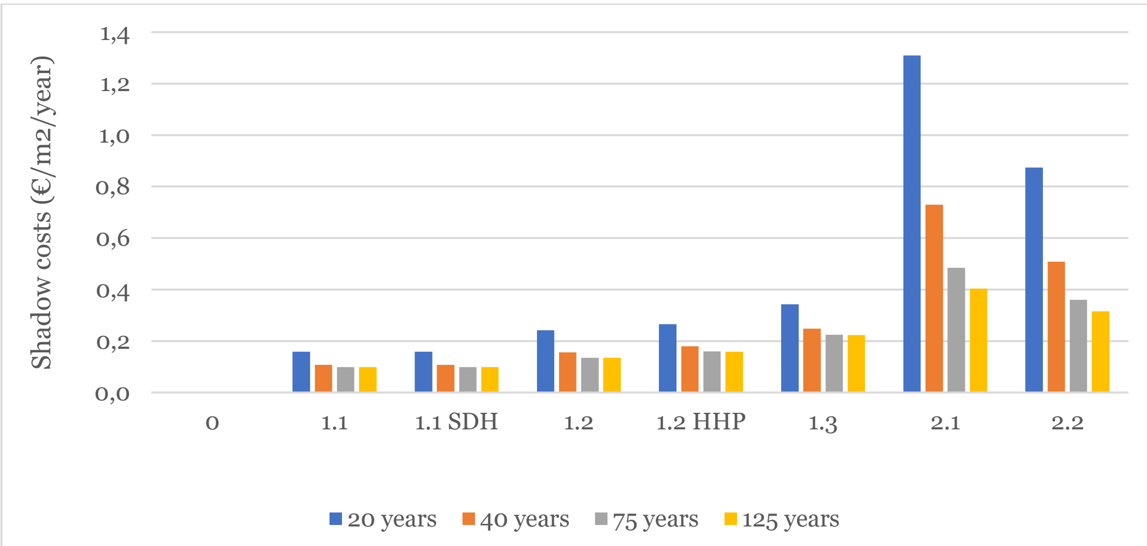


Figure 9: Shadow costs of the materials per scenario per life span. 0: BAU; 1.1: Minimal Renovation; 1.1 SDH: Minimal renovation with reduced DH impact: 70% of natural gas impact per MJ); 1.2: Standard renovation (condensing boiler); 1.2 HHP: Standard Renovation (hybrid heat pump); 1.3: Extensive Renovation; 2.1 New Conventional; 2.2 New Sustainable

7.2.2. Contribution analysis material use

Figure 10 indicates the shadow costs of the building components in all scenarios. A life span of 75 years has been assumed in this case. A table with all individual materials that are responsible for more than 5% of the material impacts per scenario can be found in appendix B.2. In the scenarios, between 3,4 and 5,1 cents per square meter per year are caused by glazing, which is a large share of the impact of the façades. The components in the new buildings have similar or higher shadow costs than all renovation scenarios. The slightly higher impacts of installations in the renovation scenarios are related to the larger floor area in new buildings, which leads to less impacts per square meter. In the minimal renovation scenario, some installations such as ventilation are not replaced, and therefore the shadow costs in this category are lower. In all scenarios, installations for heating also cause a high share of the impact. The relative impact of individual components is much lower in scenarios 2.1 and 2.2, because of a much higher amount of materials used in total. Finally, solar panels are not included in these MPG scores. See appendix B.2 for the shadow costs of PV for porch flats and *Woongebouw M*.

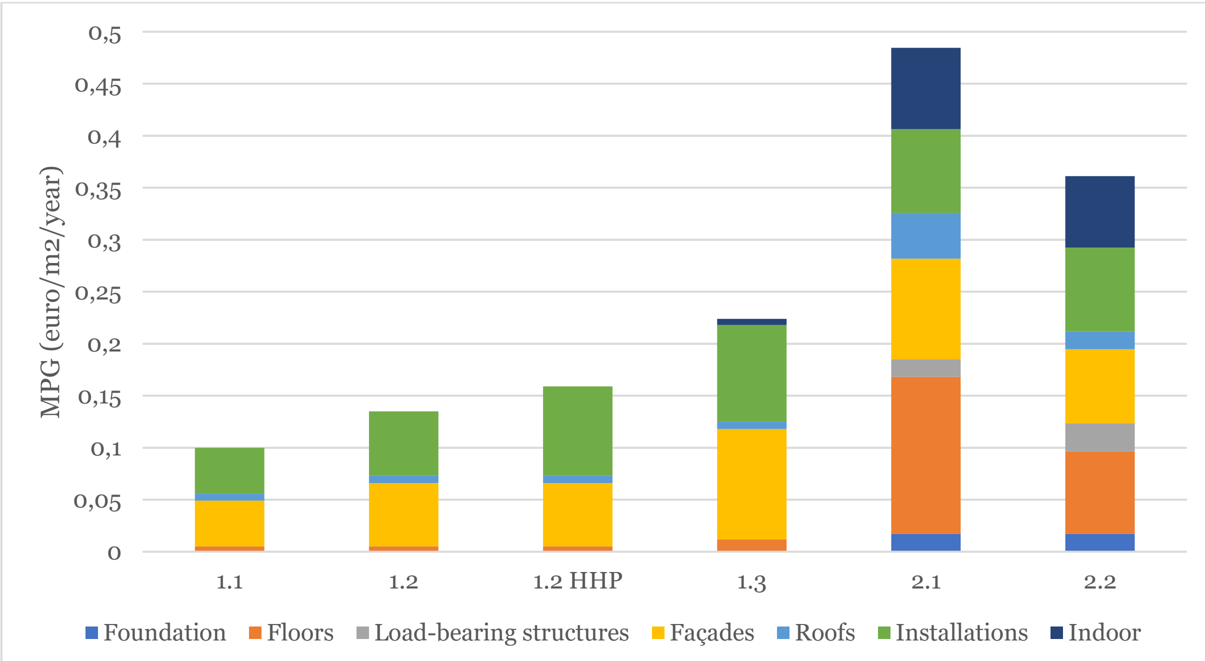


Figure 10: Contribution of building components to shadow costs (life span 75 years). Foundation: soil backfills, indoor: facilities in kitchen and bathrooms (e.g., cabinets, sinks, etc.). 1.1: Minimal Renovation; 1.2: Standard renovation (condensing boiler); 1.2 HHP: Standard Renovation (hybrid heat pump); 1.3: Extensive Renovation; 2.1 New Conventional; 2.2 New Sustainable

In the MPG scores, maintenance is included because materials are replaced after their expected service life. Since new buildings include all materials, maintenance is therefore included for more components than in the existing buildings, while it could be expected that older buildings actually require more maintenance. To assess the potential impact of this omission, the MPG scores in the conventional new building have been summed up of the materials that are not made from concrete and also not already replaced during renovation: finish layers and tiles on walls and floors, plinths, bathroom and kitchen elements, internal doors, railings and stairs and balconies, rainwater drainage, sewerage pipelines, and windowsills. These materials only form about 14% of the MPG or less than 7 cents per square meter per year in this scenario. This percentage would probably be around the maximum possible increase in shadow costs of the porch flats through maintenance. Including more maintenance would thus relatively increase the shadow costs of renovations, but not by a large amount.

7.3. MPG⁺: Materials and energy combined

7.3.1. Shadow costs per life span

Figure 11 shows the comparison of shadow costs of the scenarios per life span, separated into energy and materials. In the figure, it is assumed that electricity becomes more sustainable. The share of impacts related to energy use range between 41,8% and 100%. Except for the conventional new building scenario with a life span of 20 years, more than half of the shadow costs are caused by energy use. The BAU and minimal renovation with conventional district heating scenarios always have higher shadow costs, but the order between the remaining scenarios changes with increasing life spans. When life spans increase, the material impacts of especially new buildings decrease as well as the energy impact of scenarios which use a lot of electricity. Therefore, the conventional new building scenario only has higher shadow costs than both standard renovation scenarios with a life span of 20 years. Scenario 2.2 always scores lower than scenario 2.1 because of an inherently lower material impact while having the same energy specifications. With a short life span, these scenarios differ by 44 cents per m² per year, but after 125 years they are only 8 cents apart. The scenario with the lowest shadow costs is the extensive renovation scenario until a life span between 40 and 75 years, after which the sustainable new building scenario has lower shadow costs. The shadow costs of the conventional new building scenario are quite similar to the extensive renovation and sustainable new building from a life span of 75 years onwards.

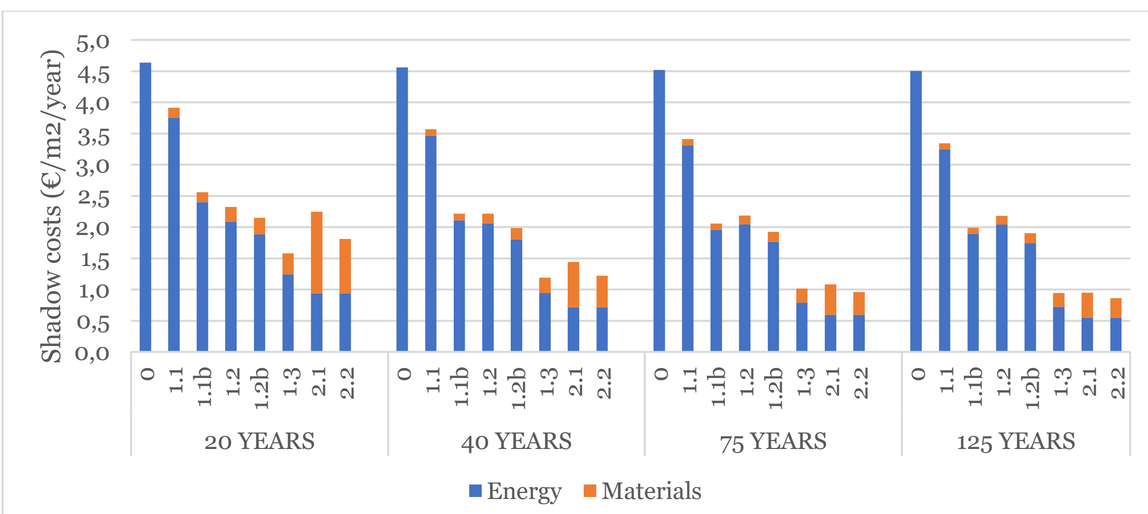


Figure 11: Shadow costs from energy and materials combined for different life spans, with reduced environmental impacts from electricity. 0: BAU; 1.1: Minimal Renovation; 1.1b: Minimal Renovation (Reduced DH impact); 1.2: Standard renovation (condensing boiler); 1.2b: Standard Renovation (hybrid heat pump); 1.3: Extensive Renovation; 2.1: Conventional New; 2.2: Sustainable New

In figure 12, the total shadow costs per life span with reducing electricity impacts have been modelled to visualize tipping points in time between different scenarios. The BAU and district heating scenario with conventional sources have been left out because the shadow costs are always higher and don't have any tipping points with other scenarios, as shown in figure 11. Figure 12 shows that the life span of a building before demolition can make a large difference in determining which scenario has the lowest impact. Sustainable district heating initially has the highest shadow costs of the scenarios in the figure, but after 40 years it becomes more sustainable than a standard renovation with condensing boiler. Next, the conventional new building has the third highest shadow costs of the remaining scenarios, but after a life span exceeding 20 years, standard insulation with a hybrid heat pump has higher shadow costs than the conventional new building. With a life span between 50 and 55 years, the shadow costs of extensive renovations and sustainable new buildings are the same. Furthermore, the difference between extensive renovations and new buildings differs by only 1 cent per m² per year with a life span of 125 years, while this difference is 66 cents with a life span of 20 years. The tipping points mostly relate to the reducing impact of electricity, which does not affect scenarios 1.2 and 1.2b as much since they use mostly natural gas. In addition, the impact of the new building scenarios decreases further due to the declining impact of materials with a long life span.

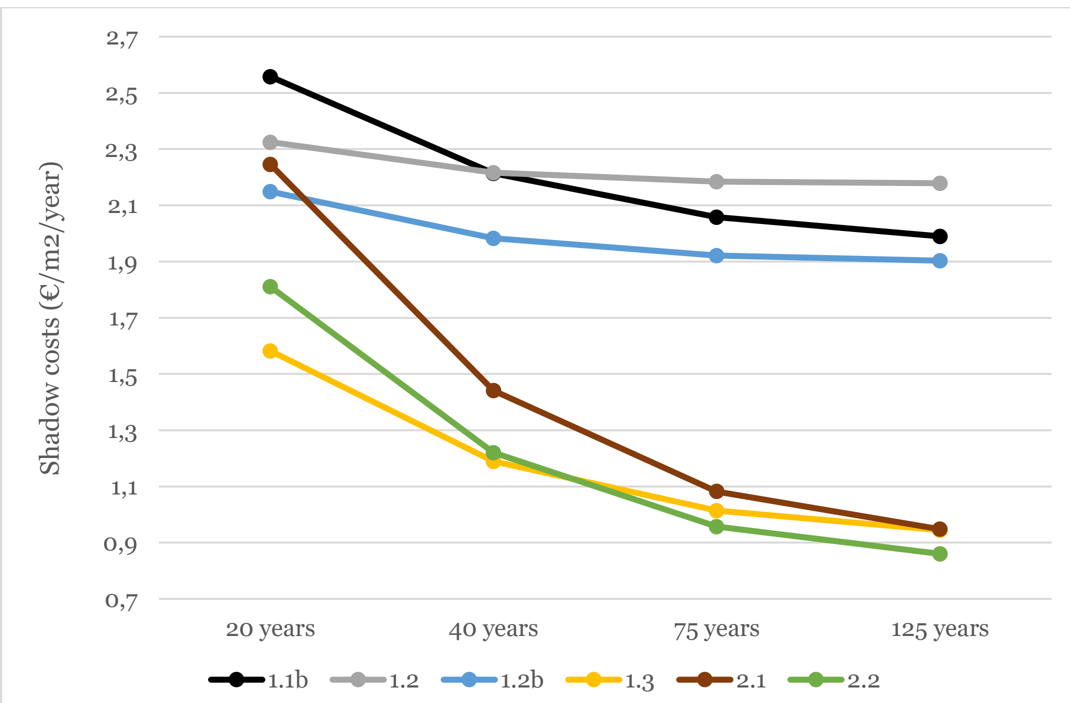


Figure 12: Shadow costs for scenarios (except 0 and 1.1) with different life spans, with reduced electricity impact. 1.1b Minimal renovation with reduced DH impact 1.2: Standard renovation (condensing boiler); 1.2b: Standard Renovation (hybrid heat pump); 1.3: Extensive Renovation; 2.1 New Conventional; 2.2 New Sustainable

7.3.2. Shadow costs per environmental impact category

Figure 13 shows the total shadow costs of the scenarios per impact category, with an assumed life span of 75 years. It is visible that when the impacts are weighted through their shadow costs, the distribution of shadow costs per scenario is quite similar among all scenarios, except for the impact of global warming varying a lot and causing most of the shadow costs. This reduction is caused by the decreasing emissions of greenhouse gases by alternative energy sources, as also indicated in the EP2 results in table 13. The decreasing use of fossil fuels, responsible for many greenhouse gas emissions, is also reflected in the diminishing shadow costs of abiotic depletion of fuels. Furthermore, human toxicity and ecotoxicity (marine water) cause most of the shadow costs, while the remaining impact categories are relatively small. The decrease in both human toxicity and marine ecotoxicity is related to the overall reduction of energy as well as the shift towards electricity, since these two impact categories cause a relatively large share of the shadow costs for especially natural gas and district heating (see table 12). The total amounts of environmental impacts and the impacts normalized to the global impacts in 1995 are listed in appendix B.3.

