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THE POTENTIAL OF COUPLING THE CIRCULAR ECONOMY AND ENERGY TRANSITION IN THE BUILT ENVIRONMENT

A mixed methods study to the potential environmental impact reduction of applying different Circular Economy strategies within Net-Zero Energy Building (NZEB) refurbishment solutions

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Abstract

Net-Zero Energy Building (NZEB) refurbishments are proposed as one of the solutions to refurbish the Dutch existing building stock and, thereby, stimulate the (low carbon) Energy Transition within the built environment. Taking into account the increasing share of 'embodied' emissions due to the improved operational performance by these solutions becomes important to further improve the sustainability of the built environment. Therefore, the Circular Economy is expected to encourage this by reducing fossil fuel use and greenhouse gas emissions. However, literature is inconclusive regarding the complementarity of these two paradigms. Therefore, this study aims to expand the body of knowledge on implementing Circular Economy strategies within Energy Transition measures by studying whether and how such strategies are already applied within NZEB refurbishments and investigate the potential environmental impact reduction of applying different Circular Economy strategies in these solutions. By using an exploratory sequential mixed methods design, this study first, qualitatively analyzed the application of Circular Economy strategies in NZEB refurbishments within seven construction companies in The Netherlands, through semi-structured interviews. Subsequently, it quantitatively assessed the potential environmental impact reduction of applying different Circular Economy strategies within NZEB refurbishments by using Life Cycle Assessment (LCA) on a case study. Regarding the first, the findings show that despite developments towards Circular Economy implementation are slowly occurring, the Circular Economy and Energy Transition still seem to be two separate worlds. More inter-organizational or strategic collaboration is expected to reduce barriers to implement Circular Economy strategies. Regarding the latter, applying Circular Economy strategies can reduce the environmental impacts of NZEB refurbishments. Especially the use of secondary materials results in the least environmental impacts, however, credits for potential benefits beyond the system boundary are found to be highest by using bio-based materials with energy recovery by wood incineration. Despite this controversial finding, it is expected that different allocation methods would influence the results significantly and that the used cut-off approach from the European CEN standards does not incentivize companies to design for multiple product cycles in light of a Circular Economy. Therefore, besides the use of secondary materials, companies should be encouraged to design products for future use.

Keywords: Net-Zero Energy Building, Circular Economy, Energy Transition, Environmental impact, Life Cycle Assessment.

Executive Summary

Introduction

Global crises, such as resource scarcity and human-induced climate change led to the emergence of several paradigms to combat these by reducing the use of fossil fuels and greenhouse gas (GHG) emissions. The (low carbon) Energy Transition (ET) encourages the use of renewable energy sources and efficiency measures, whereas the Circular Economy (CE) stimulates the reduction of fossil fuel use and GHG emissions by regenerating natural systems, designing out waste and pollution and keeping products and materials in use. In other words, it decouples economic growth from finite resource use by narrowing, slowing and closing resource loops. Although both paradigms pursue equal goals, the foundation and scope differ. Therefore, some scholars state an integration of these would help to achieve their goals, whereas others have a moderate view and consider more caution.

In The Netherlands, an enormous existing building stock exists that has to be refurbished due to developments of quality and sustainability standards. Therefore, to accelerate the ET within the built environment, Net-Zero Energy Building (NZEB) refurbishments are proposed, where buildings (residential buildings in this study) are refurbished to become energy neutral and will not use natural gas anymore. In other words, by intensive insulation and use of energy efficient building systems and installations, the building's heat demand is reduced and it [the building] generates as much (or more) energy as required for space and water heating and the use of electrical appliances on a yearly basis. Although NZEB refurbishments focus on providing comfortable, affordable and energy efficient houses, the share of 'embodied' emissions due to the increase of operational performance and additional materials can increase. Therefore, it was expected that the implementation of CE strategies would be important to increase the environmental performance of these refurbishment solutions and, therefore, stimulate the ET. Given this context, the following research questions were formulated:

1. *How and why are CE strategies already being taken into account in NZEB refurbishments?*

2. *How does the application of different CE strategies affect the environmental impact of NZEB refurbishments?*

Theory

Literature regarding the relevance and implementation of ET measures, as well as CE strategies in the construction sector was consulted. Furthermore, literature was also consulted regarding the measurement of environmental impacts and its relation to the CE. From literature, it was found that 22% of the Dutch final energy use and its respective GHG emissions was caused by the residential sector in 2017, due to building and non-building related energy use (RVO, 2018). To stimulate the ET in this sector, technology and design are of crucial importance (IEA, 2019), which can include several passive and active technological measures, such as extra insulation and the application of a heat pumps, respectively (Amoruso et al., 2018). These technological measures can be part of so-called building adaptation projects to improve the existing building conditions as well as extending the effective service life of them (Shahi et al., 2020). NZEB refurbishments can be classified into these building adaptation projects, where a distinction can be made between all-electric solutions versus the connection to a district heating system as well. Regarding the first, all energy that is used for space and water heating and the use of electric appliances comes from electricity, whereas for the latter, energy for space and water heating comes from sustainable produced heat from a district heating system. Therefore, this solution is actually a Net-Zero Electricity solution and is often more suitable for stacked or high-rise buildings.

Although the concept of the CE has evolved, it is nowadays often associated with decoupling economic growth from finite resource use (Reike et al., 2018; Wiprächtiger et al., 2020), by cycling materials throughout supply chains (Geissdoerfer et al., 2017). It is often operationalized by strategies according to the waste hierarchy, from which Reike et al. (2018) have developed a holistic typology of 10 Value Retention Options (VROs) to prioritize CE strategies.

Since the Dutch construction sector uses enormous amounts of materials, which led the sector to be responsible for more than 35% of all waste produced in The Netherlands (CE Delft, 2015), resulting in GHG and other emissions, the implementation of CE strategies was found critical to react to the planetary crises. Despite standardized practices and methods are lacking, many strategies have been proposed to implement the CE in the construction sector. Amongst others, Eberhardt et al. (2020) classified 16 Design and Construction (D&C) strategies as a result of their systematic literature review that can relate to the strategies according to the waste hierarchy. Despite they found a development towards more preventive measures, rather than end-of-pipe solutions, they also noticed a slow uptake within the sector, which could be caused by a lack of knowledge regarding the environmental benefits of the different strategies. Additional barriers to implement CE strategies within the sector have been found by Trabulsi and Sofipour (2020). For example, the crucial aspect of strategic collaboration between supply chain actors to implement CE strategies could be hampered by a general perception of negative attitudes towards reused materials by tenants, lack of logistics and recovery facilities and the procedures for quality assurance and warranties. They further found a crucial role for real estate developers to stimulate strategic collaboration between supply chain actors.

Despite the need for clear considerations and measurements to prioritize sustainable solutions, there is much debate about quantitative measures within scientific and public domains. For example, Corona et al. (2018) mentioned the following challenges regarding circularity metrics: difficulty to include all sustainability dimensions, evaluate the scarcity of materials, underrepresenting multiple cycles' complexity and the consequences of down-cycling. Although these challenges, quantitative measurements including environmental impacts, material flows and preservation of value are all important to comply with a sustainable CE. Since buildings cause various environmental impacts throughout their life time (Ingrao et al., 2018), environmental management techniques, such as Life Cycle Assessment (LCA) are proposed to assess the potential environmental impact of products or services along its service life. LCA is found to be a promising methodology to assess the environmental impact in relation to CE practices, since it can account for various impact categories relevant to a CE (Niero & Olsen, 2016), trade-offs between life cycle stages (Ingrao et al., 2018) and avoided production of virgin material (Genovese et al., 2017). However, others state that the linear nature of LCA could limit its potential to take into account CE practices (Dieterle et al., 2018).

Methodology

This study first, tried to understand the potential to adopt CE strategies in refurbishments to NZEB all-electric and NZEB plus district heat and second, explain how the application of different CE strategies affected the environmental impact of such refurbishment solutions. It used an exploratory sequential mixed methods design, where qualitative data was collected and analyzed first, before quantitative data was collected and analyzed. To answer research question 1, seven semi-structured interviews were conducted from either construction companies that had a contractor role or a supplier role, which could be more classified as partner company. All companies were involved in NZEB refurbishments and interviewees had different roles within the company. Data was transcribed and coded using Nvivo 12 Pro, using both a deductive and inductive approach.