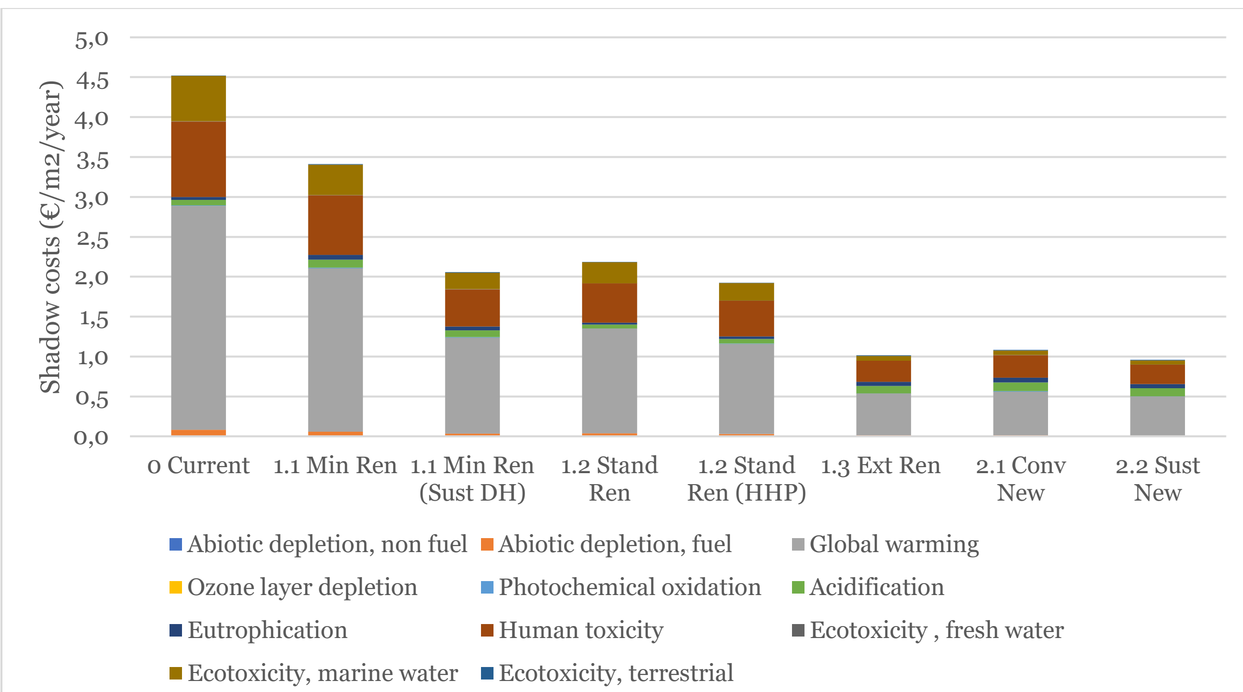


Figure 13: Shadow costs per impact category per scenario, with reduced electricity impacts, life span 75 years.

7.4. Sensitivity analysis

In this section, the sensitivity of the results has been analyzed for assumptions about energy and material use, different electricity impact reduction pathways, the choice of heating technology, the installation of solar panels, and the apartment size per resident. In all figures, the results are presented for a life span of 75 years and with reducing shadow costs of electricity, except for the sections in which the impacts of these assumptions are tested. At the end of this section, the sensitivity of the scenarios to all assessed uncertainties are summarized.

7.4.1. Energy and material use

Figure 14 shows the range of shadow cost results with a potential increase or decrease in the shadow costs. The black mark indicates the original total shadow costs value calculated with reduced electricity impacts. The possible variation assumed for this range is a 20% increase and decrease, which has been selected arbitrarily in consultancy with experts in the field. This range represents a hypothetical uncertainty of in total 40% in the amount of energy and material use. In addition, the combined ranges can also be interpreted as possible deviations in how accurately the impact factors that lead to the shadow costs represent the costs of the emissions to society. Most of the sensitivity range is related to the energy use, especially for the renovations. The extensive renovation and new building scenarios have large parts of the sensitivity ranges overlapping, related to both energy and materials. Furthermore, with a 20-years life span the shadow costs of the new buildings overlap with scenarios 1.1b through 1.2b, while the extensive renovation scenario only overlaps with the new buildings, as can be seen in appendix B.4.

The sensitivity ranges indicate that the best scenario between extensive renovations and new buildings cannot be conclusively determined based on the results of this study. Moreover, the potential shadow cost increase of around 15% from maintenance falls within the light orange areas of the renovation scenarios, so it is not expected that including more maintenance would strongly affect any conclusions. However, the difference in shadow costs of the existing buildings compared to the new buildings may be smaller than calculated in this study, due to the probable underestimation and overestimation, respectively, of maintenance. On the other hand, the renovation scenarios do not include an alternative with sustainable materials. The materials in the renovation scenarios are based on the conventional new building scenario for consistency, but it would therefore be possible to select more sustainable materials to slightly decrease the shadow costs of the renovation scenarios. Finally, an alternative for new buildings which is even more ambitious than the sustainable new building scenario could lead to shadow costs on the lower end of the material sensitivity range for scenario 2.2 in figure 14.

Many of the scenarios that overlap within this sensitivity range use similar energy sources and materials, such as the two variants of the standard renovation and both new building scenarios. In the relative scores of these scenarios, it is unlikely that assumptions and uncertainties would affect the shadow costs very differently. Different shadow costs of energy carriers, however, could make a difference for the comparison of the BAU scenario and conventional district heating. Moreover, the impacts of renewable district heating are quite uncertain, so in reality the shadow costs might not be as similar to the standard renovations as modelled. Finally, there is a different ratio of material and energy shadow costs in the extensive renovation and the new building scenarios. With more sustainable materials in the extensive renovation scenario, the shadow costs of this scenario can decrease compared to the new buildings, but this could be compensated by increased maintenance impacts.

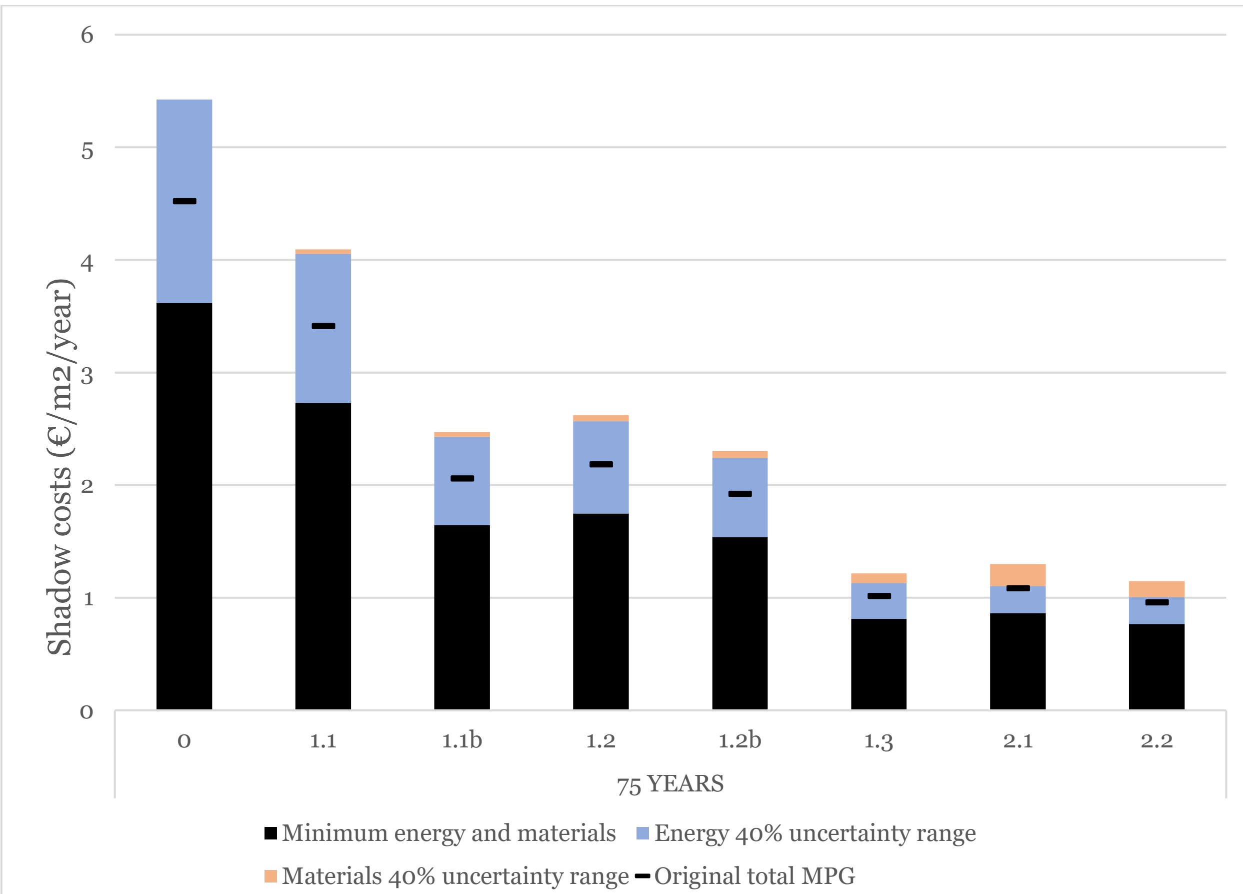


Figure 14: Sensitivity of shadow costs with range of 20% above and below original shadow cost results for both energy and materials, with reduced electricity use, for life span of 75 years. 0: BAU; 1.1: Minimal renovation (b: with renewable DH sources), 1.2 Standard renovation (b: with a hybrid heat pump), 1.3 Extensive renovation, 2.1 New building with conventional materials, 2.2 New building with sustainable materials

7.4.2. Electricity impact reduction

The shadow costs without the assumption of decreasing environmental impacts of electricity are presented in figure 15, for a life span of 75 years. In this case, the shadow costs based on EcoInvent data from 2008 are constant. The figure shows that when electricity does not become more sustainable than was the case in 2008, the sustainable new building has the lowest shadow costs, followed closely by the standard renovation scenarios and the conventional new building. With shorter life spans, the new buildings perform worse because of higher material shadow costs (see appendix B.5 for the results of all life spans). Scenario 1.3 has more impacts from both energy and materials compared to both variations of the standard renovation, because of the high electricity consumption of the heat pump. Finally, the shadow costs of all scenarios are higher than with improved electricity use.

Based on these results, it would be concluded that natural gas should remain in use, while a more sustainable energy mix of grid electricity leads to the conclusion that heat pumps, especially non-hybrid ones, are the most environmentally friendly. Although more recent data of the shadow costs of electricity are not available, it is certain that the current and future electricity mixes contain a higher share of renewable energy than modelled in this figure (CBS, 2022).

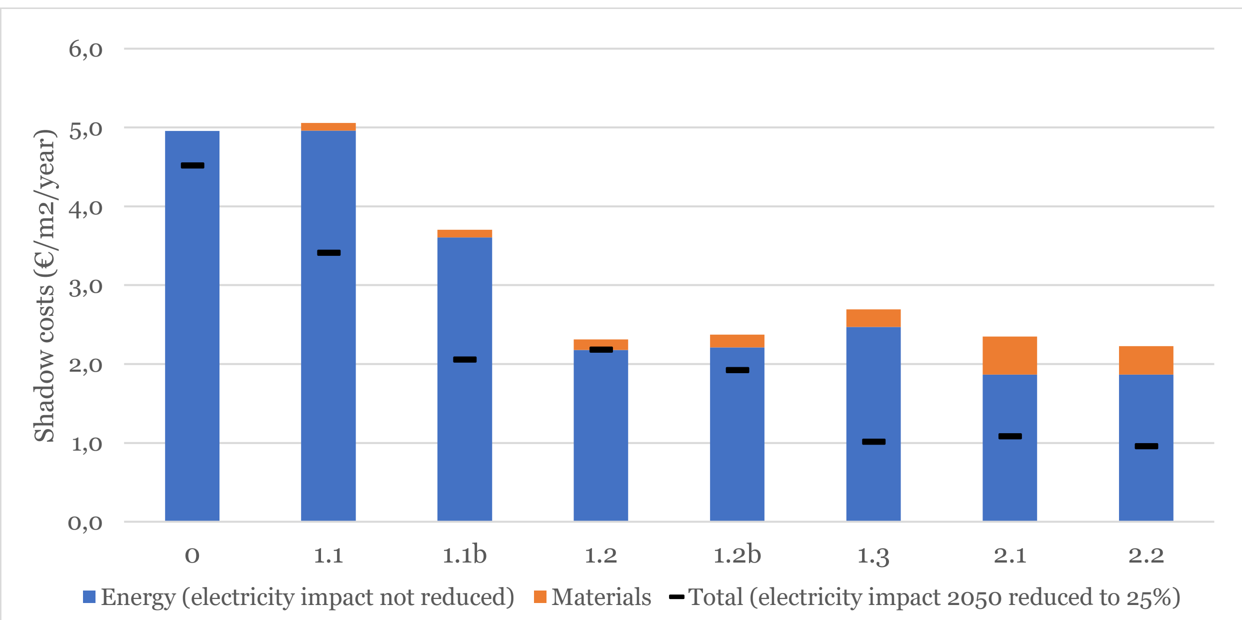


Figure 15: Shadow costs from energy and materials combined for a life span of 75 years without reduced environmental impacts from electricity. 0: BAU; 1.1: Minimal renovation (b: with renewable DH sources), 1.2 Standard renovation (b: with a hybrid heat pump), 1.3 Extensive renovation, 2.1 New building with conventional materials, 2.2 New building with sustainable materials

The shadow costs in figures 16 and 17 are based on two alternative electricity reduction percentages used to calculate the shadow costs of a 75-year life span. In figure 16, the electricity stays constant at approximately the level in 2021, which is estimated to be around 72% of the impacts in 2008. In figure 17, it has been assumed that the impacts of electricity in 2050 are not 25 but 50% of the impacts in 2008. The reason for this could be that the carbon neutral targets are not met, or that a carbon-free electricity mix still causes a lot of environmental impacts in other categories. Considering the gradual reduction of impacts, this leads to an overall 54,4% of the electricity impacts in the original 2008 data as opposed to 32%, as presented in table 6.

Figure 16 shows that in this case the new buildings have the lowest shadow costs, followed closely by the extensive renovation, and that the impacts of the scenarios decrease gradually from the standard renovations through the new buildings. The main difference with figure 15 is that the standard renovation scenarios now have higher shadow costs than the extensive renovation and new buildings. Since the standard renovation scenarios have a low electricity consumption, they barely benefit from the electricity reduction. Lastly, in figure 17 the shadow costs of the extensive renovation and new building scenarios are still similar but together differ by around 0,5 €/m2/year from the standard renovation scenarios and still both new buildings have slightly lower shadow costs than the extensive renovation. Again, the scenarios with a collective heat pump benefit the most from the electricity impact reduction. This indicates that even with a more pessimistic forecast of the electricity mix in 2050, which probably still is a more realistic assumption than a constant electricity mix at the level of 2008, extensive renovations or new buildings still lead to the lowest environmental impacts. Furthermore, the difference between them might be insignificant and depends on detailed assumptions. However, while more recent data are incorporated in the calculation of electricity impacts in figures 16 and 17, as well as the shadow costs included in the main results marked in black, the shadow costs are still derived from the electricity shadow costs in 2008 (see section 5.4.1). This method of estimating and using different data sources increases uncertainties and the likelihood of inaccuracies.

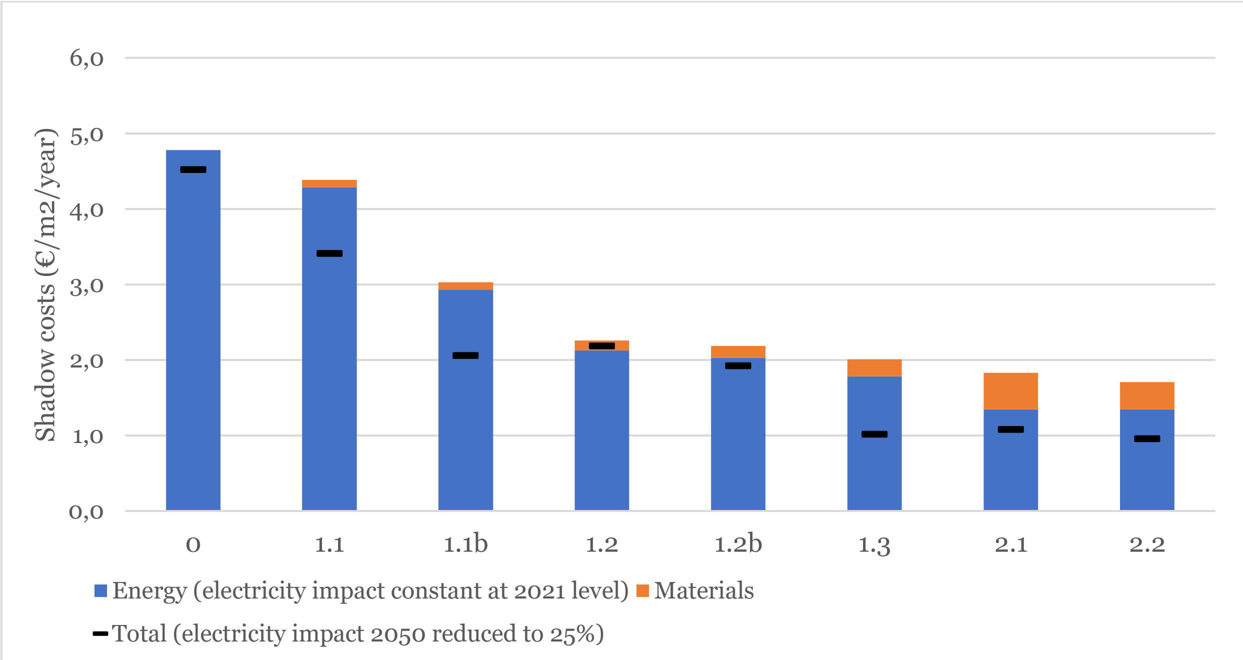


Figure 16: Shadow costs from energy and materials combined for a life span of 75 years, with shadow costs of electricity constant at estimated 2021 level. 0: BAU; 1.1: Minimal renovation (b: with renewable DH sources), 1.2 Standard renovation (b: with a hybrid heat pump), 1.3 Extensive renovation, 2.1 New building with conventional materials, 2.2 New building with sustainable materials

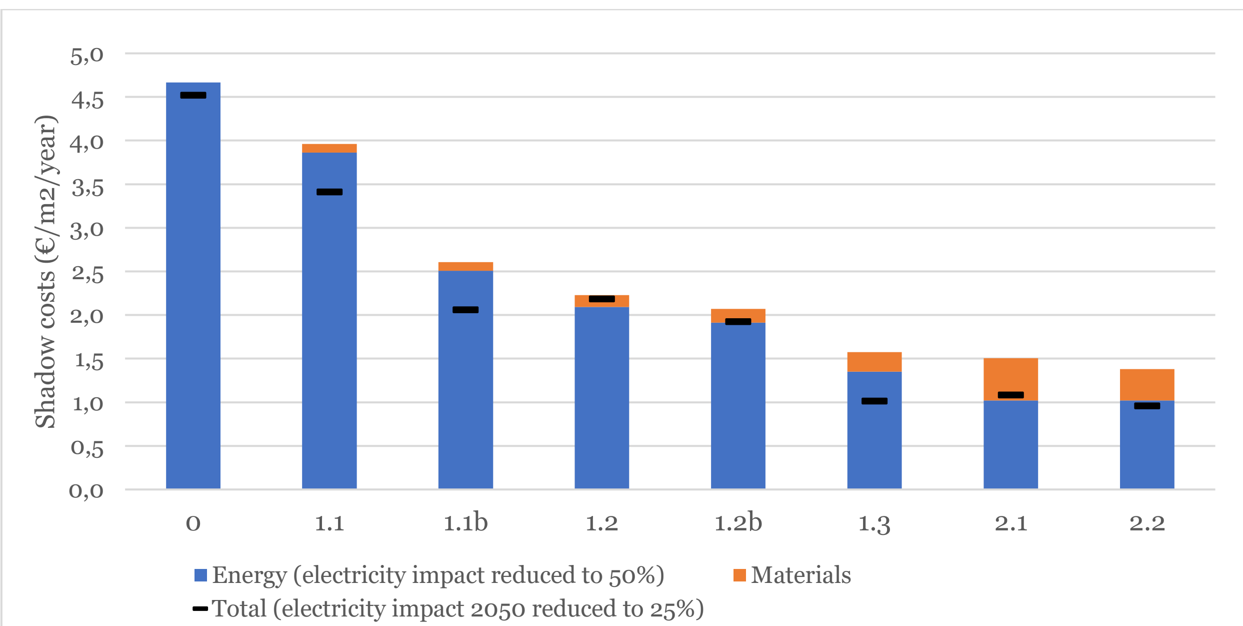


Figure 17: Shadow costs from energy and materials combined for a life span of 75 years. Shadow costs of electricity reduced to 50% of shadow costs by Alsema et al. (2016a) instead of 25%. 0: BAU; 1.1: Minimal renovation (b: with renewable DH sources), 1.2 Standard renovation (b: with a hybrid heat pump), 1.3 Extensive renovation, 2.1 New building with conventional materials, 2.2 New building with sustainable materials

7.4.3. Heating technology

The main scenarios differ in terms of insulation levels and heating technologies, among other things. This makes it difficult to determine what causes the reduction of shadow costs. To assess the shadow costs of heating, the different heating technologies have been applied to the same building in all other aspects, such as insulation level, ventilation types, etc. For this reason, all options have the same energy demand. Scenario 1.3 (Extensive Renovation), which uses a collective air-sourced heat pump, is the base case in this comparison, as well as a life span of 75 years and reducing electricity impacts. Therefore, the collective air heat pump in the figure has the same shadow costs as the extensive renovation scenario in the main results. Moreover, for domestic hot water, electric boilers are used in combination with the other heat pumps but not with the condensing boilers or district heating system.

The results, presented in figure 18, show that natural gas options and the default values for district heating on average double the shadow costs. The hybrid heat pump, which partially uses natural gas as well, also only has high shadow costs. These alternatives all require fossil fuels, and therefore contribute to the environmental impacts in especially the category of climate change. If district heating uses renewable sources, the shadow costs might be comparable to a collective air/water heat pump. Furthermore, the ground-sourced heat pump practically has the same shadow costs, probably because most of the energy is used for water heating with the electric boiler, as shown in figure 8. The larger difference between the shadow costs of the scenarios with a heat pump in section 7.3 is therefore probably caused by the showers with heat recovery, the underfloor heating in the new buildings, and the lower compactness in the new building (see table 13). Moreover, figure 18 indicates that next to the high insulation levels in the scenarios with extensive renovation or the new buildings, heating by a heat pump is the most sustainable energy source. However, a longer life span is especially beneficial for electricity use because of the expected reduction in shadow costs from electricity. Therefore, the difference between the heating technologies would probably be smaller with a shorter life span.

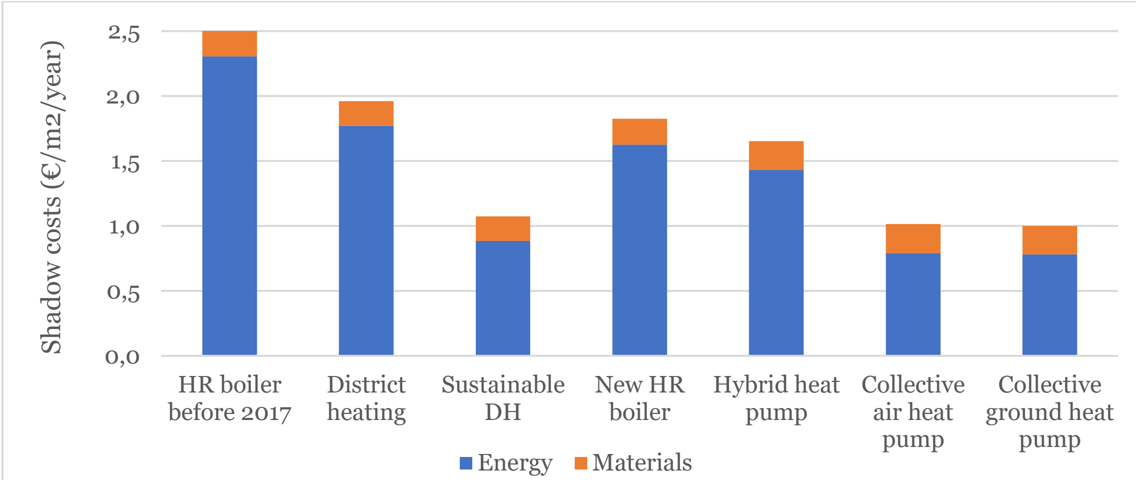


Figure 18: Shadow costs of different heating technologies applied to the building of the extensive renovation scenario. Life span 75 years, reduced electricity impacts.

7.4.4. Solar panels

Figure 19 shows the shadow cost reduction of solar panels on the roofs of the porch flat and *Woongebouw* with a life span of 75 years for scenarios 1.1b through 2.2, with reduced electricity impacts. In both buildings, approximately 80% of the roofs is covered with PV panels, leading to 460 and 510 m² of panels on the porch flat and *Woongebouw*, respectively. Per m² of floor area, the porch flats relatively have more solar panels because they have fewer and smaller apartments. While the material impacts increase a lot, the shadow total costs are reduced by the solar panels.

The generated electricity from the solar panels is subtracted from the electricity use in the buildings, but the material shadow costs increase because of the solar panels. Overall, the shadow costs of renovations decrease by 25 cents and new buildings by 18 cents per m² per year, which causes the extensive renovation scenario to have the lowest shadow costs. This shows that, if replacement buildings contain more floors than existing buildings, the relative potential of solar panels for preventing environmental impacts reduces. On the other hand, if solar panels can also be placed on façades, this difference becomes marginal.

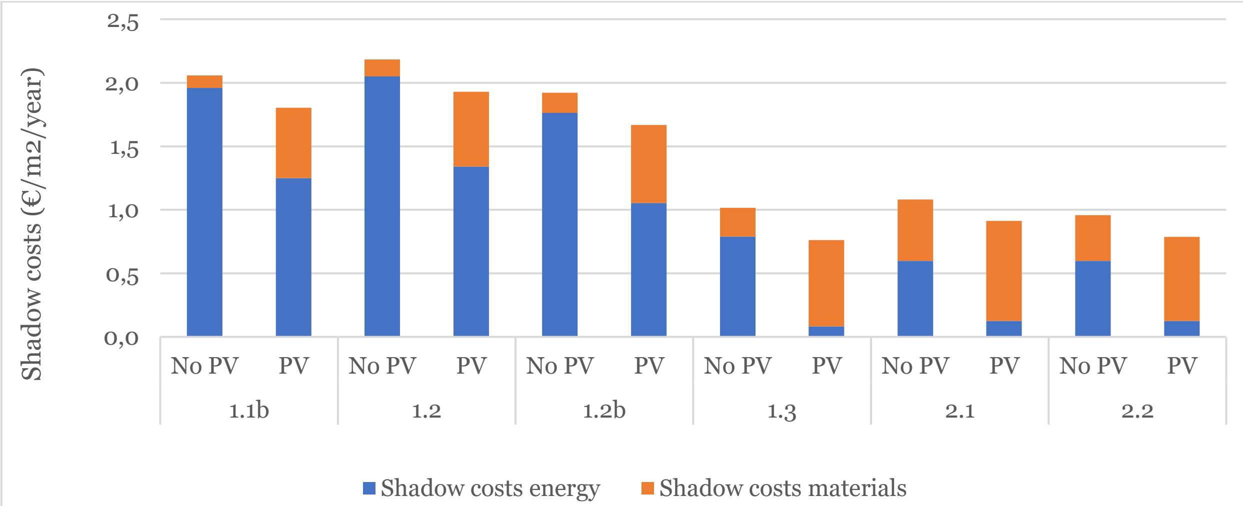


Figure 19: Shadow costs with and with solar panels on 80% of the roofs. Life span of 75 years, reduced electricity impact. 1.1b: Minimal renovation with renewable DH sources, 1.2 Standard renovation (b: with a hybrid heat pump), 1.3 Extensive renovation, 2.1 New building with conventional materials, 2.2 New building with sustainable materials

In figure 19, generated electricity is counted as negative electricity consumption because of the prevented grid power used or excess electricity fed to the grid. However, it is important to keep in mind that compensated environmental impacts do not equate to negative emissions. Furthermore, because of the decreasing shadow costs from electricity over time, the shadow cost compensation also becomes smaller with a longer building life span. However, the impacts of solar panels in the NMD are very high, so this could be an overestimation, especially when PV panel production techniques improve in the future. If the environmental impacts of PV are lower than now modelled, the difference between extensive renovations and new buildings would increase and the reduction in shadow costs from PV panels would be larger for all scenarios.

7.4.5. Energy performance gap

Studies on residential buildings in the Netherlands have found that there is often a gap between actual and theoretical energy performance (Majcen et al., 2013; Van den Brom et al., 2018). The energy use of dwellings with low energy lables (E-G) is often overestimated, and higher labels (B and A) are underestimated. Therefore, renovations from low to high labels cause much smaller energy performance improvements than expected. In the study by Majcen et al. (2013), they calculate that the actual performance of dwellings with an A label is approximately 50% higher than the theoretical performance, and for B labels this difference is about 40%. The actual energy performance of E labels, according to that study, is around 5% lower than the theoretical performance. To estimate the possible impact on the shadow costs the current study, the energy consumption results from EPA-W have been multiplied with these fractions. For A++ labels, a rough estimate of a 60% increase has been assumed. The resulting fractions are:

- 0: Business-as-usual (label E): 0,95
- 1.1a + 1.1b: Minimal renovation (label B): 1,4
- 1.2a + 1.2b: Standard Renovation (label A): 1,5
- 1.3: Extensive Renovation (label A++): 1,6
- 2.1 + 2.2: New building (label A++): 1,6

Figure 20 illustrates that the performance gap correction affects the results. Of the scenarios studied, only the energy use in the BAU situation would be lower than expected. The shadow costs of all other scenarios increase by quite similar amounts. Because of the lower shadow costs of collective heat pumps, the increase of energy consumption does not have a significant impact, so the shadow costs of the extensive renovation and new building scenarios are still the lowest. However, because of relatively more energy impacts in the extensive renovation scenario, its shadow costs are now higher than the conventional new building as well.

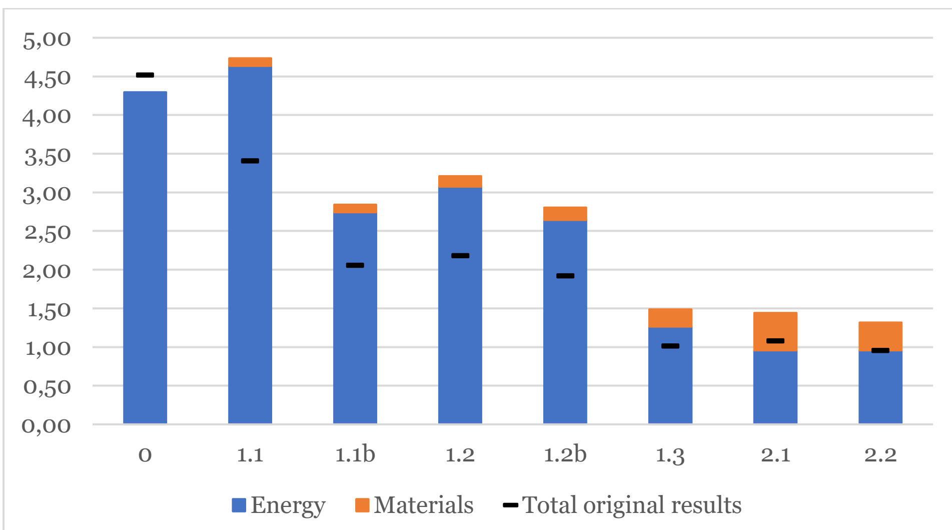


Figure 20: Shadow costs of energy and materials for all scenarios for which the energy use has been corrected with the potential performance gap. Life span 75 years, reduced electricity impacts. 0: BAU; 1.1: Minimal renovation (b: with renewable DH sources), 1.2 Standard renovation (b: with a hybrid heat pump), 1.3 Extensive renovation, 2.1 New building with conventional materials, 2.2 New building with sustainable materials

7.4.6. Apartment size per resident

The shadow costs are calculated per square meter for both existing and new buildings. However, the apartments in new buildings are about 40% larger, while they do have the same number of bedrooms. If the number of residents does not increase, the total amount of environmental impacts per apartment or resident will increase, even if the MPG+ value is the same or even slightly lower. Therefore, the shadow costs of all scenarios and life spans have also been calculated per apartment. While it is not completely fair to compare total energy use of apartments of different sizes, it is important to consider the possible effect of the new building design on shadow costs.

Table 14 shows that, after compensating for differences in apartment size, the extensive renovation scenario always has the lowest shadow cost per apartment for the studied life spans. Table 15 illustrates a similar pattern for buildings with installed solar panels on the roofs. The shadow costs of the sustainable new building are more than 25% higher than the extensive renovation scenario in all cases. Already after around 40 years, both types of new buildings still have lower impacts than the standard renovation scenario (1.2) with a condensing boiler or hybrid heat pump, regardless of solar panels. These results show that probably only extensively renovated buildings are more sustainable if the replacing buildings would contain more area per resident.

Table 14: Shadow cost per apartment for different life spans, reduced electricity, no PV

Scenario		0 BAU	1.1 Min Ren	1.1 Min Ren (SDH)	1.2 Stand Ren	1.2 Stand Ren (HHP)	1.3 Ext Ren	2.1 Conv New	2.2 Sust New
m2 BVO/ apt			82,29	82,29	82,29	82,29	82,29	82,29	116,00
Life span									
20 years	€/apt/year	382	322	210	191	177	130	261	210
40 years	€/apt/year	375	294	182	182	163	98	167	142
75 years	€/apt/year	372	281	169	180	158	83	125	111
125 years	€/apt/year	370	275	164	179	157	78	110	100

Table 15: Shadow cost per apartment for different life spans, reduced electricity, 80% roof coverage with PV

Scenario		0 BAU	1.1 Min Ren	1.1 Min Ren (Sust DH)	1.2 Stand Ren	1.2 Stand Ren (HHP)	1.3 Ext Ren	2.1 Conv New	2.2 Sust New
m2 BVO/ apt		82,29	82,29	82,29	82,29	82,29	82,29	116,00	116,00
Life span									
20 years	€/apt/year	360	296	176	155	140	90	216	166
40 years	€/apt/year	369	282	162	162	141	71	137	111
75 years	€/apt/year	351	260	148	159	137	63	106	91
125 years	€/apt/year	382	279	159	176	152	67	95	85

Summary sensitivity analysis

In summary, most of the assessed assumptions affect the total building shadow costs, but the order between the shadow costs remains similar. Only if the electricity mix in 2008 would remain unchanged until 2150, the standard renovation scenarios have the lowest shadow costs. In all other cases with a life span of 75 years and reduced electricity impacts, extensive renovations or new buildings have the lowest shadow costs. Below follows an overview of the effects that the uncertainties have on the shadow costs (in cents or euros per m^2 per year).