To answer research question 2, a LCA was conducted based on a case study from an all-electric refurbishment proposition, to compare a linear with a circular design. It followed the European CEN standards, EN 15804 and 15978, for LCAs on buildings and was modelled with One Click LCA, developed by Bionova Ltd. The goal of the LCA was twofold: (1) identify and discuss how the different impact categories, life cycle stages as well as building elements contribute to the total environmental life cycle impact of a NZEB refurbishment (all-electric), while comparing a linear with a circular design and, (2) investigate how different CE strategies may affect the environmental life cycle impacts of NZEB refurbishments. The functional unit (FU) was as follows: *providing a climate-controlled space of a residential terraced house of 148,77 m^2 gross floor area with a maximum heat demand of 50 kWh / m^2 / year to be used over a period of 50 years under standard climate conditions within The Netherlands and standard use of the building according to Dutch standards.* The difference between the linear and circular design was the use of a circular building envelope based on a wooden frame construction, rather than structural insulated panels (SIP) and different D&C strategies. The study encompassed all phases from cradle-to-grave according to the EN 15978; manufacture of construction materials (A1-3), construction processes (A4-5), use (B1-7) and the end-of-life (C1-4). However, building assessment modules B6-7 were excluded. Furthermore, potential net benefits beyond the system boundary due to reuse, recycling and energy recovery (module D) were also taken into account, but reported separately. This is more associated with a cradle-to-cradle approach. The cut-off approach, prescribed by the CEN standards was used as allocation method, including potential credits in module D due to net benefits by providing materials for further use beyond the system boundary. The life cycle inventory (LCI) consisted of all collected data regarding the life cycle stages of the refurbishment proposition converted to the functional unit. CML – IA 2012 was used as impact assessment methodology and following impact categories were included: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP) and total use of primary energy (TUPE) (ex. used as raw materials). Besides the calculation of mid-point indicators, impacts were weighted according to the shadow costs weighting factors, often used for the construction sector. Furthermore, a sensitivity analysis was conducted to compare three additional CE scenarios: (1) the use of bio-based materials, (2) use of secondary materials and (3) lifetime extension of the materials by reusing them at the end-of-life. Also, the life cycle gaps (LCG) were calculated to improve the interpretation of the results in light of a CE.

Results

Research question 1

- A NZEB refurbishment can include several combinations of (technological) measures, however, it is always a combination of measures to the building envelope for increased insulation and installations. A NZEB all-electric solution is more commonly realized than a NZEB plus district heat solution.

- Various Design & Construction (D&C) strategies were applied by the interviewees to realize their NZEB refurbishment solution, although material selection/substitution was mostly mentioned, followed by prefabrication, reusing existing buildings/components/materials and use of secondary materials. No consensus regarding the environmental performance of different materials led to different material selections by the interviewees.
- The challenges interviewees experienced regarding NZEB refurbishments have an institutional, economic and cultural nature and it was found that these could influence each other. For example, the inconsistent policies of corporations that were experienced by the interviewees hampers industrialization, which increases costs. Rising costs limit the marketability of NZEB refurbishment solutions, which reduces the continuous workflow. Such a continuous workflow was mentioned as required to build factories for industrialization. It seems that a positive feedback loop is at play.

- The Circular Construction Economy (CCE) is slowly developing and CE implementation is lacking within the sector in general and in NZEB refurbishments in particular, despite the many discussions within the sector. However, from the applied CE strategies, higher order and shorter loop VROs predominate.
- From the interviewees, it became clear that the ET and CE are still two separate worlds, which can be due to first, a negative or neutral perspective on the importance of a CE for accelerating and achieving ET targets and second, no consensus regarding the definition of a CCE.
- Many barriers were experienced by the interviewees to implement CE strategies within NZEB refurbishment, more than drivers. They are classified in institutional, market and cultural barriers, which can interact with each other. Market barriers were found to be predominate.

Research question 2

- The circular design had lower impacts in all categories with the greatest difference in eutrophication potential (EP) between both designs, due to the use of galvanized steel for the roof and mortar for the external façade within the linear design.
- Cradle-to-gate impacts (A1-3) contributed most in almost all categories of both designs, with the biggest difference in photochemical ozone creation potential (POCP) due to the use of expanded polystyrene (EPS) and polyisocyanurate (PIR) in the linear design.
- Potential external impacts due to the avoided emissions beyond the system boundary (module D) were found highest for the linear design, due to the default end-of-life scenarios per material type, instead of additional CE strategies. Still, the total impacts were lower for the circular design.
- A difference of 19% was found between both designs according to the overall weighted impacts, whereas global warming potential (GWP) and acidification potential (AP) contributed most to the overall environmental impact, with a contribution of 56% and 26%, respectively.

- Although building systems and installations contribute significantly to the most contributing categories, the benefits beyond the system boundary were rather low relative to other building elements.
- The biggest differences between both designs were found within the roof, due to the use of galvanized steel and PIR insulation, which is replaced by bio-based and low impact materials within the circular design that also have additional benefits beyond the system boundary. For the external walls and façade, EPS insulation versus bio-based and rock wool insulation led to the difference between both designs.

- The environmental impact for GWP in kg CO_2-eq./FU between the different CE scenarios within the sensitivity analysis, excluding module D, did not differ significantly. However, the use of secondary materials led to the greatest environmental benefits in the current product system, since these come free of burden.
- The effect of different CE strategies depends on the scope of the analysis, cradle-to-grave or cradle-to-cradle by including the net benefits and loads beyond the system boundary. The use of bio-based materials with energy recovery by wood incineration at the end-of-life led to the greatest potential environmental benefits beyond the system boundary, although extending the lifetime of materials by reuse was a close second. However, from the life cycle gap analysis (LCG-A), the bio-based scenario was preferable and, therefore, fit better into a CE perspective according to the allocation method used. Whether this is justified is discussed in the next section.

Discussion

The slow uptake of CE strategies within NZEB refurbishments, especially regarding building systems and installations, could be explained by the negative or neutral attitude towards the importance of a CE for achieving the ET or by the fact that no consensus exists about the definition of a circular economy within the construction sector. However, it could also be explained by the lack of inter-organizational or strategic collaboration between supply chain actors, such as amongst corporations, between corporations and other market actors and amongst market actors. This lack of strategic collaboration derived from the experienced barriers to apply CE strategies within NZEB refurbishments from the interviewees, which interact with each other. However, according Trabulsi & Sofipour (2020), these collaborations are of crucial importance, since CE implementation in itself requires a systems perspective that goes beyond the boundaries of single organizations and, furthermore, given the fragmented nature of the construction sector with many different actors involved, such collaborations become particularly important. Furthermore, corporations could play a more active role in incentivizing such collaborations.

This study also found that the implementation of CE strategies could reduce the environmental impact of NZEB refurbishments. However, the preferred strategies to focus on, depend on the scope of the analysis. In other words, whether only the current system is taken into account or also potential subsequent product systems. From the results, the use of secondary materials led to the greatest environmental impact reduction in the current product system, but the study from EIB and Metabolic (2020) found that the theoretical possible supply of secondary materials is too low compared to the demand. Therefore, additional strategies are required. However, the use of bio-based materials with energy recovery by wood incineration at the end-of-life led to the highest potential net benefits beyond the product system, although the difference with reusing materials at the end-of-life was not significant. This finding contradicts the literature regarding the order of value retention options, where it is assumed that energy recovery is worse than recycling or reuse. However, this result can be explained by the allocation method used prescribed by the European CEN standards, which provide extra credits for the avoided production beyond the system boundary by material incineration at the end-of-life that provide 'greener fuels', depending on what is being substituted and how efficiently. Furthermore, since credits are provided now, whereas the potential 'benefits' are in the future, this approach leads to high uncertainty due to the developments of sustainable energy productions. Also, the use of this allocation approach does not incentivize to design product for multiple product cycles. Because of these mentioned reasons, the use of this allocation method from a CE perspective is questionable.