- Sensitivity range of 20%: Shadow costs increase or decrease by 19-90 cents. The biggest impact probably applies to scenarios with different energy carriers. Decreased impacts from using more sustainable materials in renovations but also more impacts from maintenance probably balance each other out.
- Electricity impact reduction: If the impacts of electricity reduce less quickly than expected, the shadow costs of extensive renovations and new buildings increase by about 50 cents. New buildings use less electricity, so those shadow costs are slightly lower than extensive renovations.
- Heating technology: Both types of heat pumps and sustainable district heating have similar shadow costs per kWh. For the energy demand of the extensively renovated porch flat, the energy carriers which use fossil fuels cause an increase of 64 cents (hybrid heat pump) to 1,49 euros per square meter per year (HR boiler from before 2015) compared to a collective heat pump.
- Solar panels: The shadow costs of all scenarios decrease when solar panels are installed, but the shadow costs of renovations reduce by 25 cents instead of 18 due to relatively more surface of solar panels compared to the gross surface area of the buildings.
- Energy performance gap: Only the BAU scenario decreases in shadow costs, the shadow costs of the other scenarios increase in a comparable way because they have higher energy labels. Similar to the effect of the electricity impact reduction, correcting for the energy performance gap makes new buildings slightly more sustainable than the extensive renovation because the latter has a higher energy demand. The shadow costs of these three scenarios increase by about 40 cents after correcting for the energy performance gap, up until an increase of 1,33 €/m^2/year for the minimal renovation scenario (1.1).
- Apartment size per resident: When considering the environmental impacts per apartment as opposed to square meter, extensive renovations are always the scenario with the lowest shadow costs. Afterwards, the sustainable and new building still have lower shadow costs than the other renovation scenarios after a life span of about 40 years.

8. Discussion

8.1. Comparison to existing studies

8.1.1. Similarities with earlier findings

Some of results are in line with previous studies in which renovation and building replacement has been compared for multi-family buildings. Itard and Klunder (2007) state that transformations, which is the renovation scenario resulting in a similar energy demand as new buildings, is better than a new building with conventional materials when a life span of 50 years is assumed. However, transformations entail a change in floor plan, which is not included in the extensive renovation scenario in the current study. In addition, transformed buildings still have the same surface area as existing buildings in the study by Itard and Klunder (2007). These transformations always lead to less environmental impacts than rebuilding. When comparing the shadow costs per apartment in this study, thereby taking away the effect of increasing the apartment size, extensive renovations also always lead to less environmental impacts.

Anink et al. (2010) studied office buildings in the Netherlands and conclude that for office buildings with energy labels D or lower, drastic renovations or rebuilding are the most sustainable option. They assumed a different life span for renovations than for new buildings, namely 40 and 50 years, respectively. They also found that with a 25% shorter life span, rebuilding causes more environmental impacts than renovations. The current study analyzed residential buildings, for which the assumed patterns of energy consumption are different than for offices. Furthermore, it is not assumed by Anink et al. (2010) that electricity will become more sustainable. However, since all scenarios use natural gas heating, this does not influence the results as much as in the current study.

De Oliveira et al. (2021) also found that their extensive renovation scenario including a heat pump led to the least environmental impacts on terraced and detached houses, compared to other retrofit options. However, since the façade insulation for porch flats in this study was limited by thickness of the cavity walls, the extensive renovation scenario of this building type still included the use of natural gas instead of a heat pump. In this case, the shadow costs of the extensive renovation were higher than the less ambitious renovation scenario. In the current study, the sensitivity analysis of the heating technologies also indicates that next to the insulation, the heat pump in the extensive renovation scenario also causes a large decrease in shadow costs compared to natural gas (see figure 18).

8.1.2. Differences with earlier findings

In contrast to the findings of Blom et al. (2010), heat pumps come out in the present study as the most sustainable energy carrier. In the paper by Blom et al. (2010) this is only the case if electricity is also generated by local solar panels. They assumed a heat pump using exhaust air for heating with a COP of 3,2 and an outside air heat pump with a COP of 2,3 for hot water. The authors state that the increase in environmental impacts of using heat pumps instead of alternatives such as natural gas boilers can be caused by the unsustainable sources of electricity at the time and the fact that the relatively new heat pumps had a lot of potential for innovation. It is likely that the heat pumps in the NMD have indeed been innovated since the one studied by Blom et al. (2010). The more sustainable heat pumps and the reduced electricity impacts in this study are probably the reason why heat pumps with an electric boiler for hot water result as the most sustainable heating technology in the current study.

The respective environmental impact values of energy and materials seem to be more similar together in the study by Itard & Klunder (2007). In the results of the current study, energy almost always contributes to most of the environmental impacts, also when considering the individual environmental impact categories. These differences can also probably be attributed to the differences in energy sources between the scenarios in the present study. Furthermore, Meijer and Kara (2012) conclude that after a life span of 30 years, rebuilding is preferred over standard renovations. However, in this case the insulation levels in the existing buildings were significantly lower than expected for new buildings. This is likely the reason why this tipping point in the present study occurs much later, around 50-55 years.

In conclusion, because of different assumptions and more recent data, the results of similar studies performed in the past differ in many ways from the present study.

8.2. Limitations

8.2.1. Generalizability

The assumptions made in this study have been based on the perspective of housing corporations in the Netherlands. This decision led to the selection of post-war porch flats as reference buildings. Furthermore, the aim for maintaining affordability caused the focus on conventional measures, collective solutions, and medium-sized apartments. Because of this, the findings in this study can only be applied to other low-budget projects which compare the renovation of porch flats with buildings such as *Woongebouw M* and which include similar scenarios as used in this study. These scenarios could be more roughly compared to other projects through the energy labels if the buildings or scenarios are not the same. In addition, if porch flats are already renovated to the same level of one of the renovation scenarios, a comparison could still be possible with that scenario, the remaining renovation scenarios, if any, and the new building scenarios. In this case, the impact of materials will likely be lower as for instance more insulation components are already in place.

In the sensitivity analysis, many important assumptions have been tested, such as the amount of energy and material use, the selection of heating technology, the installation of solar panels, and the apartment sizes. Based on these results, it seems that the finding that collective heat pumps are the most sustainable energy carrier and that solar panels on existing buildings reduce environmental impacts can be more widely generalized.

The MPG^+ results of this study cannot be generalized to other countries since all assumptions and data have been based on the Dutch context. The impacts of materials and natural gas vary locally, due to for instance different transportation distances, and the electricity mix used is specific only to the Netherlands. Furthermore, porch flats are a typical building in the Netherlands, but they may not be comparable to buildings in other countries at all. Finally, the scenarios have been developed based on Dutch legislation regarding energy and material performance, so these may not apply to other countries.

The principles of the MPG^+ method, in which the life cycle impacts of energy and materials are summed up to compare renovations to rebuilding, can be generalized. The results in this study show that, especially with short life spans, there is a tradeoff between energy and material use for the overall impact of a building. Most importantly, in the current study rebuilding can cause more environmental impacts than extensive renovations, while the energy use is always lower in the new building scenarios. This conclusion would not have been drawn if energy use was the only factor considered.

8.2.2. Assumptions

Method

In this study, the MPG^+ method has been used, because it connects well with the MPG and nZEB calculations that are required for building permits according to the Building Decree. However, the MPG^+ scores are highly dependent on the environmental database and the impact factors for energy carriers. The environmental impacts of many items in the NMD are not public if the product is producer specific. In that case, only the shadow cost of a product or the emissions of the whole building per impact category can be found out. This is not a problem for calculating the material performance of a building, but from a scientific perspective this lacks transparency.

Databases are generally behind on products that have recently been released, especially when the environmental impact assessment of a product needs to be verified by an external party. Furthermore, the environmental impacts of many materials in the NMD are untested. While the impacts of these products are increased by 30% to prevent underestimating the environmental impacts, the uncertainty of the actual shadow costs of these materials is a serious limitation of the NMD and the MPG^+ method. Moreover, for the MPG, default values for the end-of-life (EOL) phase are considered in the NMD. Reusing materials in the case of building replacement could decrease the environmental impacts of a new building because of reduced raw material use, waste processing, and transportation costs. In a full LCA, the impact of circularity on the environmental impacts could be tested. Finally, the material selection is very dependent on the availability within the NMD.

Keijzer et al. (2021) analyzed what would happen to the environmental impacts of a building if the temporary CO_2 uptake of wood is incorporated in the LCA calculations, which currently is not allowed in the MPG. They found that the global warming impacts of buildings with a wooden foundation reduced drastically or even became negative. Global warming causes a large portion of the shadow costs in all scenarios, as illustrated in section 7.3.2, so if the MPG^+ method would include biogenic CO_2 uptake the shadow costs of the sustainable new building would probably decrease below all other scenarios.

Performing an LCA with the use of a database such as EcoInvent could make the findings in this study more transparent. Also, it is easier to determine how representative and sustainable a product is when it can be compared to a larger selection of alternatives. On the other hand, a full LCA is more time consuming than an MPG calculation.

It is difficult to say how the results would be different if the MPG and NMD had not been used. However, many materials with high environmental impacts, such as glazing and heating technologies, are the same or similar among the scenarios. In addition, the renovation material selection has been informed by the conventional new building as much as possible. The use of more sustainable materials could make a difference in shadow costs, but this will not be possible for all materials and the shadow costs of materials can simply not be zero. Furthermore, in most scenarios in this study, the shadow costs of buildings are caused mostly by energy use. Therefore, it is expected that the findings would be somewhat similar if another method had been used. In any case, the main findings, namely that extensive renovations or new buildings with high energy efficiency and heat pumps lead to the lowest shadow costs, are expected to hold up with other LCA studies. However, this should be validated in a future study.

Units

The results in this study are based on the material and energy use of apartment buildings, for which the shadow costs are divided over the gross floor area. In practice, energy efficiency measures such as the energy label and TOjuly depend a lot on the compactness of an apartment and are therefore calculated separately for each unit. The energy use results can therefore not be assumed to be correct for every individual apartment, they only represent averages for the building.

The scenarios in this study are compared by shadow costs. This method of weighing different environmental impacts and creating a single unit that represents the damage costs to society is uncertain and not internationally standardized (De Oliveira Fernandes et al., 2021). A potential 300% increase of the shadow costs per unit of environmental emission, as predicted by Van Haagen et al. (2022), would lead to higher total shadow costs in this study but would not affect the relative results of the scenarios. However, if the shadow costs increased according to Van Haagen et al. (2022) without adjusting the maximum MPG values in the Building Decree accordingly, it would be more difficult to receive a permit for new buildings. Since the shadow costs are currently not a required measure to assess renovations in the Building Decree, these interventions would not be affected by an increase in the shadow costs.

The focus on shadow costs per year per square meter can have a large impact on the comparison of renovation and rebuilding. As shown in the sensitivity analysis in section 7.4.6, a larger apartment size per resident may cause overall shadow costs to increase, even though this is not shown when comparing the buildings per square meter. Furthermore, the increased apartment size in the new building probably relatively leads to slightly less materials per square meter of surface area because some materials may be required less often, such as the walls between apartments and front doors.

All scenarios for renovating and rebuilding are compared for the same life span. While the energy use does not change with longer life spans, the same impacts of materials are spread out over more years when the building stays in place for a longer period. By calculating impacts for different life spans, this has been partially addressed. However, it is likely that renovated buildings will be demolished earlier than new buildings. Comparing scenarios for the same life span can therefore work in the disadvantage of new buildings. It is possible to compare the yearly shadow costs of renovation and rebuilding scenarios which are based on life span assumptions, for instance in figure 11. As an example, it may be more realistic to compare the standard life span of 75 years of new buildings to renovation which only expanded the building life cycle by 40 years, which would relatively decrease the impacts of new buildings.

This study only compared the environmental impacts of building scenarios in terms of shadow costs. In practice, many other factors also need to be considered. Especially in social housing, livability, energy poverty, and costs should inform the decision between renovations and rebuilding next to sustainability concerns. Therefore, even though many uncertainties that influence the shadow costs have been incorporated in this study, the findings should still not be seen as one-size-fits-all solutions for all porch flats in the Netherlands.

Scenarios

The results in this study are completely based on a set of scenarios, which therefore influence the results and conclusions. Firstly, even the minimal renovation scenario included insulation of the entire building envelope and a change in heating type. It is possible that a renovation with fewer components but using higher standards for those would lead to similar energy improvements while causing less nuisance and/or material shadow costs. Furthermore, transformations are not included as a renovation alternative because they cannot be applied to every building. However, Itard & Klunder (2007) found that this type of renovation led to the least environmental impacts. Therefore, it is possible that the conclusions in this study would have been different if transformations had been included in the analysis.

In terms of energy efficiency, a report by W/E Adviseurs (2021a) indicates that energy neutral and passive buildings lead to lower shadow costs than buildings following current nZEB standards. Therefore, it is likely that rebuilding with these standards is the most sustainable option. However, since housing corporations are assumed to have a limited budget, buildings with energy standards which do not go far beyond the current policy requirements are probably more appropriate for this target group.

Buildings

The building selection in this study, regarding both the individual dimensions and the building types, has an influence on the results. In addition to the aforementioned differences in apartment size, the new buildings are less rectangular than the porch flats. In replacing a porch flat with *Woongebouw M*, the street plan would have to be changed and probably some green area needs to be removed or replaced. These considerations are not incorporated in this study, but in practice the removal of green space would be a disadvantage of new buildings.

Only one building type has been incorporated into the rebuilding scenarios of this study, so the shadow costs of other buildings may be different. However, the maximum MPG value of new buildings is 0,8 euros per square meter per year and this value is expected to decrease to 0,5. Similarly, the energy consumption cannot be much higher because of nZEB standards. Especially with solar panels on the roofs, the shadow costs of alternative buildings can therefore not be much higher than the studied scenarios, so this is not expected to affect the results of this study. However, using natural gas in a nearly-zero energy building would probably still increase the shadow costs, based on the results in this study. On the other hand, buildings made completely from wood could lead to even lower environmental impacts of the new buildings.

Energy use assumptions

The results of this study would be different if other energy technologies had been selected. For instance, after an extensive renovation, existing buildings would also be suitable for low-temperature district heating systems (RVO, 2021). If these used renewable energy sources, it is possible that this energy carrier is even more sustainable than estimated as renewable district heating in this study (see section 5.4.2). Finally, electric boilers have been selected to supply hot water in combination with collective heat pumps, because they were available in the NMD as well. RVO (2016) lists an instantaneous water heater instead, while a booster heat pump would lead to slightly less fossil primary energy use in EPA-W.

Especially in the short term, low-temperature district heating could be more sustainable than heat pumps because the environmental impacts of electricity are still high. Moreover, many district heating networks in the Netherlands use waste heat or waste incineration. In this study, the impact factors of district heating are based on estimates for fossil-fuel based and renewable district heating, so it is difficult to apply the results to cities where specific district heating networks are planned or already in place. Furthermore, default values for the primary energy factors have been used for the calculations of energy demand, primary fossil energy consumption, and other results in EPA-W, following NTA8800:2022 (NEN, 2022). Especially for district heating, these values may therefore be incorrect. It is expected that the shadow costs of most district heating networks will fall within the range of the two variations studied in this study (see section 7.4.3 for a comparison of heating technologies), but future research is needed to create more accurate estimates for the environmental impacts of district heating.

In EPA-W, several characteristics of installations have been selected as *Unknown*. In the software, this often leads to conservative values, so that building permits are not issued unjustly. Since there were no regulations regarding energy use when porch flats were built, it has been assumed that the conservative values are probably appropriate to ensure the reference porch flat is in any case not overly optimistic for most porch flats in the Netherlands. However, the impacts of existing porch flats may therefore be lower than calculated in this study, especially regarding the business-as-usual scenario. For new buildings, more energy efficient technologies were selected in EPA-W because they are not limited by existing structures.

The consumer behavior that leads to the use of energy in the studied buildings is based on standard use profiles (NEN, 2022), so it cannot be stated that the actual energy demand in buildings will be the same as assumed in this study. The energy consumption is also considered to be constant, while it is possible that energy consumption will change because of climate change. Energy consumption in EPA-W is also not based on the number of residents or bedrooms, so especially the demand for hot water can be very different. Apart from the number of residents, user behavior largely influences the energy use. Especially for housing corporations, a strategy to inform tenants about energy efficiency could be implemented in addition to other measures to ensure that environmental impacts are actually reduced. Moreover, electricity use for lighting and appliances is not included in this study. The total electricity consumption would therefore be higher, but this affects the shadow costs of all scenarios in the same way. The results should therefore be used to compare scenarios and not as representations of the total energy use or shadow costs of the buildings.

Electricity generation by solar panels is modelled as negative shadow costs, compensating completely for the same amount of electricity used. In practice, factors such as the time-of-day influence how many environmental impacts are prevented. During non-peak hours or moments with a lot of sun and wind, the electricity mix will include more renewable energy than during peak hours or without sun and wind energy. Furthermore, because of this intermittent demand and supply, there would still be a need for fossil fuels even if the total amount of electricity use was compensated by electricity generation. Thus, although buildings could be modelled as energy neutral, this does not mean that they are fossil-free.

Materials use assumptions

The selection of materials in this study is mainly based on a graduation project by Klaver (2018) in which material scenarios for *Woongebouw M* have been created, based on availability in the NMD. Since the report by Klaver (2018) is not an academic, peer-reviewed source, it is possible that the selection is not completely feasible from an architectural perspective.

The difference between the conventional and sustainable new building scenarios, as well as the material contribution analysis and sensitivity analysis, give an indication of the impact of material selection within the MPG+ method. The use of materials with high shadow costs such as concrete should be avoided if the building will only stay in place for a short period. However, the MPG+ results in figure 12 show that after about 25 years, the new building with conventional materials still has lower shadow costs than all other renovation scenarios, which use fossil energy and have less insulation. Based on the sensitivity analysis (figure 14), it seems that the possible deviation in shadow costs from materials only matters for scenarios that use a lot of materials for which the shadow costs are otherwise quite similar but will not result in drastically different conclusions about the most sustainable intervention. However, overall the use of sustainable materials always reduces the environmental impacts.

8.2.3. Data uncertainties

Energy use uncertainties

The data on environmental emissions for energy sources are outdated or represent rough estimates. The environmental impacts for electricity are based on data from 2008. Although the shadow costs have been corrected through the impact reduction pathways explained in section 5.4.1, it is not sure if the climate neutral targets in 2050 will be reached for electricity or if the reduction will occur as modelled. Furthermore, the reduction is based on CO_2 emissions and targets, but is applied to all impact categories. In practice, the relative environmental impacts will probably change, for instance for non-fuel abiotic depletion compared to the abiotic depletion of fuels. These uncertainties point more towards the importance of reducing electricity demand and installing PV panels. The difference between the scenarios with a heat pump and the remaining scenarios is smaller if electricity does not become as sustainable as expected in this study, as reflected in section 7.4.2.

The environmental impact data used in this study for natural gas and district heating originate from 2004. Although the variation is likely smaller than between electricity mixes in different years, the environmental impacts of natural gas can deviate with different countries of origin. Due to for instance earthquakes in Groningen, but also boycotts for geopolitical reasons, the calorific value and transportation distances of natural gas may vary and affect the associated environmental emissions. Furthermore, the environmental impacts of district heating are estimated through a multiplication factor applied to all the natural gas shadow costs. In addition to a high chance of discrepancies with the actual shadow costs for a specific district heating system, the relative shadow costs caused per environmental impact are most likely not the exact same. With a conservative and progressive estimate of the total shadow costs of district heating, the impacts per kWh of district heating networks in the Netherlands could be somewhere in between the shadow costs of the two versions of the minimal renovation scenario (1.1a and 1.1b), but this cannot be guaranteed.

A more comprehensive set of impact factors for energy carriers could change the results, because the shadow costs from energy would be affected differently per scenario. By assessing the influence of a sustainable district heating alternative and improving electricity impacts, some of these uncertainties have been evaluated. When comparing the total environmental impacts of the scenarios, a larger set of impact factors would be reflected in deviations in the shadow costs per kWh energy consumption. The sensitivity analysis in section 7.4.1 indicates how a hypothetical increase or decrease of 20% in energy shadow costs could affect the relative score of the scenarios. The three scenarios with the lowest shadow costs – extensive renovations and both new building scenarios – would all be affected in the same way since they all use electricity as the only energy source.

Since energy use causes most of the impacts of the studied buildings, the uncertainties regarding the shadow costs imply that the results may be incorrect, especially with regards to the individual environmental impact categories. Considering the expected increase in the shadow costs (Van Haagen et al., 2022), it may be more likely that the shadow costs are underestimated and not overestimated. On the other hand, global warming potential causes more than half of the environmental impacts in all scenarios, and large relative differences between the global warming potential of the scenarios correspond to the differences in the overall shadow costs, as shown in figure 13. While climate change impacts are very uncertain, they are being widely studied and many policies such as the climate neutrality targets for 2050 only look at GHG emissions. Based on the results in this study, it seems that this focus can be justified.

Material use uncertainties

Even if all the materials selected from the Environmental Database would be used in the scenarios and would all be tested, uncertainties about the environmental emissions are unavoidable. There are inherent uncertainties in the LCA method due to the large number of assumptions, for instance regarding energy sources, transportation distances, and material origins. Especially in a large database, it is difficult to ensure the consistency and accuracy of all entries. Furthermore, the LCAs are performed at one point in time, and they often do not incorporate assumptions of future developments. These innovations may lead to less environmental emissions than indicated in the Environmental Database.

In summary, the many limitations and uncertainties affect the results in different ways. In some cases, this can be advantageous for renovation scenarios and in others for new buildings, but there does not seem to be a clear direction. Some of the most influential assumptions regarding life span, electricity impacts, solar panels, and apartment size, have been addressed in the sensitivity analysis. In many cases, the overall shadow costs of scenarios are affected by uncertainties and assumptions, but the relative shadow costs between the scenarios seem more robust. Most notably, either extensive renovation or rebuilding seems to have the lowest shadow costs under most circumstances. The results of this study are aimed at housing corporations that compare the renovation of porch flats with replacing these buildings with buildings with more and larger apartments. Generalizations of the findings to other contexts can only be made very carefully while considering the potential impacts on the relative environmental impacts of the alternatives.

9. Conclusion

9.1. Research aim

The aim of this study is to compare different scenarios for renovating typical buildings owned by housing corporations with scenarios for replacing them with new buildings in the context of the Climate Agreement. This is done by combining the environmental impacts of energy consumption and material use of different interventions for porch flats, while including fossil-free heating technologies and up-to-date building standards. These results can be used by municipalities and housing corporations with porch flats in their building assets to incorporate sustainability into the decision-making process to reduce energy poverty and decrease environmental impacts.

9.2. Key results

The results indicate that extensive renovations and new buildings, both with insulation at nZEB levels and using a collective heat pump, are the most environmentally friendly options compared to less ambitious renovation scenarios. Extensive renovations or new buildings with sustainable materials have similar shadow costs for a life span of more than 40 years. With shorter life spans, extensive renovations are more sustainable options. After a life span of 75 years, new buildings with conventional materials have comparable environmental impacts to extensive renovations and sustainable new buildings, although the shadow costs remain slightly higher. An important consideration is that the shadow costs are measured per square meter, while the apartments in the new building are larger. If the number of residents per apartment does not increase as well, the overall environmental impacts will increase.

9.3. Research questions

1. What are realistic building renovation or replacement scenarios for housing corporations in the Netherlands?

Housing corporations offer social housing, for which it is important that the rent remains affordable for tenants. Therefore, conventional types of insulation and installations as well as collective solutions have been selected as much as possible. In new buildings it is easier to create an optimal building design compared to improving energy efficiency in existing buildings. Therefore, three scenarios with different ambition levels have been created for renovations to cover a wide spectrum of possibilities. These scenarios include different installations for heating, domestic hot water, and ventilation, which are appropriate for the insulation levels. In practice, the options for district heating and heat pumps depend on local development plans and individual building characteristics. With this perspective in mind, the following scenarios have been devised:

Table 16: Scenarios for calculating environmental impacts of the renovation or replacement of post-war porch flats

Category	Scenario	Energy Label
0. Baseline	**0. Business as Usual**: No intervention	E
1. Renovation	**1.1a Minimal Renovation** to required level for medium temperature district heating network with conventional sources (minimal renovation standards Building Decree) **1.1b Minimal Renovation** with district heating with renewable sources	B
	1.2a Standard Renovation with a condensing boiler **1.2b Standard Renovation** with a hybrid heat pump	A
	1.3 Extensive Renovation to required level for collective heat pump (nZEB standards)	A++
2. Demolition and new construction	**2.1 New Conventional:** residential building with conventional materials (nZEB standards)	A++
	2.2 New Sustainable: residential building with sustainable materials (prefabricated, biobased; nZEB standards)	A++

2. What are the environmental impacts of different scenarios for renovating a post-war porch flat or constructing a new multi-family building?

The shadow costs of energy and materials in the main scenarios are repeated below in figure 21. If porch flats with an energy label E are not renovated, they lead to shadow costs of about 4,50 €/m²/year. Minimal renovation with district heating decreases the shadow costs by 0,73 to 1,16 €/m²/year, depending on the life span. When district heating uses renewable energy sources, the shadow costs reduce even further compared to the current situation. This leads to shadow costs between 2, - and 2,50 €/m²/year. After a standard renovation and with a new condensing boiler, the shadow costs of the porch flats are around 2,25 €/m²/year, practically independent of the life span. The installation of a hybrid heat pump with standard renovations further reduces the shadow costs to 1,90-2,15 €/m²/year. Finally, an extensive renovation with a collective heat pump leads to shadow costs between 0,94 and 1,58 €/m²/year. In all scenarios, the lower range of the shadow costs are associated with the longest life spans, due to the assumed reduction of electricity impacts and material shadow costs. Since the standard renovation with gas boiler scenario barely requires any electricity, the shadow costs decrease only a few cents. Lastly, the shadow costs of the renovation scenarios are mainly related to the energy consumption of the buildings.

The shadow costs of new buildings range between 0,86 and 2,25 €/m²/year and are very much dependent on the life span. Because the same energy use is assumed in both alternatives, the scenario with sustainable materials always causes lower shadow costs than the same building made from conventional materials. The difference between the scenarios decreases with an increasing life span. Only with a life span of 20 years, the shadow costs of materials in the conventional building (1,31 €/m²/year) are higher than the energy shadow costs (0,88 €/m²/year). In all other rebuilding scenarios, energy use causes the more shadow costs than materials, but they are much more comparable than for renovations.

The shadow costs of all scenarios are dominated by the impacts caused by the global warming potential, as shown in section 7.3.2. The shadow costs in this category also decline the most with increasing insulation levels and alternatives energy carriers. Human toxicity is the next impact category with the highest shadow costs. The impacts of marine water ecotoxicity are relatively high in the current, minimal renovation, and standard renovation scenarios.

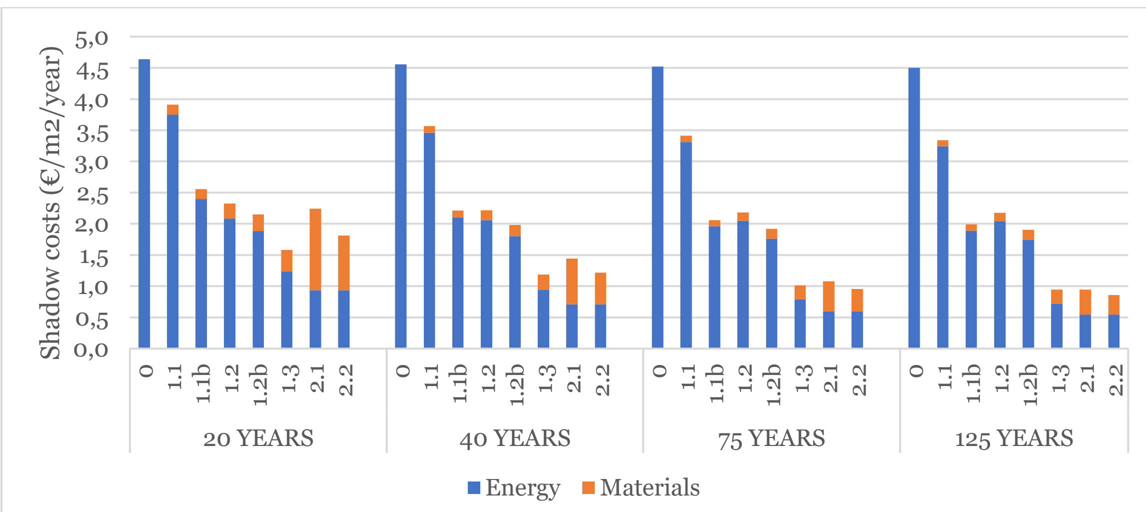


Figure 21: Shadow costs from energy and materials combined for different life spans, <u>with</u> reduced environmental impacts from electricity. 0: BAU; 1.1: Minimal Renovation; 1.1b: Minimal Renovation (reduced DH impact); 1.2: Standard renovation (condensing boiler); 1.2b Standard Renovation hybrid heat pump); 1.3: Extensive Renovation; 2.1: Conventional New; 2.2: Sustainable New

3. What key parameters have a large impact on the comparison between the environmental impacts of renovating or replacing buildings owned by housing corporations?

Many different factors have an impact on the comparison of the scenarios in this study. In the main scenarios, the scenarios with the lowest shadow costs are either extensive renovations or new buildings, ideally with sustainable materials. When considering a potential 20% deviation from the shadow costs calculated in this study, the shadow costs extensive renovations and new buildings largely overlap. In every case, the current situation and minimal renovations with conventional sources lead to much higher shadow costs than extensive renovations or new buildings. It is possible that standard renovations with hybrid heat pumps also have similarly low shadow costs as conventional new buildings with a short life span. Only if electricity causes the same environmental impacts as the Dutch electricity mix in 2008, standard renovations lead to the lowest shadow costs (see figure 15), but this is not considered realistic. Furthermore, minimal renovations with a sustainable district heating network may have similar shadow costs to standard renovations, despite having less insulation.

Several studies stress the importance of building life span when studying the environmental impacts of building refurbishments or replacements. The current study also shows that renovations are more sustainable with shorter life spans while new buildings benefit from a long life span, because the environmental impacts can then be spread out over a longer period. As shown in figure 12, the extensive renovation has the lowest shadow costs with life spans below approximately 50-55 years. Afterwards, the sustainable new building scenario has the lowest shadow costs. From then onwards, the shadow costs of new buildings with conventional materials also have somewhat similar shadow costs.

Energy use has a lot of uncertainties while also causing a large portion of the shadow costs. Therefore, the small differences between scenarios may not be significant, which indicates similar shadow costs of extensive renovations and new buildings as illustrated in section 7.4.1 of the sensitivity analysis. The scenarios with the lowest shadow costs use a collective heat pump, but those buildings are also the most energy efficient. However, applied to the same building, the results in section 7.4.3 still show that collective heat pumps are the most sustainable energy generation alternative. On the other hand, in an optimistic situation a district heating network with renewable energy sources can have shadow costs that are only slightly higher than the shadow costs of an air-sourced heat pump.

The placement of solar panels relatively reduces the shadow costs of all scenarios by negating a large part of the electricity use, as shown in section 7.4.4. With the assumption in this study that new apartment blocks would be higher and solar panels are only placed on roofs, the shadow costs of renovations are reduced more than for new buildings. This is because new buildings with more floors contain relatively less roof space per square meter of gross floor area than. With solar panels, the shadow costs of extensive renovations seem to remain lower than those of sustainable new buildings with life spans below 75 years; with longer life spans the two scenarios perform similarly.

The increased apartment size of the replacing buildings is not reflected in the shadow costs that are calculated per square meter. While the quality of living for tenants may increase with larger apartments, tables 14 and 15 show that extensive renovations are always more sustainable than new buildings when considering the shadow costs per apartment or resident.

Adapting the shadow cost calculations based on the energy performance gap or different assumptions for the reduction of electricity shadow costs do not have a large effect on the results. The main difference between the scenarios that are corrected by these aspects is that new buildings seem to have slightly lower shadow costs than the extensive renovation scenario, because new buildings use less energy. The existence of the energy performance gap does imply that the energy consumption in most of the scenarios in this study is underestimated, as shown in section 7.4.5. Furthermore, even if electricity does not become more sustainable than in 2021, the scenarios with a heat pump have the lowest shadow costs, as seen in figure 16.

In summary, the shadow costs of the scenarios are highly influenced by uncertainties, life spans, heating technologies, solar panels, and apartment size. However, the conclusion that extensive renovations and new buildings are the scenarios with the lowest shadow costs holds up regardless of the assessed uncertainties. With the scenarios selected in this study, extensive renovations seem to lead to the least environmental impacts when you consider the overall shadow costs per apartment. Nevertheless, the impacts of extensive renovations and rebuilding are often similar and are related to the lowest shadow costs compared to other scenarios.

How do the environmental impacts of different renovation scenarios for typical buildings of housing corporations compare to demolishing and rebuilding in the context of the Dutch climate goals?

Shadow costs

The impacts of the current situation and minimal renovations with conventional district heating are always higher than minimal renovations with renewable district heating, standard or extensive renovations, and new buildings. Furthermore, extensive renovations and new buildings most likely cause less environmental impacts than the other renovation scenarios, especially when sustainable building materials are used. This is due to the reduction in shadow costs from energy use because of improved insulation levels, the use of heat pumps, and a more sustainable electricity mix in the future.