Managerial and policy implications

- From this study, it became clear that data availability was a limitation to assess the environmental impact of NZEB refurbishments and the potential application of CE strategies. Since data submission by companies to organizations that manage databases is a voluntary activity, a lot of potentially useful data is not available for LCA practitioners, especially regarding building systems and installations, despite their major contribution to the impacts. Construction companies and their suppliers should be incentivized to first, assess the impacts of their products and materials within and beyond the product system and second, to submit the results to useful databases. Stroomversnelling could play an active role in this by stimulating knowledge dissemination regarding the importance of knowledge creation and sharing by supply chain actors. To enhance the potential and credibility of this, close collaboration with organizations that manage these databases, such as the foundation of the National Environmental Database (NMD), could help.

- Corporations are found critical actors to incentivize innovations towards a CE. Furthermore, better strategic collaboration amongst corporations and between corporations and other market actors could reduce the barriers for CE implementation, particularly regarding quality assurance and warranty procedures as well as circular supply chain factors, e.g. logistics and recovery responsibilities. Stroomversnelling could play a more active role in satisfying their common needs, for example, by stimulating the innovative use of software tools, such as building information modelling (BIM) to fit CE needs, quality assurance and warranty procedures could by improved, which was a major barrier for CE implementation.

- To use the full potential of CE strategies within NZEB refurbishments to reduce environmental impacts, it is important to broaden and shift the focus of CE applications. Given the major impacts of building systems and installations, compared to their CE potential in subsequent life cycles, it is relevant to stimulate the sector to take more action regarding circular applications for these building elements. Stroomversnelling could actively involve these actors, such as manufacturers of building systems and installations. Also, the allocation method prescribed by the European standards, EN 15804/15978 cut-off approach, mostly incentivize companies to use secondary materials, instead of also designing products for multiple product cycles. Therefore, in light of a CE perspective, companies should also be incentivized to design products for future use, which is questionable by use of this allocation procedure.

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List of Abbreviations

Abbreviation	***Explanation***
AP	Acidification potential
BIM	Building information modelling
CCE	Circular Construction Economy
CE	Circular Economy
CEN	European Committee for Standardization
CFF	Circular Footprint Formula
CO_2	Carbon Dioxide
CSC	Circular supply chain
DH	District heat
ECI	Environmental costs indicator
EP	Eutrophication potential
EPD	Environmental Product Declaration
EPS	Expanded polystyrene
ET	Energy Transition
FU	Functional unit
GHGs	Greenhouse gases
GPS	Graphite polystyrene
GWP	Global warming potential
LCC	Life cycle cost
LCG	Life cycle gap
LCG-A	Life cycle gap analysis
LCSA	Life cycle sustainability assessment
LD	Linearly degressive
MPG	Environmental Performance of Buildings
NMD	National Environmental Database
NO_x	Nitrogen oxides
NOM	Net-Zero Energy Building
NZEB	Net-Zero Energy Building
ODP	Ozone depletion potential
PEF	Product Environmental Footprint
PIR	Polyisocyanurate
POCP	Photochemical ozone creation potential
SBK	Foundation for Building Quality
SIP	Structural insulated panel
TNO	Netherlands organization for applied scientific research
TUPE	Total use of primary energy
VROs	Value Retention Options

1. Introduction

The increasing demand for raw materials, including the combustion of fossil fuels for energy and material production, such as coal, natural gas and oil causes greenhouse gases (GHGs) to be emitted, including carbon dioxide (CO_2). These emissions have a linear effect on what scientists and the public call global warming, which leads to increased climate change (IPCC, 2014). Besides, finite resources are getting scarcer, which is a result of the so-called 'take-make-waste' economy, where precious materials are being wasted in supply chain systems (Ellen MacArthur Foundation, 2019). Resource scarcity, increasing GHG emissions and its resulting climate change are therefore regarded by scientists as mainly human-induced problems (IPCC, 2014; Jackson, 2009).

Different paradigms emerged in response to this planetary crisis to steer more sustainable practices. The low carbon energy transition (ET) is one of such, which encourages the use of renewable energy sources and energy efficiency measures to reduce the use of fossil fuels and the emission of GHGs (Chen & Kim, 2019; PBL, 2016). According to the IEA[1] and IRENA[2] (OECD/IEA & IRENA, 2017), the production and use of energy is responsible for around two-thirds of the global GHG emissions and the energy sector is therefore put under pressure to combat climate change.

Furthermore, the Circular Economy (CE)[3] is a different paradigm to reduce GHG emissions and the use of fossil fuels (Ellen MacArthur Foundation, 2015). However, the CE tries to achieve this by regenerating natural systems, designing out waste and pollution as well as keeping products and materials in use (Chen & Kim, 2019; Ellen MacArthur Foundation, 2017). It is defined as:

> An economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations (Kirchherr et al., 2017, p. 224).

Scholars (Kirchherr et al., 2017) stress the connection with sustainable development, the systemic nature and the importance of business models and consumers as enablers of a CE.

Although both paradigms strive to achieve the reduction of GHG emissions and the use of fossil fuels, the foundations as well as other aspects are different. Whereas the ET tries to achieve this by mainly replacing the use of fossil fuels by renewable energy sources and efficiency measures, the CE focuses on recycling, reusing and the replacement of fossil resources by more sustainable resources (Stadszaken, 2020). Furthermore, whereas the ET is mainly focused on direct emissions

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[1] International Energy Agency (IEA) is an autonomous agency which promotes energy security amongst its member states as well as providing authoritative research and analysis regarding ensuring reliable, affordable and clean energy (OECD/IEA & IRENA, 2017).

[2] International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future (OECD/IEA & IRENA, 2017).

(Drissen & Vollebergh, 2018) and energy as fuels and use patterns, the CE discourse includes indirect emissions and non-energy use (NEU)[4] of fuels as well (Chen & Kim, 2019).

Despite these differences, scholars and the public argue that a coupling of these two paradigms would complement each other in tackling climate change, as well as resource scarcity (Chen & Kim, 2019; ECN, 2016; Ellen MacArthur Foundation, 2019). For example, PBL[5] (Drissen & Vollebergh, 2018) has found that 30 to 40 percent of the fossil energy use could be reduced, as well as the respective GHG emissions, by also implementing CE strategies within measures associated with the ET. However, others state that more caution is required and that trade-offs exist, for example when recycling could be more energy intensive and add additional emissions than the use of virgin materials (Allwood, 2014; Genovese et al., 2017). Therefore, existing literature is inconclusive on the complementarity of CE and ET and careful considerations are required before simply implementing CE strategies within ET measures for a more sustainable consumption pattern.

1.1 Context of the Internship Organization

The aforementioned literature review of the relevant phenomena and academic debates are relevant to the Dutch organizations Squarewise and Stroomversnelling[6]. Squarewise is a social enterprise, based in Amsterdam focused on sustainable transitions in the built environment by connecting knowledgeable partners and providing strategic advice, exemplary projects and ventures (Squarewise, 2020). Stroomversnelling is a non-profit organization based in Utrecht that innovates within the domain of the energy transition in the built environment (Stroomversnelling, 2015, 2020). It is founded by housing corporations (referred to as corporations in the remainder of this text) and construction companies and collaborates with all supply chain partners within the sector (Stroomversnelling, 2015, 2020).

To accelerate the ET in the built environment, Stroomversnelling is involved in several solutions. One of these solutions is *nul-op-de-meter* (*NOM*) all-electric refurbishments, translated in English as ‘zero-on-the-meter’ building propositions and will be referred to as net-zero energy buildings (NZEB) all-electric refurbishments[7] in the remainder of this text. This solution is regarded as ‘all-electric’, since the total energy demand is provided by electricity. However, all-electric solutions are often not yet suitable for high-rise due to the high demand of energy generation at the building. Therefore, Stroomversnelling is also involved in other solutions regarding NZEB refurbishments, including the connection to a district heating (DH) system and will be referred to ‘NZEB plus district heat’ in the remainder of this text (Stroomversnelling, 2016). They do not require additional electricity use, but they do require heat originated from the DH system and, therefore, they are not completely net zero energy, but net zero electricity (Stroomversnelling, 2016). Refurbishments to NZEB all-electric and NZEB plus district heat are appropriate representations

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[4] Non-energy use (NEU) of fuels can be required to produce materials, e.g. plastics.