The shadow costs of extensive renovations and new buildings are quite similar compared to the other scenarios, especially when considering a potential sensitivity range of 20% around the main results in this study. Without solar panels, the extensive renovation scenario has the lowest shadow costs for a life span of less than 75 years. Afterwards a sustainable new building becomes more environmentally friendly. With a life span of around 75 years, new buildings with conventional materials also may be comparable to the other two scenarios. If all buildings have solar panels, these conclusions do not change a lot. If solar panels are only possible on either extensively renovated buildings or (sustainable) new buildings, the one with solar panels is the most sustainable scenario. However, when considering the shadow costs per apartment, extensively renovated buildings always have lower shadow costs than new buildings.

Context

Dutch climate policy very much follows the European targets that are based on the Paris Agreement. These policies mostly focus on phasing out natural gas and renovating the houses with labels E, F, and G. Apart from sustainability, these policies are also motivated by the housing crisis, earthquakes caused by natural gas mining in Groningen, and geopolitical issues regarding natural gas. For new buildings, the standards for nearly-zero energy buildings need to be followed. As the name suggests, these buildings are not completely energy neutral. Energy use from the built environment may pose a problem in the future, since the aim is to be climate neutral in 2050 (Ministry of EZK, 2019) while new buildings are intended to last for at least 75 years. Furthermore, solar panels are currently required in the MPG calculations of new buildings, possibly hindering the installation of solar panels on the entire roof surface.

Housing corporations also set targets to improve buildings with the worst energy labels. However, other factors that influence the living quality, such as noise disturbance, inaccessibility, and inappropriate floor plans, can make housing corporations decide to demolish porch flats and rebuild. On the other hand, they need to get approval from the tenants for the intervention and provide substitute housing if necessary. Furthermore, housing corporations are dependent on the demand for social housing in society and have a social responsibility to provide sufficient and appropriate housing. Therefore, housing corporations work with cycles of about 30-40 years to assess their building assets, as opposed to the 75 years usually assumed for new buildings to stay in place. This does not mean that buildings are demolished after that period, but it is difficult to guarantee that their use will not change within that period. Finally, apartments in porch flats are quite small, so it is possible that replacing buildings are designed for a larger surface area per resident (Van Vlaenderen & Singelenberg, 2007).

Conclusions in the present context

Based on the findings, several conclusions can be drawn. Firstly, natural gas and district heating systems based on fossil fuels should be phased out. Collective heat pumps are the most sustainable energy technology but require a significant amount of insulation. If district heating can use renewable sources, or waste heat that would otherwise be lost, they are a good alternative to heat pumps. Secondly, because of the environmental impacts related to energy use and the many uncertainties, reducing energy use is a good way to minimize environmental impacts. This can be achieved through insulation, but solar panels can reduce a lot of environmental impacts. Especially in the short term the electricity mix is currently still based on a lot of fossil fuels, so in this period solar panels prevent the most shadow costs. Because of this, the current inclusion of solar panels in the MPG is counteractive in the aim to reduce the environmental impacts from buildings. In addition, installing solar panels also contributes to making the electricity mix more sustainable.

Considering the Dutch context, the uncertainties about apartment size and solar panels, and the short decision-making cycle of housing corporations, extensive renovations are in most cases a no-regret solution compared to nearly-zero energy buildings. This solution is the most sustainable in the short-term, and if it is concluded later that they should be demolished this is still better than any other renovation option or doing nothing. Because the energy consumption is very similar to new buildings, there is no large difference in terms of fossil fuel dependency or energy poverty. It may not be in line with the climate neutral targets in 2050 if nearly-zero energy buildings are built now, when they will still require some energy use in the future. Therefore, it would be better if buildings are extensively renovated now and only rebuilt when the Building Decree probably requires new buildings to be energy neutral or passive. Furthermore, renovations also make more sense with finding a solution to the housing crisis and for preventing nuisance to tenants due to temporary replacement. In short, extensive renovations are in general probably a more resilient option because the renovated buildings are more suitable for different societal crises and more flexible for future policy changes, while new buildings are only slightly more sustainable and may create a lock-in effect.

9.4. Recommendations

9.4.1. Future research

Future research can firstly address the many uncertainties mentioned in this study. Shadow costs are controversial and dependent on many assumptions. The shadow costs per environmental emission should therefore be studied further. Moreover, a follow up study of the report by Keijzer et al. (2021) should determine whether biogenic CO_2 uptake should be counted differently in LCAs. Also, the emissions per energy source should be defined based on more recent sources and for a wider spectrum of energy carriers. District heating with various sources, such as combined heat and power plants, waste incineration, and biomass could be included in addition to a low-temperature system. Furthermore, individual heat pumps could be relevant to compare to collective heat pumps. The pathways to a climate neutral society in 2050 should also be defined better, for instance for the electricity mix in the Netherlands. Finally, the Environmental Database should be expanded further with more building components, most notably sustainable alternatives, and more items in the database should be tested.

Follow-up studies can also use a similar methodology as this thesis report and expand the scenarios used, so that the comparisons apply to more real-life projects. Firstly, more building types can be analyzed, such as gallery flats and row houses. If applied to sufficient typologies, spatial visualizations of recommended interventions could be created to determine areas with potential for a district-based approach. Furthermore, in all buildings, a zero-energy and passive building scenario for both renovations and new buildings should be included, because they probably have a better overall performance than the scenarios studied in this paper, as suggested by W/E Adviseurs (2021a). Finally, the results could be verified with calculations for existing porch flats or even other existing multi-family buildings to assess the generalizability of the findings and establish potential performance gaps for both energy and materials.

Many of the uncertainties and discussion points in this study are caused by the dependency on the MPG^+ method, including the use of the NMD and the established impact factors for energy carriers in the Netherlands. It is recommended that the current study is compared with an LCA of at least one of the scenarios, with the use of a more transparent and complete database such as EcoInvent. If this LCA leads to very different results, the current study should be repeated in the form of an LCA to validate the conclusions drawn in this report. The differences between MPG$^+$ and LCA results should be seriously assessed to determine how to improve the MPG$^+$ method.

9.4.2. Policy recommendations

Several suggestions about effective and ineffective policies can be derived from the findings in this study. While life span is an important factor for determining the shadow costs of a building, the most important recommendation to housing corporations would be to not demolish and rebuild if the new dwellings will only remain in place for a short time. Because of the high costs and workload required for such a project, it is not expected that this consideration will quickly be overlooked. Furthermore, in general it is better for the environment to select the materials with the lowest shadow costs if possible. Although the energy carrier and insulation level are much more influential for the overall environmental impacts, the availability of sustainable materials should be a factor in comparing scenarios that are otherwise similar in shadow costs. Furthermore, solar panels always decrease the environmental impacts of a building, so these should be installed on buildings whenever possible.

Municipalities are often involved in the development of district heating networks. The difference in shadow costs between both minimal renovation scenarios show how much impact the source of district heating can have. Because of the highly variable shadow costs of a district heating system, it is essential that the expected environmental impacts of a new network are studied. With the use of waste heat or renewable options, district heating can prevent environmental impacts. However, if the district heating network will also rely on fossil fuels or possibly also biomass, a heat pump is probably a more sustainable option. Furthermore, investments in new, renewable district heating networks would cause more accessibility to sustainable heating.

Both local and national policies focusing on renovations should provide a clearer direction towards high energy efficiency levels, such as an energy labels of A++. If renovations take place anyways, the additional nuisance and costs of more ambitious renovations is relatively small. Renovations towards lower energy labels can create a lock-in effect and cause the buildings to require another intervention in a few years. Similarly, hybrid heat pumps only slightly decrease the shadow costs compared to condensing boilers, so it is better to insulate sufficiently for the installation of a completely fossil free heat pump. Furthermore, considering other important factors such as the housing crisis and global issues regarding natural gas, extensive renovations are probably a no-regret solution compared to rebuilding.

In the municipality of Leiden, for instance, there are ambitious plans to become climate neutral in 2050, but the plans are somewhat vague and mostly mention phasing out natural gas, installing solar panels, insulating houses with low energy labels, and no-regret measures for medium temperature district heating (Municipality of Leiden, 2020; Municipality of Leiden, 2021; Over Morgen, n.d.). The results in this study show that these interventions are not sufficiently effective on their own. Therefore, it is recommended that municipalities steer housing corporations more towards extensive renovations.

On a national level, the target values for existing buildings are mentioned as an important aim in policies, such as the energy performance and sustainability agreements between housing corporations and the Ministry of Internal Affairs (RVO, 2021). However, in practice the renovations may end up being less ambitious when for instance costs and nuisance play a role. It is recommended to give the target values a more formal role and to create a stronger incentive towards extensive renovations, through for instance stricter energy efficiency requirements during drastic renovations.

In the national Building Decree, solar panels are part of the MPG score, where they are responsible for a large share of the material performance of buildings (see figure 19). The results in this study show that even with very high material shadow costs, the reduction of electricity use through solar panels causes the overall impacts of a building to decrease. It is recommended that solar panels do not count for the MPG of a new building, to avoid discouraging the installation of solar panels on new buildings. The current electricity mix still causes a lot of environmental impacts, which can be avoided in the short term with local solar panels. Simultaneously, the solar panels will contribute to increasing the share of renewables in the electricity mix, which is also supposed to be climate neutral in 2050. For the same reasons, solar panels should be included more explicitly in policies about sustainable buildings. For instance, in the energy performance and sustainability agreements between AEDES and the Ministry of Internal Affairs, solar panels are not mentioned (Ministry of BZK, 2022).

9.4.3. Decision tree for housing corporations

The conclusions based on the shadow costs in the previous sections are summarized in the decision tree in figure 22. These recommendations are created to assist the decision-making process for housing corporations that want to incorporation sustainability in the deliberation between renovating or rebuilding a porch flat. Only extensive renovations or new buildings come out as suggested interventions because those scenarios always have the lowest shadow costs with the assumptions made for this study. If multiple scenarios are recommended, they are mentioned in the expected order of shadow costs from low to high. In these cases, the shadow costs of the other scenarios are less than approximately 20% higher than the scenario that is listed first.

Based on the sensitivity analysis, the impact of life span, solar panels, and apartment size have been included in the decision tree. Between the extensive renovation and new buildings, heating technology does not make a difference in the results. Furthermore, the effects of the remaining uncertainties – more sustainable materials used in renovations, a different reduction in the shadow costs of electricity, and the energy performance gap – are expected to balance each other out for these scenarios.

In question (1) and the first follow-up question, it is asked whether the new buildings will be designed to contain more square meters per resident. This can be the case if for instance the floor area is larger, but the same number of bedrooms is present. Although this may not affect the MPG+ score, the overall environmental impacts do increase in this case. The suggested scenarios above the dotted line are therefore based on the shadow cost results per apartment in section 7.4.6. These results have been explored further by experimenting with several percentage differences in apartment size between the existing and new building, to come to the distinction of 20%. Another way to avoid an increase in overall shadow costs would be to include more and smaller bedrooms in *Woongebouw* M than assumed in this study. However, if it is important for livability, for instance, that the apartments increase or if it is preferable to use the shadow costs per m^2 as the leading indicator, the decision tree can be continued at question (2).

The bottom part of the decision tree is based on the MPG scores of the scenarios with and without solar panels. The shadow costs of the scenarios with solar panels are discussed in section 7.4.4 for one life span, but the results for all life spans of extensive renovations and both new building alternatives with and without solar panels are jointly also displayed in appendix B.6. However, it is important to note that the MPG scores are based on apartments and buildings with different sizes, and then divided over the gross surface area. Therefore, it is not completely certain that the scores would be the same if the new building would be the size as the porch flats.

Solar panels are shown to affect the relative shadow costs of the scenarios, but it is possible that the roofs of existing buildings are not suitable for solar panels. Furthermore, installing solar panels on new buildings may not be allowed, because it could cause the MPG to exceed the maximum standards. Because of this consideration, questions (2), (3), and (4) ask about the possibility of installing solar panels on both, neither, or one of the scenarios. The option that solar panels are possible on the sustainable new building but not on the conventional new building is not explicitly incorporated in the decision tree. If this is the case, conventional new buildings have much higher shadow costs, so questions (2) or (4) can then be answered as if only extensive renovations or sustainable new buildings are the available options.

The questions about the building life span determine all outcomes in the decision tree. The life spans are based on the scenarios but are often slightly rounded up or down. In the bottom of figure 22, the tipping point seemed to be completely in between the life spans of 75 and 125 years, so the suggested scenarios are based on a life span of 100 years. Furthermore, it is probably not possible to predict the building life span with certainty, but then an educated guess can be taken based on the individual context of a housing corporation and the specific building which is evaluated. Otherwise, the distinctions in solar panel installations and life spans for the suggested interventions can still be used to make a more informed decision when considering to renovate or replace a porch flat.

Finally, all recommended scenarios use a collective heat pump, but if this is not an option it is also possible to replace this with a district heating system with renewable sources such as geothermal energy.

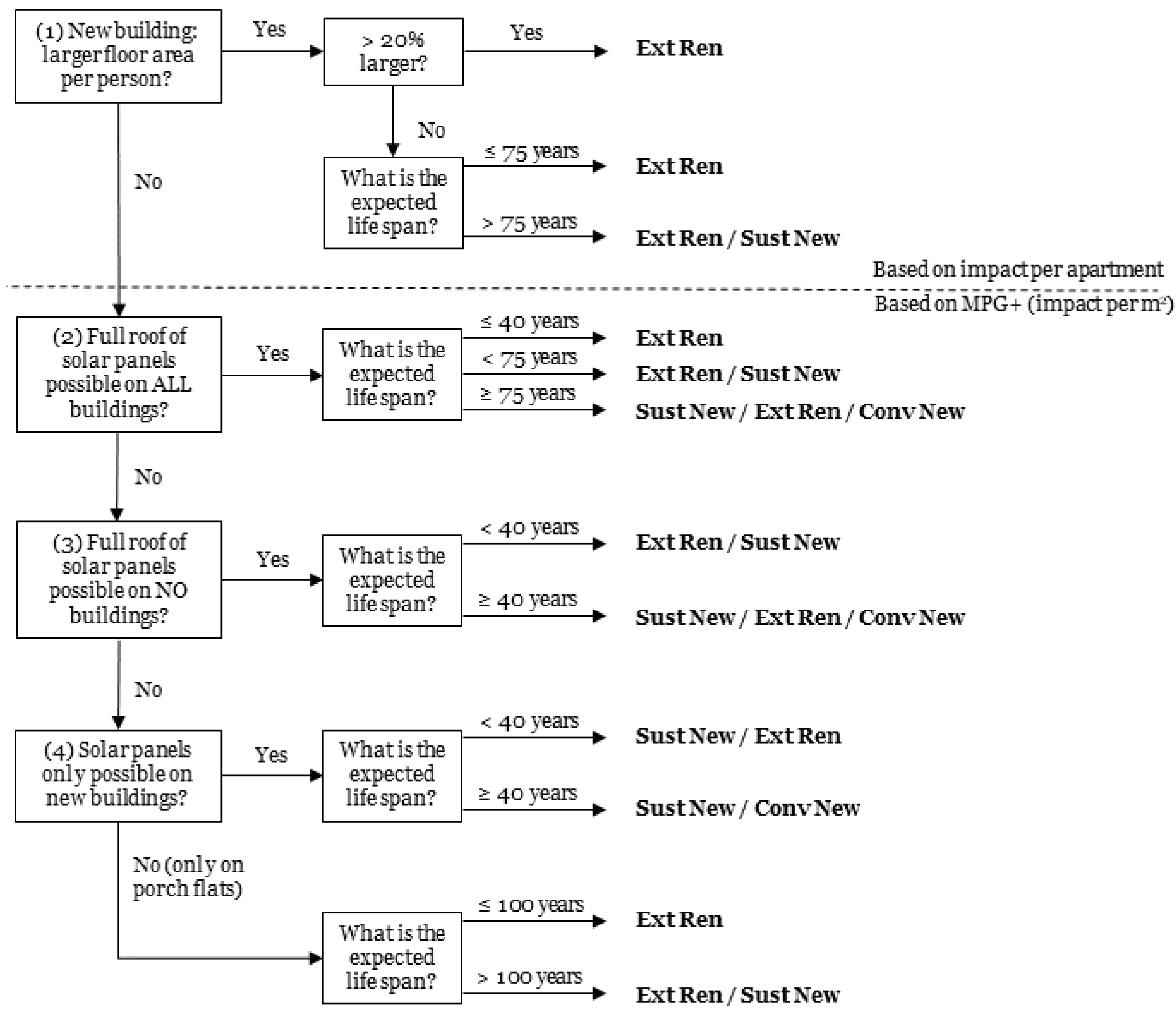


Figure 22: Decision tree aimed at housing corporations to determine the most environmentally friendly energy intervention for porch flats. Abbreviations scenarios: Ext Ren – Extensive Renovation; Conv New – Conventional New building; Sust New – Sustainable New building.

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- Tabel 5.1A + 5.1B: Nieuwbouw Rc waardes
- Artikel 5.6.2: Renovatie Rc waardes

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Appendix

A. Assumptions

A.1. Materials required for MPG

Table 17 lists the materials that should be included for MPG calculations. Below it is a list of materials not to include.

Table 17: Materials required to be included in the MPG (Stichting Bouwkwaliteit, 2017)

Section	Subsection	Element code (NMD)	Component
Foundation	**Soil facilities**	11.01	Filling sand
		13.01	Dampproofing on soil
	Foundation construct	16.01	Foundation on steel (beams and strips)
		16.01	Beam roster foundation
		17.01	Foundation piles
	General substructure	16.03	Basement wall
		16.05	Basement wall insulation
Structure	**Inner walls**	22.02	Load-bearing inner walls
		22.02	Solid non-load-bearing inner walls
		22.02	Apartment separating wall
	Outer walls	00.01	Curtain wall style
		21.01	Inner cavity leaf
		41.01	Outer cavity leaf
		41.02	Curtain wall panel
		41.02	Façade finish
		41.04	Cavity insulation
	Façade openings	31.02	Window frame (façade)
		31.02	Door frame (façade)
		31.04	Door (façade)
		31.05	Garage doors
		31.07	Glazing (façade)
		31.08	Lower front fill (e.g., shopfront, storefront, glass front)
		31.11	Slabs
	Roofs	47.02	Roof boarding
		47.04	Roof sealing
		47.06	Ballast layer (until 30° tilt)
		47.07	Flat roof insulation
		48.07	Sloped roof insulation
		27.01	Support structure flat roof
		27.02	Support structure sloped roof

	Roof finish	47.04	Roof cover flat roof
		47.05	Roof cover sloped roof
	Roof openings	37.04	Continuous rooflight (glazing)
		37.04	Continuous rooflight (frames)
		37.04	Domelights
	Support structures	28.01	Beams
		28.02	Columns
		28.04	Lintels
	Floors	13.02	Ground floor
		13.02	Floor on solid ground
		23.01	Story floor
		43.03	Floor insulation
Finishing	**General**	40.02	Fire resistant coating
		40.03	Noise resistant coating
	Railings	34.02	Railings
	Inner walls	00.01	Profile element wall
		22.01	System walls
		22.01	Sheet material element wall
		41.04	Insulation element wall
		42.02	Wall finish (indoors)
		42.02	Painting (indoors)
		42.02	Tiling work wall
	Inner wall openings	31.02	Window frame (indoors)
		31.02	Door frame (indoors)
		31.04	Inner door
		31.07	Glazing (façade)
	Outer walls	41.03	Painting (façade)
	Outer wall openings	31.09	Window sills
		31.13	Sun blinds
	Roof finish		Eaves fascia (*dakrand-boeiboord)*
	Miscellaneous	00.01	Slats and battens
		13.01	Foils
	Roof finish	45.01	Profiles ceiling system
		45.02	Ceiling finish
	Floor finish	42.01	Plinths
		43.01	Screed
		43.02	Floor tiling work
		43.02	Data / computer floors
Installations E	**Electrotechnical facilities**	60.02	Solar energy generation
		60.01	Electrical lines
Installations W	**Drains**	52.01	Outdoor sewerage
		52.02	Connecting pipe sewerage
		52.03	Indoor sewerage
		52.05	Rainwater drainage
		52.04	Gutters

	Air treatment	57.01	Ventilation system
		57.02	Air distribution systems
	Heat generation	51.01	Generator domestic hot water
		51.01	Generator heating
	Cold generation	55.01	Generator cooling
	Transmission system	55.03	Cold transmission system
		56.03	Heat transmission system
	Pipelines	53.01	Water pipelines
		54.01	Gas pipelines
Amenities	**Transport amenities**	24.01	Stairs residential buildings
		24.02	Stairs utility buildings
		66.01	Elevator cabin
		66.02	Elevator installation (excluding cabin)
	Kitchen amenities	73.01	Kitchen blocks
		73.02	Counter tops
	Sanitary amenities	74.01	Toilets
		74.01	Urinals
		74.02	Sink combinations
	Terrain	90.03	Pavements
		90.01	Property partitioning
		90.02	Privacy fencing

Do not include:

- Loose cupboards and inventory
- Equipment (among others, formwork, except permanent formwork)
- Electrotechnical installations: communication, IT
- Lighting
- Upholstery
- Carpeting
- Water taps, shower heat, (gas) taps, electrical fixtures
- Buildings, other than separate storage areas
- Terrain facilities, light poles
- Planting

A.2. Building Dimensions

Adaptations to building dimensions compared to Van der Loos (2017) and Klaver (2018):

- The porch flat dimensions have been constructed based on different sources describing reference buildings for post-war porch flats (Vringer & Blok, 1993; Agentschap NL, 2011a; EPISCOPE, 2016). None of these sources describe the complete set of building dimensions, as they focus on aspects regarding energy efficiency or total amounts of material alone. Vringer and Blok (1993) were the only ones describing a number of floors and apartments. However, a design with four floors, 28 apartments, including alternating apartments and basements on the ground floor as quite uncommon and probably has led to an overestimation of energy-loss surfaces in the current and renovation scenarios.

- The internal floor plan by Klaver (2018) is not completely consistent with the external building dimensions in the Sketchup model. As shown in figures 4 and 5, the internal area for the staircase and elevator is longer is the 3D drawing, which makes the two middle apartments longer as well, compared to the four corner apartments. The only impact is that the distribution of window area per apartment may be slightly disproportionate. For the entire building, this should not have a significant impact because the results are calculated per square meter by dividing all impacts evenly.

- The dimensions of doors are based on the Building Decree (Ministry of BZK, 2021). The thickness of window and door frames was estimated at six centimeters based on the door height in the files of Vabi (Vabi Support, 2022a) (2,4 meters) and one of the standard sizes of doors in new buildings (2,34 meter; Verdouw, n.d.). These same dimensions have been used for the external, shared doors in porch flats. The height of internal doors with skylights has been based on the height of the only option in the NMD (Stichting NMD, 2022a).

- Other assumptions: the thickness of windows (note: this does not refer to the glazing), dimensions of showers, the height of ceramic tiles in bathrooms and toilets, the length of stair railings, ventilation grilles, lintels (*lateien*), water seals (*waterslagen*), and windowsills.

- The porch flat is oriented with the front entrance towards the north. An east-west orientation has slightly higher shadow costs (~2 kWh/m2/year for scenario 1.3 - ~8 kWh/m2/year for scenario 0 → less than 5%)

A.3. Energy inputs

Additional assumptions EPA-W

Next to the installations and constructions, some general information is required in EPA-W about the created objects and geometries. The assumptions made for these sections are found below.

Objects

As general information about the constructions, it is necessary to specify construction and renovation year, infiltration level, surface area, and building mass, among others. A summary can be found in table 18. The construction year of porch flats is set at 1955 as the average of 1946 and 1964, which is the period in which the reference post-war porch flats have been built according to Agentschap NL (2011a). The renovation year for porch flats and construction year for *Woongebouw M* are set at 2025, and for the current scenario a small previous renovation has been assumed in 1995. In GPR, however, the construction year of both buildings is set at 2025. Because no existing materials are included in the scenarios, the years before the intervention should not count for the building life span.

It has been assumed there is no night ventilation and that it is unknown whether there are pipelines outside of the thermal shell. For scenario 0, the current situation, it is assumed that there has been one earlier renovation step in 1995, which is why the apartments all use an HR boiler and have mostly double glazing. Furthermore, infiltration level is considered unknown, so fixed Qv10 values based on the construction and renovation years have been used. The mass of *Woongebouw M* is heavy (> 750 kg/m²), as determined by Van der Loos (2017). Finally, porch flats are considered slightly lighter because of the frequent use of hollow concrete floors (Broekhoven, n.d.). The use of this type of floor leads to a building mass of 500-750 kg/m² according to the EPA-W documentation (Vabi Support, 2022b).

Table 18: General building specifications in Objects section of EPA-W

	Porch flats	Woongebouw M	Unknown:
Construction year	1955	2025	
Renovation year	1995, 2025	x	
Building mass (kg/m2)	500-750	>750	
Qv10 measured	No	No	Based on construction/renovation year

Geometry

There are three ways in which the inputs are slightly different from a real-life situation. Firstly, the shadow of the overhang of the balconies on porch flats have not been modelled. This could lead to an overestimation of the amount of heat from solar energy. However, it was left out because it was shown in the EPA-W software that this did not make any difference for a single apartment.

For porch flats, the insulation of the façade would automatically lead to the stairwells to be insulated as well, in any case for cavity wall insulation or external façade insulation. However, it was only possible to specify insulation of the walls of the apartments or to say that they bordered an unheated room with temperatures close to the outdoors. For this reason, the walls next to the stairwells have been modelled to be insulated themselves, instead of the façades at the level of the stairwells. For the material impacts, it has been considered that the façade would be insulated. Similarly, the inner stairwell in *Woongebouw M* is not heated. However, the only heat-loss surfaces are the floor and roof, all other areas are next to the apartments. For this reason, the stairwell has also not been included as a heat-loss surface for apartments in *Woongebouw M*.

Complete overview energy inputs and justifications

All inputs used for the energy calculations in EPA-W can be found in the following sheets in the Excel document *Building*:

- EPA-W installaties: All inputs for the installations
- Portiekflat dimensions: Dimensions used for the objects in EPA-W for the renovation scenarios
- Woongebouw dimensions: Dimensions used for the objects in EPA-W for the rebuilding scenarios
- Electricity impact reduction: Calculations for shadow cost reduction percentages per life span
- DH impact reduction: Estimation of impact of alternative sources for district heating based on an LCA study (Bartolozzi et al., 2017)

A.4. Material inputs

Additional assumptions GPR

The material selection has been based on Klaver (2018). The conventional (2.1) and sustainable (2.2) new building scenarios are copied from the *Basis* and *Duurzaam 2* variants by Klaver (2018). Subsequently, the materials in the renovation scenarios have been kept the same as the conventional scenario as much as possible.

Additional assumptions and deviations from Klaver (2018):

- The parcel borders are assumed to span only the surface of the building plus the areas at the ground floor below balconies on higher floors, so there is only a small paved area.
- Central stairs and stair railings have been added instead of the internal stairs listed by Klaver (2018).
- For consistency, skylights have also been added to wooden internal door frames in the sustainable scenario to substitute the steel door frames in the conventional scenario and the doors in all scenarios have been made the same size.
- Because the insulation in the porch flats is added later, different types were selected.
    - 1.1 Minimal renovation: Cavity wall insulation
    - 1.2 Standard renovation: Inner wall insulation
    - 1.3 Extensive renovation: Façade insulation
- GPR assumes individual ventilation systems, for which the amount is derived from the usable floor area. In EPA-W the ventilation systems are assumed to function for an entire column. This leads to 8 ventilation systems in porch flats and 6 in the new buildings. The impact in GPR may therefore be slightly overestimated.

Complete overview material inputs and justifications

All inputs used for the material calculations in GPR Gebouw can be found in the following sheets in the Excel document *Building*:

- Portiekflat dimensions: Dimensions used for the material amounts in GPR
- Woongebouw dimensions: Dimensions used for the material amounts in GPR
- Portiekflat materials: Materials entered in GPR Gebouw for the renovation scenarios
- Woongebouw materials: Materials entered in GPR Gebouw for the rebuiding scenarios

B. Results

B.1. Energy shadow costs without reduced electricity impacts

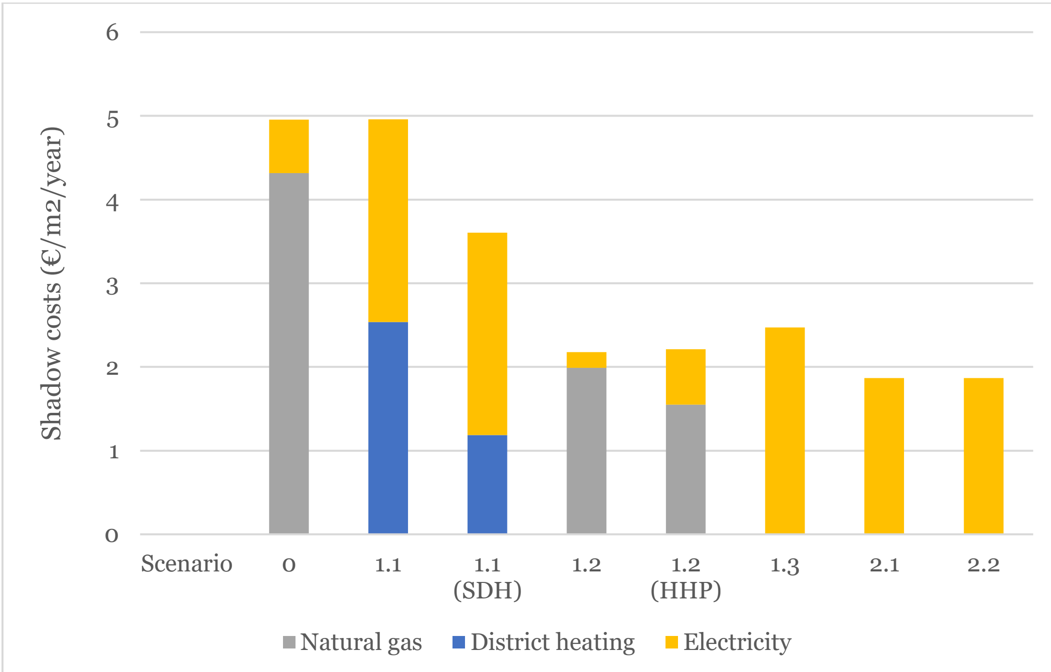


Figure 23: Shadow costs from different energy carriers per scenario per square meter per year, without reduced electricity impacts. 0: Business as Usual; 1.1: Minimal renovation (SDH: with renewable district heating sources), 1.2 Standard renovation (HHP: with a hybrid heat pump), 1.3 Extensive renovation, 2.1 New building with conventional materials, 2.2 New building with sustainable materials

B.2. Shadow costs of building components

Table 19: Contribution analysis materials: All components responsible for more than 5% of MPG

Ranking	1		2		3		4	
Unit / Scenario	MPG (€/m²/yr)	Perc. of MPG	MPG (€/m²/yr)	Perc. of MPG	MPG (€/m²/yr)	Perc. of MPG	MPG (€/m²/yr)	Perc. of MPG
1.1 Minimal Renovation (1.1a + 1.1b)	HR++ Glazing		District heating deliver sets		Heat distribution pipes		Radiators	
	0,037	37,60 %	0,027	27,7 %	0,01	14,4 %	0,005	5,4 %
1.2a Standard Renovation with HR boiler	HR++ Glazing		HR boiler heating + DHW		Heat distribution pipes		Indoor facade insulation	
	0,046	33,9 %	0,035	25,6 %	0,01	7,8 %	0,01	7,3 %
1.2b Standard Renovation with HHP	HR++ Glazing		Hybrid heat pump heating + DHW		Heat distribution pipes		Indoor wall insulation	
	0,046	28,80 %	0,059	36,9%	0,01	6,6 %	0,01	6,2 %
1.3 Extensive Renovation	Triple glazing		Electric boilers		Sunscreens		Air-sourced heat pump	
	0,051	13,0 %	0,046	11,7 %	0,043	11,0 %	0,015	6,6 %
2.1 Conventional New building	Wide slab floors + pressure layer		Triple glazing		Electric boilers		Sunscreens	
	0,1033	21,3 %	0,0343	7,1 %	0,0328	6,8 %	0,0291	6,0 %
2.2 Sustainable New building	Channel plate floors		Triple glazing		Electric boilers		Sunscreens	
	0,0458	12,7 %	0,0343	9,1 %	0,0328	9,1 %	0,0291	8,0 %

Shadow costs of PV:

- Porch flats (460 m² PV; gross floor area 2304 m²): 0,454 €/m²/year
- Woongebouw M (510 m² PV; gross floor area 3828 m²): 0,303 €/m²/year

B.3. Environmental Impacts

Table 19: Environmental impacts
Life span 75 years, no improved electricity, no PV

Table 20: Normalized environmental impacts
Life span 75 years, no improved electricity, no PV