[5] *Planbureau voor de Leefomgeving (PBL),* translated in English as Environmental Assessment Agency, is the Dutch national institute for strategic policy analysis in the fields of the environment, nature and spatial planning (PBL, 2020).

[6] Stroomversnelling can be translated in English as ‘accelerating electricity’ or ‘rapids’.

[7] NZEB refurbishments are defined as the refurbishment of buildings where the in- and outgoing energy flows for building related energy (e.g. space heating, -cooling, use of warm tap water) and the use of home appliances is equal to zero or lower on a yearly basis, with standard climate conditions as they apply in The Netherlands and standard use of the building (RVO, 2020). This goes further than nearly-zero energy buildings (nZEB).

of actions regarding the ET, since they include energy efficiency measures and the use of renewable energy sources.[8][9]

Although NZEB all-electric and NZEB plus district heat refurbishments are mainly focused on providing comfortable, affordable and energy efficient houses, Squarewise and Stroomversnelling believe that the ET cannot be achieved without the CE. Since the share of environmental impacts related to 'embodied' emissions[10] instead of operational energy use increases due to new energy efficient solutions and its materials (EIB & Metabolic, 2020), they acknowledge that CE can play an important role in making the built environment more sustainable. However, they notice that CE strategies are barely implemented within the sector. Therefore, they first want to gain insights in whether and how CE strategies are currently being taken into account within refurbishments to NZEB all-electric and NZEB plus district heat and, second, how the application of different CE strategies would affect the environmental impact of NZEB refurbishments.

Through this research, Squarewise and Stroomversnelling will gain insights in the potential to implement CE strategies in NZEB refurbishments[11] to make the built environment more sustainable.

1.2 Research Questions and Objectives

This study aims to shed light into the potential to adopt CE strategies within NZEB refurbishments by studying whether and how CE strategies are already taken into account in current practice. Furthermore, it aims to investigate the potential environmental impact reduction of introducing different CE strategies in these solutions. Since CE initiatives within political and industrial domains begin to develop, understanding environmental impacts resulting from the complex material life cycles of buildings becomes important to identify potentials for a CE within the construction sector (Eberhardt et al., 2019).[12] Therefore, the following research questions have been formulated:

RQ1: *How and why are CE strategies already being taken into account in NZEB refurbishments?*

RQ2: How does the application of different CE strategies affect the environmental impact of NZEB refurbishments?

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[8] NZEB all-electric and NZEB plus district heat refurbishments allow a maximum heat demand of 50 kWh/m^2/yr (Stroomversnelling, 2016).

[9] This study is focused on refurbishments of residential buildings instead of new constructions, since the amount of energy efficient new constructions increases faster than of refurbishments (Becchio et al., 2016), despite the challenge of renovating the enormous existing stock due to sustainability demands and quality requirements (EIB & Metabolic, 2020). Furthermore, Stroomversnelling is focused on residential instead of non-residential (utility) buildings and the global final energy consumption by end-use of residential buildings is nearly a factor of three higher than of non-residential buildings, 24,3 PWh and 8,4 PWh respectively (Ingrao et al., 2018).

[10] 'Embodied' emissions are emissions from the production and manufacturing of materials (Röck et al., 2020).

[11] Both types of solutions are relevant to study since the Dutch Climate Agreement, which includes measures to achieve the reduction of GHG emissions (Rijksoverheid, 2019), stresses the potential for achieving ET targets with those and with recent refurbishments, often a choice is made between all-electric or connecting to a DH system.

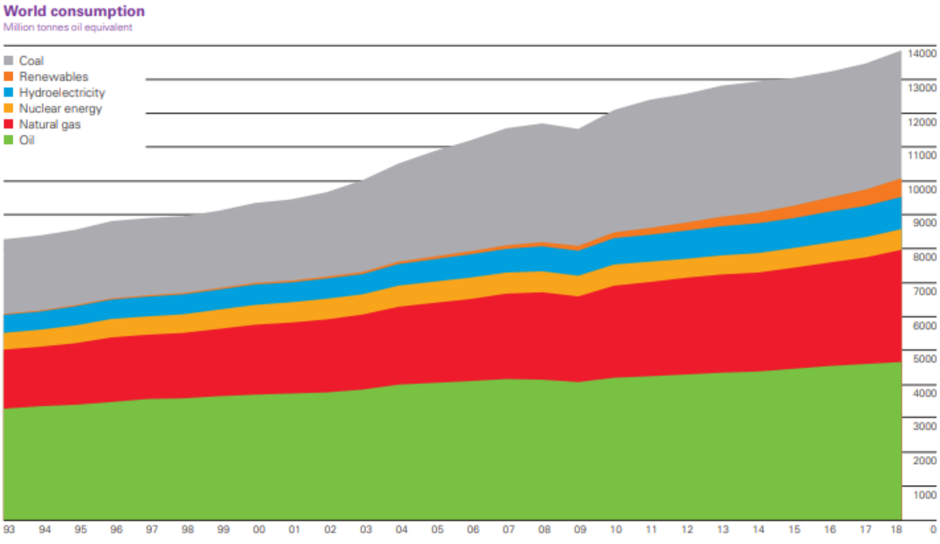
[12] Since the construction sector can be divided in several sub-sectors, it should be clear that this study is focused on the residential sector.

Research so far is inconclusive about the complementarity of CE and ET. Therefore, from a scientific perspective this research has relevance, since it complements the theoretical knowledge about CE strategies within ET measures in a specific sector and, furthermore, it provides insights into the measurements of impact of different CE strategies. Since the CE and ET are both important sustainability paradigms, from a societal point of view, this study can provide insights into how the Dutch construction sector as well as Squarewise and Stroomversnelling could provide more comfortable and sustainable housing solutions to society by both taking CE and ET measures together as an example for other countries or regions.

2. Theory

2.1 Energy Transition in the Construction sector

Energy transition (ET) studies deal with structural changes in the energy system and its use patterns (Chen & Kim, 2019). The current energy system is dominated by coal, natural gas and oil (see figure 1), which leads to human-induced climate change (EEA, 2017). However, the opposite effect where climate change impacts the current energy system is also present (Schaeffer et al., 2012). Therefore, governments try to steer society to a low carbon energy system (Rijksoverheid, 2019).



Global energy consumption increased by 2.9% in 2018. Growth was the strongest since 2010 and almost double the 10-year average. The demand for all fuels increased but growth was particularly strong in the case of gas (168 mtoe, accounting for 43% of the global increase) and renewables (71 mtoe, 18% of the global increase). In the OECD, energy demand increased by 82 mtoe on the back of strong gas demand growth (70 mtoe). In the non-OECD, energy demand growth (308 mtoe) was more evenly distributed with gas (98 mtoe), coal (85 mtoe) and oil (47 mtoe) accounting for most of the growth.

Figure 1: World consumption of energy by fuel from 1993 - 2018 (Dudley, 2019)

To achieve such a low carbon ET, the Dutch construction sector has to play a substantial role, since it was responsible for about 22% of the final energy use[13] in 2017 and 11% of the GHG emissions in 2018 (RVO, 2018). Although a reduction in final energy use was observed in recent years, since 2017 it has increased again, despite the approximately constant building related energy use.[14] A reason for this is the increasing demand in non-building related energy use[15] (RVO, 2018). In addition to the reduction of energy consumption through efficiency measures, there is a need to decarbonize electricity production (IEA, 2019). From a global perspective, the IEA (2019, p. 1) states: "In fact, since 2000, the rate of electricity demand in buildings increased five-times faster than improvements in the carbon intensity of the power sector". Besides the environmental relevance, acting too late has severe economic effects (IEA, 2019). Therefore, the construction sector has to find and implement relevant measures to meet the ET targets in collaboration with the energy sector.

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[13] Calculated energy use at the end-user in PJ (RVO, 2018).

[14] Energy use related to the demand of the building, e.g. heating and warm tap water minus the generation of electricity by for example PV (RVO, 2018).

[15] Energy use for household appliances (RVO, 2018).

The IEA (2019, p. 1) states "technology and design are at the heart of a sustainable buildings sector." Near-zero energy construction and deep energy refurbishments can reduce the sector's energy use (Amoruso et al., 2018; Dulac, 2017) by nearly 30% to 2050, even with doubling of global floor area (IEA, 2019). Although deep energy refurbishments should be key to achieve a more sustainable construction sector, a study from Mata et al. (2020) found that global political roadmaps to achieve zero and low energy and carbon buildings are mostly focused on new and public construction. This is surprising, because existing buildings form the majority in numbers and floor area and are often already less energy efficient. Chel and Kaushik (2018) state four main aspects for energy efficiency, allocated to different lifecycle stages: (nearly) passive building design, low energy materials during construction, energy efficient equipment during its use and the integration of renewable energy technologies for various applications. Amoruso et al. (2018) state that passive as well as active measures are critical.[16] Table 1 shows examples of common technological measures that can be applied simultaneously in various building solutions.

Table 1: Technological energy transition measures for the construction sector.

Technological measures			
Passive	**Description**	**Active**	**Description**
Extra insulation	Reduces the transfer of (thermal) energy (expressed in R-value) between two sides of a material or construction, which depends on the material or construction.	Heat pump	Device that transfers thermal energy from a source to a thermal reservoir.
Low U-window	The U-value refers to the rate of heat loss of a window assembly (insulating properties), often, triple-pane windows have lower U-values than double-pane.	Smart devices (demand-side)	Devices that allow the monitoring and management of energy usage, e.g. by the use of smart apps.
Ventilation	Ventilation refers to refreshing the air, either mechanically or naturally, to improve comfort, indoor climate and moderate internal temperatures.	Solar thermal	Solar thermal technologies capture the thermal energy from the sun for heating and/or electricity production.
Heat recycling (air and water)	To recover energy from water or air by a heat exchanger	Photovoltaics	Technology which converts the sun's radiation to produce electricity.
Energy-saving appliances	Energy-saving household appliances, e.g. LED lighting.	Energy-saving appliances	Energy-saving household appliances, e.g. dimmers or timers for lighting.
		Thermal energy storage (TES)	Storage of thermal energy to be used later by different technologies.
		Woodstove (bio)	Heating technology that burns wood-derived biomass fuel

Sources: Amoruso et al., 2018; Becchio et al., 2016; Parameshwaran, Kaleiselvam, Harikrishnan & Elayaperumal, 2012; Tambach, Hasselaar & Itard, 2010; Wurtz & Delinchant, 2017)

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[16] Passive measures try to reduce total energy consumption by reducing energy loss. Active measures try to reduce the need for external energy by controlling energy consumption and increasing efficiency or the use of renewable energy production (Amoruso et al., 2018).

These technological measures can be applied to the building solutions relevant for this study, NZEB all-electric and NZEB plus district heat refurbishments. According to Voss et al. (2011, p. 1), NZEBs describe the integration of the building and the energy grid (figure 2 below). NZEB all-electric refurbishments can be achieved by a combination of several measures described above in table 1, e.g. excellent insulation and airtight envelope, smart installations and energy generation (Sartori et al., 2012; Vereniging De BredeStroomversnelling, 2018).

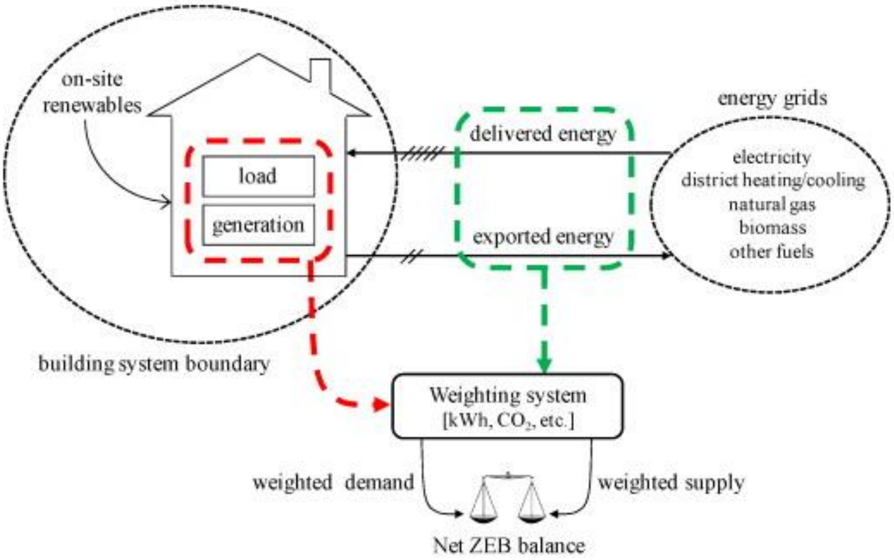

Figure 2: Sketch of connection between buildings and energy grids (Sartori et al., 2012).

Next, district heating refurbishments can also apply a combination of technological measures mentioned in table 1, although this depends on the type of district heating. It makes use of a network of underground pipes to warm up buildings (RVO, 2020a). They can be classified between low (LT) and high (HT) temperature networks (40 ◦-90 ◦C), which refers to the temperature of the water. The lower the temperature, the less energy loss. Connecting to a LT heating system, in comparison with HT, is often accompanied with additional technological measures described in table 1, e.g. extra insulation, ventilation and additional installations. Regarding NZEB plus district heat, measures to lower the heat demand result in a required flow temperature of maximum 70 ◦C.

The above measures are often applied in so called building adaptation projects to improve the existing building conditions and extend the effective lives of buildings. However, the scopes of these building adaptation projects often vary and the terminologies to refer to such projects are often used interchangeably (Shahi et al., 2020). Scopes include: rehabilitating failing structures, improving environmental performances and changing functional uses. Furthermore, the structural characteristics vary between structural, non-structural or both. To clarify the difference between such building adaptation projects for researches and practitioners, Shahi et al. (2020) developed a definition framework which is visualized in figure 3 below. Whereas refurbishment refers to improving the existing conditions of buildings and may include the addition of elements, either by energy retrofits (retrofitting), restoration of deteriorating building structures (rehabilitation) or replacing and/or repairing outdated components or restructuring interior spatial layout (renovation), adaptive reuse refers to extending the useful service life of buildings, either by changing the function (conversion) or recovering existing materials (material reuse). Shahi et al. (2020) state, although some of these interventions result in the reduction of energy demands, they may have substantial other life cycle environmental impacts. Therefore, careful considerations are required. This study is mainly focused on the refurbishment category, although the material reuse of projects will be also taken into account, however, this is not the starting point.

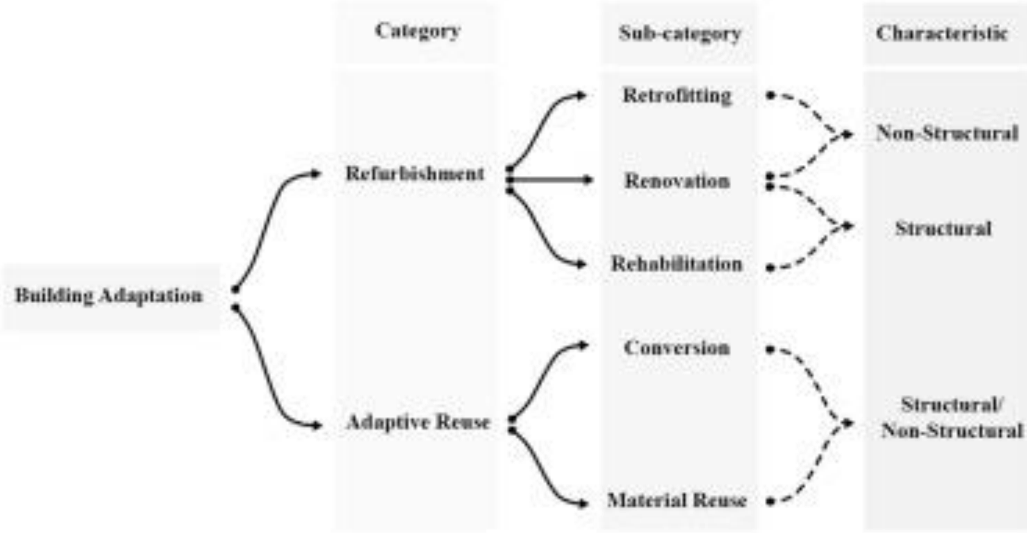

Figure 3: Categorization of building adaptation projects (Shahi et al., 2020).