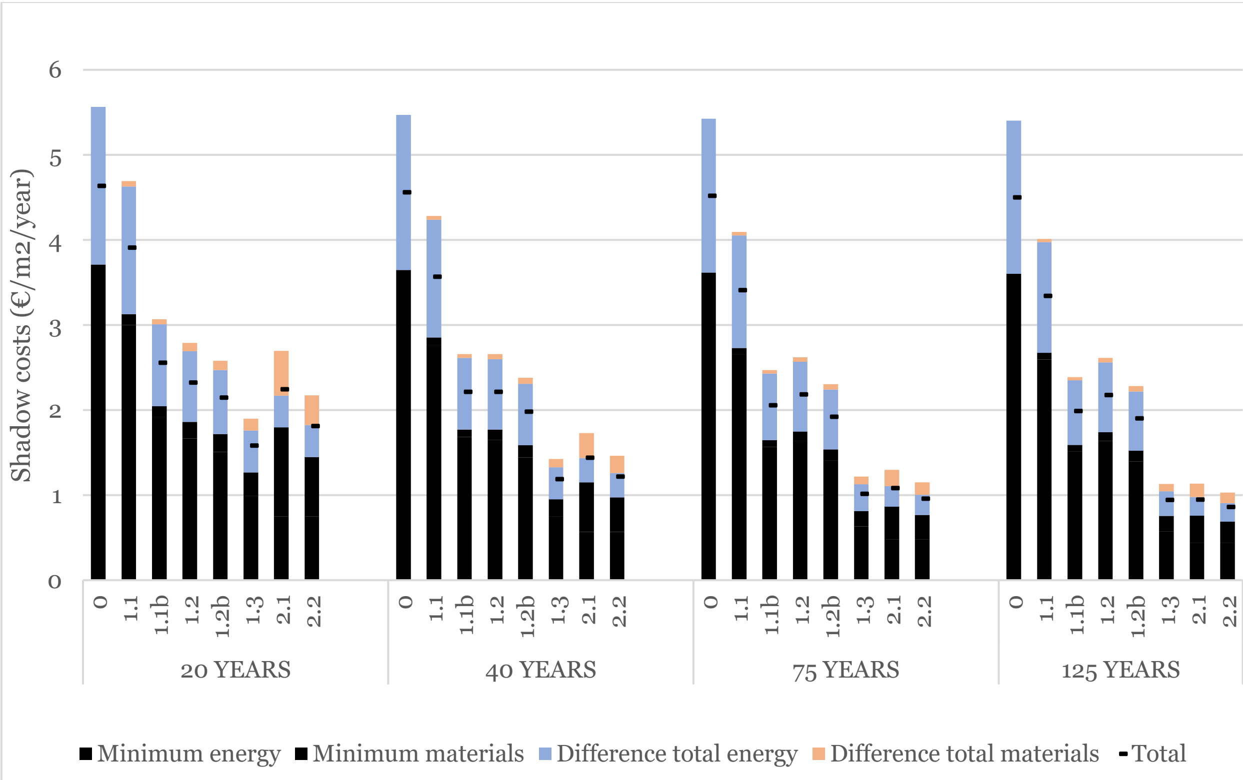
0: Business as Usual; 1.1: Minimal renovation (b: with renewable DH sources), 1.2 Standard renovation (HHP: with a hybrid heat pump), 1.3 Extensive renovation, 2.1 New building with conventional materials, 2.2 New building with sustainable materials

Impact category	Units	0	1.1	1.1b	1.2	1.2 HHP	1.3	2.1	2.2
Abiotic depletion	kg antimony eq. / m2BVO / yr	5,00E-01	3,53E-01	2,01E-01	2,30E-01	1,89E-01	4,95E-02	5,31E-02	4,67E-02
- Abiotic depletion (non fuel)	kg antimony eq. / m2BVO / yr	4,99E-06	7,01E-05	6,96E-05	2,58E-05	3,69E-05	1,23E-04	9,89E-05	2,00E-04
- Abiotic depletion (fuel)	kg antimony eq. / m2BVO / yr	5,00E-01	3,52E-01	2,01E-01	2,32E-01	2,71E-01	7,55E-02	7,28E-02	6,63E-02
Acidification	kg SO2 eq. / m2BVO / yr	1,62E-02	2,50E-02	2,10E-02	1,18E-02	1,29E-02	2,28E-02	2,67E-02	2,43E-02
Eutrophication	kg PO4--- eq. / m2BVO / yr	3,99E-03	6,53E-03	5,58E-03	2,69E-03	2,99E-03	5,93E-03	6,67E-03	6,12E-03
Global warming (GWP100)	kg CO2 eq. / m2BVO / yr	5,61E+01	4,10E+01	2,41E+01	2,62E+01	3,04E+01	1,04E+01	1,09E+01	9,76E+00
Ozone layer depletion (ODP)	kg CFC-11 eq. / m2BVO / yr	3,02E-06	2,07E-06	1,15E-06	1,44E-06	1,68E-06	4,02E-07	5,01E-07	4,27E-07
Human toxicity	kg 1,4-DCB eq. / m2BVO / yr	1,06E+01	8,37E+00	5,21E+00	5,54E+00	6,39E+00	2,94E+00	3,15E+00	2,69E+00
Fresh water aquatic ecotox.	kg 1,4-DCB eq. / m2BVO / yr	2,29E-02	4,88E-02	4,38E-02	2,19E-02	2,36E-02	5,35E-02	7,33E-02	6,00E-02
Marine aquatic ecotoxicity	kg 1,4-DCB eq. / m2BVO / yr	5,71E+03	3,82E+03	2,06E+03	2,65E+03	3,12E+03	5,86E+02	5,57E+02	5,10E+02
Terrestrial ecotoxicity	kg 1,4-DCB eq. / m2BVO / yr	3,84E-02	1,27E-01	1,24E-01	1,65E-02	8,49E-03	1,29E-01	1,21E-01	1,07E-01
Photochemical oxidation	kg ethylene eq. / m2BVO / yr	5,36E-03	4,38E-03	2,78E-03	2,96E-03	3,43E-03	2,21E-03	3,58E-03	2,56E-03

Impact category	Units	0	1.1	1.1	1.2	1.2 HHP	1.3	2.1	2.2
Abiotic depletion total	kg antimony eq. / m2BVO / yr	1,39E-09	9,81E-10	5,59E-10	6,40E-10	5,27E-10	1,38E-10	1,48E-10	1,30E-10
- Abiotic depletion (non fuel)	kg antimony eq. / m2BVO / yr	1,39E-14	1,95E-13	1,93E-13	7,17E-14	1,03E-13	3,42E-13	2,75E-13	5,57E-13
- Abiotic depletion (fuel)	kg antimony eq. / m2BVO / yr	1,39E-09	9,80E-10	5,59E-10	6,46E-10	7,52E-10	2,10E-10	2,02E-10	1,84E-10
Acidification	kg SO2 eq. / m2BVO / yr	5,04E-14	8,01E-14	6,78E-14	3,77E-14	4,01E-14	7,96E-14	1,32E-13	1,04E-13
Eutrophication	kg PO4--- eq. / m2BVO / yr	2,95E-14	4,83E-14	4,12E-14	1,99E-14	2,21E-14	4,38E-14	4,93E-14	4,53E-14
Global warming (GWP100)	kg CO2 eq. / m2BVO / yr	1,32E-12	9,62E-13	5,66E-13	6,15E-13	7,13E-13	2,45E-13	2,57E-13	2,29E-13
Ozone layer depletion (ODP)	kg CFC-11 eq. / m2BVO / yr	5,25E-15	3,60E-15	1,99E-15	2,49E-15	2,92E-15	6,98E-16	8,68E-16	7,40E-16
Human toxicity	kg 1,4-DCB eq. / m2BVO / yr	1,86E-13	1,47E-13	9,11E-14	9,69E-14	1,12E-13	5,15E-14	5,52E-14	4,71E-14
Fresh water aquatic ecotox.	kg 1,4-DCB eq. / m2BVO / yr	1,12E-14	2,39E-14	2,15E-14	1,07E-14	1,16E-14	2,62E-14	3,59E-14	2,94E-14
Marine aquatic ecotoxicity	kg 1,4-DCB eq. / m2BVO / yr	1,12E-11	7,46E-12	4,03E-12	5,18E-12	6,10E-12	1,15E-12	1,09E-12	9,96E-13
Terrestrial ecotoxicity	kg 1,4-DCB eq. / m2BVO / yr	1,43E-13	4,70E-13	4,62E-13	6,14E-14	3,15E-14	4,78E-13	4,50E-13	3,97E-13
Photochemical oxidation	kg ethylene eq. / m2BVO / yr	5,59E-14	4,57E-14	2,90E-14	3,09E-14	3,58E-14	2,30E-14	3,74E-14	2,68E-14

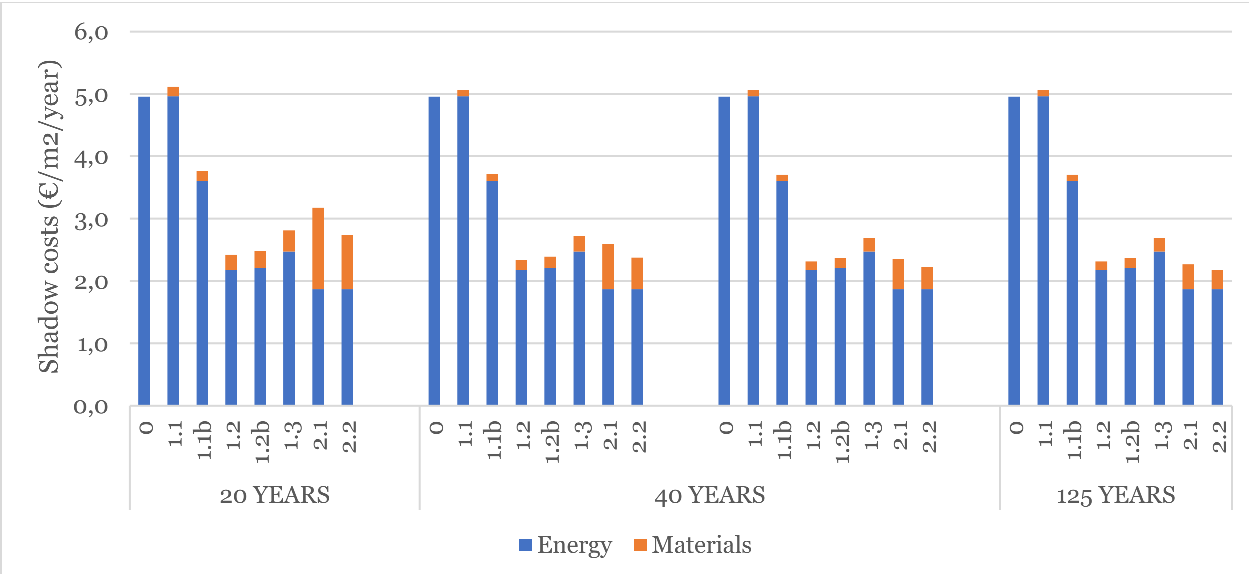
B.4. Sensitivity ranges

Figure 24: Sensitivity range of energy and materials for all life spans and scenarios. 0: BAU; 1.1: Minimal renovation (b: with renewable DH sources), 1.2 Standard renovation (b: with a hybrid heat pump), 1.3 Extensive renovation, 2.1 New building with conventional materials, 2.2 New building with sustainable materials



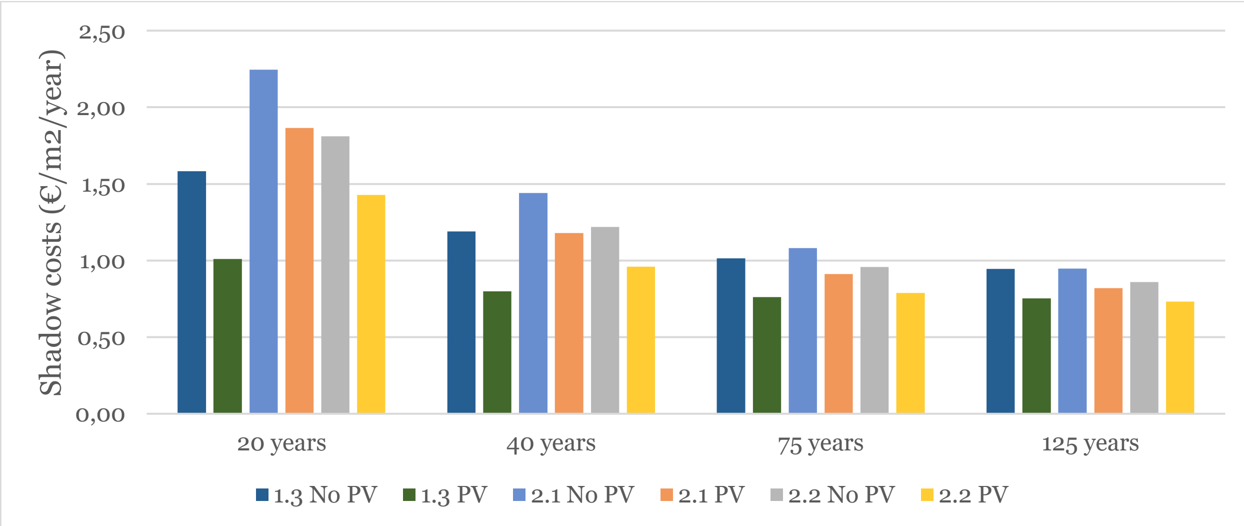
B.5. Shadow costs without electricity impact reduction

Figure 25: Shadow costs from energy and materials combined for all life spans without reduced environmental impacts from electricity. 0: BAU; 1.1: Minimal renovation (b: with renewable DH sources), 1.2 Standard renovation (b: with a hybrid heat pump), 1.3 Extensive renovation, 2.1 New building with conventional materials, 2.2 New building with sustainable materials



B.6. Solar panels for different life spans

Figure 26: Shadow costs of Extensive Renovations, Conventional New buildings and Sustainable New buildings for different life spans, with reduced electricity impacts. 1.3 Extensive renovation, 2.1 New building with conventional materials, 2.2 New building with sustainable materials. PV: With solar panels, No PV: Without solar panels



C. Excel file guide

All the calculations have been made in an Excel file, which is added to the current document as an additional, digital appendix. The file is appendix C, this page is only the guide.

Please contact the daily thesis supervisor (Arjen Meijer) to gain access to the data.

The Excel file has been built up in the following way:

<u>Inputs</u>

1. Scenarios	Scenario overview, comparable to table 9.
2. Portiekflat Dimensions	Dimensions used for the objects in EPA-W and material amounts in GPR for the renovation scenarios
3. Portiekflat Materials	Materials entered in GPR Gebouw for the renovation scenarios (including calculation for number of individual heat pumps, see *Warmteopwekkingsinstallaties W-bouw*)
4. Woongebouw Dimensions	Dimensions used for the objects in EPA-W and material amounts for the rebuilding scenarios
5. Woongebouw Materials	Materials entered in GPR Gebouw for the rebuilding scenarios (including calculation for number of individual heat pumps, see *Warmteopwekkingsinstallaties W-bouw*)
6. EPA-W Installations	All inputs for the installations

<u>Results energy and materials</u>

7. EPA Results	Energy use per scenario/energy carrier/application. Also includes calculations for results per m2 and figures for contribution analysis energy.
8. MPG Results	Environmental emissions per impact category per scenario
9. MPG Components	Data from GPR Gebouw to create contribution analysis materials

<u>Calculations</u>

10. Electricity impact reduction	Calculations for shadow cost reduction percentages per life span
11. DH Impact reduction	Estimation of impact of alternative sources for district heating based on an LCA study (Bartolozzi et al., 2017)
12-15 MPG⁺ 20/40/75/125	MPG⁺ results for all scenarios including all intermediate calculation steps
14.1 MPG⁺ 75 PV	MPG⁺ results (only life span 75 years) for all scenarios with a full roof of PV panels
14.2 MPG⁺ 75 Energy carriers	MPG⁺ results (only life span 75 years) for scenarios where different energy carriers have been applied to the extensive renovation building
16. Normalization	Environmental impacts per category normalized to World 1995 normalization factors
17. Results, figures, tables	MPG⁺ results used to create the figures and tables

Abstract

The built environment is responsible for a substantial amount of energy use and greenhouse gas emissions. To improve energy efficiency and reduce environmental impacts, buildings can be renovated or replaced with more energy-efficient alternatives. Although new buildings often cause less environmental impacts from operating energy use, the higher material requirements cause additional environmental impacts. Housing corporations own more than 25% of residences in the Netherlands and need to decide between different energy efficiency improvement methods for their building stock. Therefore, the proposed thesis has the following research question: *What are optimal building renovation or replacement solutions for housing corporations to improve energy efficiency and reduce environmental impacts in the context of the Dutch climate goals?* Environmental impacts of materials and energy have been calculated according to the MPG^{+} method, which follows the life cycle assessment approach. The results show that extensively renovated porch flats and new buildings lead to similar amounts of environmental impacts if both use a collective heat pump and are insulated according to nearly-zero energy building standards. The comparison between the environmental impacts of extensive renovations and building replacement depends on the expected building life span after the intervention, the quantity of solar panels, and the use of sustainable materials. Renovations including lower energy efficiency levels or fossil energy sources cause more environmental impacts. The MPG^{+} method aligns with the Dutch policy context but lacks transparency, completeness, and data certainty. The alternative scenarios in this study are compared per square meter, so the overall environmental impacts may increase if the relative apartment size per resident is greater in the new building. Considering the Climate Agreement, the housing crisis, and many uncertainties, extensive renovations are recommended as a no-regret solution for housing corporations.