So although some of these refurbishments bring benefits regarding the reduction of GHG emissions due to the increasing operational performance, studies have found that the share of ‘embodied’ emissions substantially increase (Ingrao et al., 2018; Ness & Xing, 2017; Röck et al., 2020) and that most of the emissions occur upfront when the temporal distribution of GHG emissions is studied, i.e. high initial GHG emission investments (Röck et al., 2020). For example, Zimmermann et al. (2020) state that a study on more than 650 building LCA cases have shown that materials account for half, sometimes up to 90% of the CO_2 emissions in energy efficient buildings, especially changes to the building skin and internal spaces add notable resources and impacts (Castro & Pasanen, 2019). However, this does not necessarily mean that total emissions along the service life increase. It only means that ‘embodied’ emissions due to the materials used become more important to subsequently focus on to further reduce emissions, than emissions due to the use of building. Therefore, it is important to pay attention to ‘embodied’ emissions, which is relevant to the CE.

2.2 Circular Economy in the Construction sector

The CE has its roots in various concepts, e.g. Industrial Ecology, Cradle-to-Cradle, Regenerative design and more (Ellen MacArthur Foundation, 2017; Ghisellini et al., 2016; Reike et al., 2018; Saidani et al., 2017). Throughout history the CE paradigm has evolved from being merely focused on output measures to reduce environmental harm, to a way to decouple resource use and economic growth (Wiprächtiger et al., 2020), i.e. a “way out of the ‘resource trap’” (Reike et al., 2018, p. 249) and for businesses to manage their sustainability impact (Saidani et al., 2017), especially for energy and material intensive businesses (Genovese et al., 2017).

Although the CE is often criticized by scholars and practitioners for being conceptually ambiguous (Geissdoerfer, et al., 2017; Kirchherr et al., 2017; Reike et al., 2018; Schöggl et al., 2020), the general idea is to encourage cycling materials throughout supply chains to reduce the use of fossil fuels and its respective GHG emissions (Ellen MacArthur Foundation, 2017), either direct or indirect emissions (Drissen & Vollebergh, 2018).

From a longitudinal review of Schöggl et al. (2020), the CE literature can be divided into a management and technical focus, with in both either a beginning-of-life (BOL) focus and end-of-life (EOL) focus, with associated concepts as design and innovation and waste treatment and recycling, respectively. The first focus is often related to more higher order value retention, whereas the latter is more related to lower order value retention, which will be explained below. Furthermore, they (Schöggl et al., 2020) also found that CE has a subset relationship with sustainability, since often only a limited number of environmental impacts are addressed, e.g. resource use, CO_2 emissions and waste. Lastly, they found that the CE from a consumer perspective is barely studied, despite the fact that higher order value retention options are closely related to the consumer and, therefore, can be regarded as a blind spot in the CE discourse (Schöggl et al., 2020).

Among the leading strategies to operationalize the CE in practice, there are different waste hierarchies, which rank several strategies according to an order of priority or circularity (Cramer, 2017). However, confusion exists surrounding different waste hierarchies among and within multiple disciplines (Reike et al., 2018). Therefore, Reike et al. (2018) aggregated and summarized the divergent perspectives into a holistic typology of 10 value retention options (VROs), which can be used as a heuristic to lead CE activities in practice (see table 2).

Table 2: Value Retention Options (VROs) (Based on Reike et al., 2018).

Value Retention Options (VROs)		**Operationalization principles**
Client/user choices	Refuse (R0)	Refuse use of certain hazardous materials. Design production processes to avoid waste or any virgin materials.
	Reduce (R1)	Use less materials per unit of production, in other words ‘dematerialization’.
	Resell/Reuse (R2)	Enable multiple reuses of products by for example buying, collecting, inspecting, cleaning and/or selling of used products.
Product upgrade	Repair (R3)	Repair products or let them be repaired, with or without the change of ownership and ad-hoc or planned repairs.
	Refurbish (R4)	Replace or repair components to upgrade the product, while the structure of a multi-component product stays intact.
	Remanufacture (R5)	Full structure of a multi-component product is disassembled, cleaned, checked and when necessary replaced or repaired in an industrial process.
Down-cycling	Repurpose (R6)	Reuse discarded components of a product and adapt them for another function by for example designing, developing, reproducing and selling the product.
	Recycle (R7)	Buy and/or use processed materials from post-consumer products (secondary recycling) or post-producer waste (primary recycling).
	Recover (R8)	Buy and/or use recovered energy from waste treatment or biomass.
	Re-mine (R9)	High-tech extracting, reprocessing and/or using valuable resources from landfills or waste plants.

The term ‘value retention option’ refers to the intrinsic value of resources, besides the economic one. However, improving the intrinsic value of products may lead to trade-offs in environmental impact (Saidani et al., 2019). Therefore, other scholars (e.g. Haupt & Hellweg, 2019) operationalize ‘value’ by using the initial environmental impact to produce a product, which represents the efforts that can be retained. Furthermore, Reike et al. (2018) cluster the VROs according to the length of the loops as well as the actors involved and distinguish between two different lifecycles, where the VROs can apply to: Product ‘Produce and Use’ and ‘Concept and Design’ lifecycle. See figure 4 and 5 for their visualization.

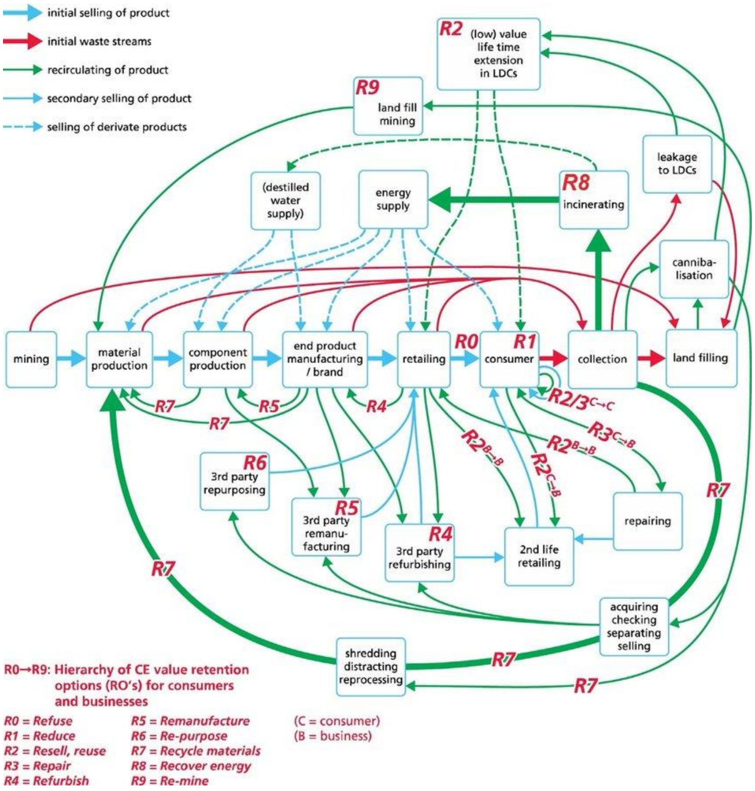

Figure 4: Circular economy retention options: The Product Produce and Use lifecycle (Reike et al., 2018).

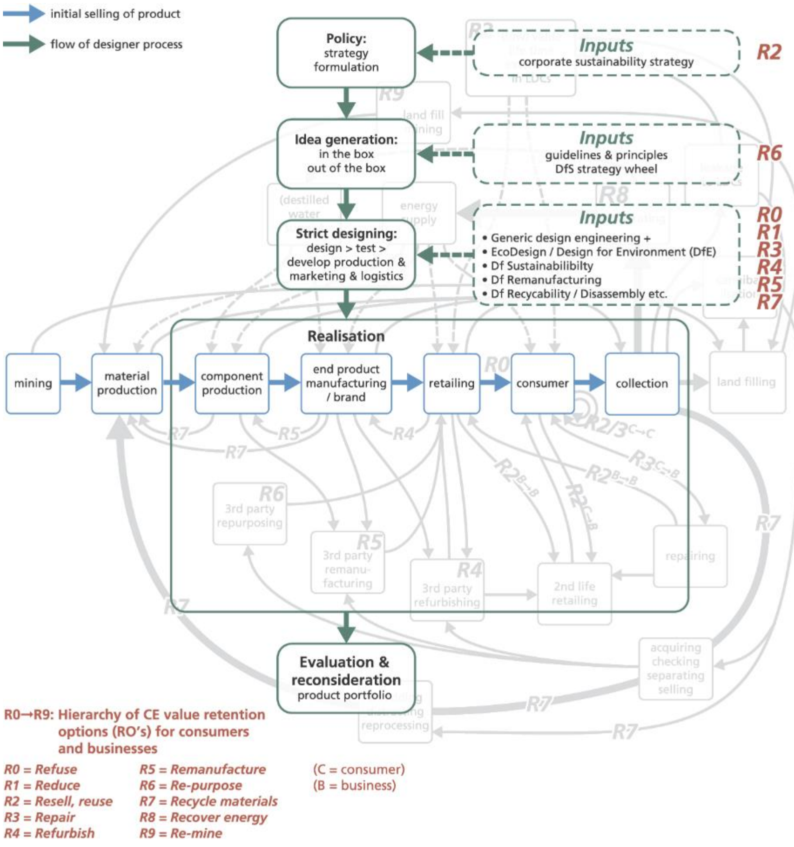

Figure 5: Circular economy retention options: The Product Concept & Design lifecycle (Reike et al., 2018).

The construction sector has to play an important role to implement CE strategies, since it is significantly material and energy intensive (De Jong & Bosmans, 2019; Eberhardt et al., 2019a; RWS, 2015; Wu et al., 2019), which leads to enormous waste streams (EEA, 2020; Manfredi & Pant, 2011) and resulting GHG emissions (Nußholz et al., 2019). More than 35% of the Dutch waste originates from building and demolition waste (CE Delft, 2015). There is widespread consensus about the relevance of CE within the construction sector, however, there is a lack of standardized methods and practices (Benachio et al., 2020). Because of the waste challenges, the VROs described above can be appropriate operationalization strategies for CE in the construction sector.

In respond to this, many strategies to implement the CE in the construction sector have been formulated. Whereas some refer to technical and biological material flows (Bertino et al., 2019; EEA, 2020; Migliore et al., 2020; Orsini & Marrone, 2019), others to the related organizational aspects, e.g. business model innovations (Nußholz et al., 2019). Some present case studies of circular strategies in different life cycle phases (EEA, 2020; Huovila et al., 2019; UK-GBC, n.d.) and as different levels of value retention (Gorecki, 2019). Regarding the latter, although recycling (down-cycling) is highly advanced in the Dutch construction sector, this purpose is getting saturated (RWS, 2015) and studies (EIB & Metabolic, 2020) found that the material demand exceeds the possible supply of secondary resources. Therefore, additional strategies are suggested: increase the applications for secondary materials, reduce primary resource use by design (e.g. modular) and smarter building processes, increase lifetime of buildings and use alternatives with the lowest environmental impact (EIB & Metabolic, 2020). Also, software tools are proposed to be applied differently to fit CE needs. For example, the study of Charef & Emmitt (2020) found that although the use of building information modelling (BIM) to manage a building's life cycle is still rare, it can be used in many different ways to overcome barriers to CE and, therefore, support the implementation within the construction sector (Charef & Emmitt, 2020).[17]

Next, Eberhardt et al. (2020) conducted a systematic literature review to assess several building design and construction (D&C) strategies which relate to the concept of the CE for new buildings which resulted in a taxonomy of 16 D&C strategies. Although this study has been done for new buildings, most of D&C strategies could also relate to refurbishments. Furthermore, they also assessed the level of application[18] and readiness.[19] Table 3 below shows the identified D&C strategies sorted on popularity, i.e. amount of encounters within literature, including a short description and their encountered relationship within literature.

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[17] Building information modelling (BIM) is defined as a 'digital representation of an asset' (Charef & Emmitt, 2020, p. 6). It can be used to achieve various objectives throughout an asset's life cycle.

[18] To what extent the D&C strategy is related to building, component or material application level.

[19] To what extent the D&C strategy is related to theoretical, experimental or consolidated level of readiness.

Table 3: Design & Construction Strategies and their relation to CE (Based on Eberhardt et al., 2020).

Design & Construction Strategy (occurrences)	**Description from literature**	**Relation to CE strategies**
Assembly/disassembly (32)	Is used to design the building, components or materials to be easily assembled/disassembled to enable e.g. direct reuse or recycling, ease of maintenance/operation and ease of adaptability/flexibility. A precondition is reversible connections.	Reuse, reduce, recycle, repair, replace, energy recovery
Material selection/substitution (25)	Choosing or substituting materials for materials that are e.g. local, renewable, natural/eco/bio, have lower environmental impact, of high quality, durable, easy assembly/disassembly, reusable and recyclable, C2C certified, pure, maintenance free, retain or increase their value, match the performance lifespan, non-toxic/ hazardous, etc.	Reuse, reduce, recycle, repair
Adaptability/flexibility (21)	Designing to be able to e.g. adapt to available materials, accommodate changes in future use/ function requiring modifications/remodeling/ expansion, secure easy and low cost operation/ maintenance, prolong the lifespan of the building, components or materials, reuse and recycle, enable/enhance design for disassembly, close materials loops, distinguish between long and short-life materials as well as low- and high-value materials.	Reuse, reduce, recycle, repair, replace, refurbish
Modularity (17)	Is used to e.g. allow for easier building/component adaptability/flexibility (upgrade, demounting/disassembly, replacement, reconfiguration, reuse and recycling), build cheaper standard buildings and lean production.	Reuse, reduce, recycle, repair, replace, refurbish
Prefabrication (17)	Also known as off-site construction. Is used to ensure e.g. reclamation, reusability and recyclability, construction time optimization, enhanced assembly and disassembly, enhanced adaptability, avoidance of off-cut materials, etc.	Reuse, reduce, recycle
Secondary materials (15)	Integrating materials that are recycled in order to slow and close resource loops.	Reuse, reduce, recycle, refurbish
Durability (13)	Designing or using high quality durable long performance lifespan components and materials that are easy to maintain and upgrade and can handle several service lives.	Reuse, reduce, repair, remanufacture
Standardization (12)	Is used to e.g. maximize recovery of materials at end-of-life, ensure reuse and recycling options, limit the number of different components used, avoid material off-cuts, prolong product lifespan, etc.	Reuse, reduce, recycle
Component and material optimization (11)	Reducing the amount of materials used as well as the number of different types of components and materials used.	Reuse, reduce, recycle
Reusing existing buildings/components/materials (11)	Is used to directly reuse existing buildings, components or materials for new construction projects.	Reuse, reduce, recycle, refurbish, remanufacture
Optimized shapes/dimensions (10)	Design to precise material measurements specification in order to: suit appropriate means of handling components and materials, enhance/enable future adaptability/flexibility by e.g. avoiding over ordering and onsite material cut-offs. E.g. by simplifying the building form, using lightweight structures or reducing the customers' spatial needs by optimizing floor areas.	Reuse, reduce
Accessibility (8)	Also known as 'open design'. Used to provide good access to connections between components to enhance design for assembly/disassembly, to ease maintenance, maximize recovery of materials at end-of-life.	Reuse, reduce, recycle, repair, replace
Layer independence (6)	Is used to make building components and materials independent from each other's	Reuse, reduce, recycle, repair,

	lifespan for easier operation and maintenance, material recovery, separation and adaptability/flexibility.	replace, remanufacture
Material storage (5)	Is used to design buildings as material deposits to avoid degradation of material quality over time by temporarily storing the materials in the building and minimizing in-between stockholding that may damage materials by using principles such as just-in-time delivery of the materials to subsequent building projects.	Reuse, reduce, recycle
Short use (3)	Opposite of Design for durability: the building is only designed for its specific use and performance span. Material and product choices are adjusted accordingly.	Reuse, recycle
Symbiosis/sharing (2)	Is used to utilize residual resource outputs from one building as feedstock for another, often in relation to industrial parks e.g. sharing/outsourcing surplus water, waste and energy.	Reuse, reduce, recycle

Their study (Eberhardt et al., 2020) has found that most D&C strategies were applied in relation to reduce, reuse and recycle, with reuse having the most encounters. This indicates, they state, that literature is mostly focused on direct reuse, i.e. “extending resource life either by slowing or closing resource loops” (Eberhardt et al., 2020, p. 9), with assembly/disassembly as the dominant D&C strategy. The importance of the possibility for easy assembly/disassembly, i.e. design for (dis)assembly or deconstruction (DfD) is confirmed by Fayyad and Abdalqader (2020), since the reason for demolition is often the lack of adaptability, despite the high demands of energy and material losses. Furthermore, assembly/disassembly and secondary materials were mostly mentioned in relation to reduce and material selection/substitution to recycle. Repair, refurbish and remanufacture are substantially less mentioned, whereas energy recovery is only mentioned once. Besides, the study has found that more preventive developments are developing in both research and industry by up-front reuse and recycling, in contrast to earlier research and industry, where the focus was mostly on end-of-pipe solutions (Eberhardt et al., 2020). Although these more progressive developments are occurring, they also found the slow uptake of CE strategies is, among others, found to be caused by the lack of knowledge about the environmental benefits.

To continue on this, others have found different barriers to CE implementation within the construction sector in general, and material reuse in particular and the possible approaches to tackle these. For example, Trabulsi and Sofipour (2020) found that strategic collaboration between different actors is essential to transition from a linear to circular economy. However, this is hampered by several factors: general perception of negative attitudes towards reused materials by tenants, lack of logistics and recovery facilities and the procedures for quality assurance and warranties. First, there is a general perception among different actors that tenants have a negative attitude towards reused materials. However, this argument has been disproved showing that the majority of tenants have a positive attitude towards reused materials (Trabulsi & Sofipour, 2020). Second, the lack of logistics and recovery facilities can be tackled by a clear distribution of responsibilities. However, different incentives and a market demand for reused products are required. Last, their study has found that no procedures for quality assurance and warranties for reused products exists. However, digitalization and product data throughout the product’s life cycle could help. Despite these barriers, Wegdam (2020) conducted a study on the Dutch SME construction sector and found that construction companies are also stimulated to apply CE strategies, for example due to increased competitiveness, environmental-, financial- and client-based reasons.

Trabulsi and Sofipour (2020) further found that real estate developers have a significant role in stimulating strategic collaboration and the implementation of CE within the sector. They found that real estate developers can create a positive context for material reuse and collaboration by first, "planning and designing for reuse at an early stage and to allocate enough time for the demolition contractor to properly dismantle materials" (Trabulsi & Sofipour, 2020, p. 58) and second, by "formulating their demands and requirements in a certain way" (Trabulsi & Sofipour, 2020, p. 58), for example by being less specific in the requirements to provide more flexibility for the contractors. Despite the significant role of the real estate developers is clear, allocation of responsibilities between different actors is required to successfully implement a CE in the construction sector.

Despite these challenges to implement a CE within the construction sector, the environmental benefits of applying certain D&C strategies and value retention options depend on the specific application. Therefore, choosing the D&C strategies and value retention options with the lowest environmental impact requires careful consideration and measurement (Eberhardt et al., 2019a; Eberhardt et al., 2020; Platform CB'23, 2019). Furthermore, as stated above, according to Eberhardt et al. (2020) the slow uptake of these CE strategies is found to be caused by unknown environmental benefits. Therefore, it is yet unknown which of these are already applied or may apply in NZEB all-electric and NZEB plus district heat refurbishments.

2.3 Measurement of Environmental Impact and Circular Economy

There is much debate about the measurements of CE activities (Camacho-Otero & Ordoñez, 2017), however, clarity about this is essential for designing policies and business strategies and to prioritize sustainable solutions (Corona et al., 2019). Corona et al. (2019) state the following challenges regarding circularity metrics: difficulty to include all sustainability dimensions, evaluate the scarcity of materials and underrepresenting multiple cycles' complexity and the consequences of down-cycling. Regarding the complexity of multiple cycles, Eberhardt et al. (2019, p. 7) states: "It becomes clear that the potential benefit of reusing and recycling the materials and components is not gained immediately but at the point of future retrieval." Furthermore, Reike et al. (2018) state that measurements of impacts of the different VROs and especially trade-offs are scarce. However, quantitative measurements including environmental impacts, material flows and preservation of value are all important to comply with a sustainable CE (Haupt & Hellweg, 2019; Platform CB'23, 2019; Walker et al., 2018). Whereas often mass-based indicators that provide a limited representation of the environmental impact are used (EIB & Metabolic, 2020), Haupt and Hellweg (2019) developed an impact-based indicator, called Retained Environmental Value (REV) to calculate the environmental impact of different VROs.

Since buildings result in significant energy and other environmental impacts distributed throughout their whole life cycle, applying life cycle thinking is relevant to find ways to reduce this impact (Ingrao et al., 2018). Therefore, Life Cycle Assessment (LCA) can be used. LCA is regarded as an environmental management technique among others, e.g. environmental impact assessment, risk assessment, environmental auditing and environmental performance evaluation (ISO, 2006). It is currently regarded as a promising methodology to measure the potential environmental impacts[20] of products and services throughout their life cycle and to include CE

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[20] LCA addresses potential environmental impacts, since it uses relative expressions that are related to a functional unit of the product of system, integrates data over time and space, includes inherent uncertainty and addresses some possible future impacts (ISO, 2006). The main purpose of the functional unit is to provide a reference to which the input and output data are normalized (ISO, 2006a).

(Corona et al., 2019; Chen & Huang, 2019; Tóth Szita, 2017), since it can account for avoided production of virgin material (Genovese et al., 2017) and includes many impact categories relevant to the CE (Niero & Olsen, 2016). However, LCA is often associated with a linear approach, so including CE also requires to rethink how LCAs are being done and structured (Dieterle et al., 2018; Eberhardt et al., 2019). Therefore, Dieterle et al. (2018) proposed a complementary interpretation analysis, called the life cycle gap analysis (LCG-A), to highlight the theoretical system losses or so-called life cycle gaps associated with the potential environmental impacts, between the current and ideal closed system. This helps to incorporate the CE mindset within LCA. Furthermore, trade-offs can exist between environmental impacts of building refurbishments. For example, when the building envelope is refurbished, it can have substantial improvements in energy performance in the operating phase due to the insulating properties. However, this intervention may have significant environmental consequences during the construction phase. Therefore, Ingrao et al. (2018, p. 561) state:

> In cases like this, LCA can be applied to find and test the improvements that can be made to achieve the balance, and make sure that those energy performances are associated with low environmental impacts in the life cycle of the BEES.[21]

Besides, it can also be used to assess different D&C strategies. For example, Ingrao et al. (2018, p. 561) state:

> LCA can be applied to prove the environmental benefits resulting from dry assembly solutions for the building envelope that, followed by the disassembly of the component materials and products at the end-of-life of the building, can enable their recovery and recycling.

Next, some studies (Laurent et al., 2012; Huijbregts et al., 2010) have found a strong correlation of CO_2 emissions (impact-based indicator) and Cumulative Energy Demand (resource-based indicator) with the total environmental impact of products, especially for infrastructure- and building-related products and can therefore be regarded as suitable indicators used in LCA. However, the above correlation is weaker when the emissions of toxic substances are substantially present (Laurent et al., 2012) or when bio-based products are taken into account (Weidema et al., 2008). Hossain and Ng (2018) found that few LCA studies on buildings take into account both energy and carbon and they argue to take other impact categories into account as well when a comprehensive assessment is strived for. Furthermore, Ingrao et al. (2018) state from several documented studies that impact categories that describe well the impacts of buildings are: acidification, eutrophication, abiotic depletion, global warming and energy use. Due to this ambiguity, CO_2 can be regarded more as a 'transition' indicator to eventually move towards more holistic approaches. This study tries to take a step in the direction of a holistic approach by going beyond the consideration of CO_2 and energy and also include additional impacts mentioned above.

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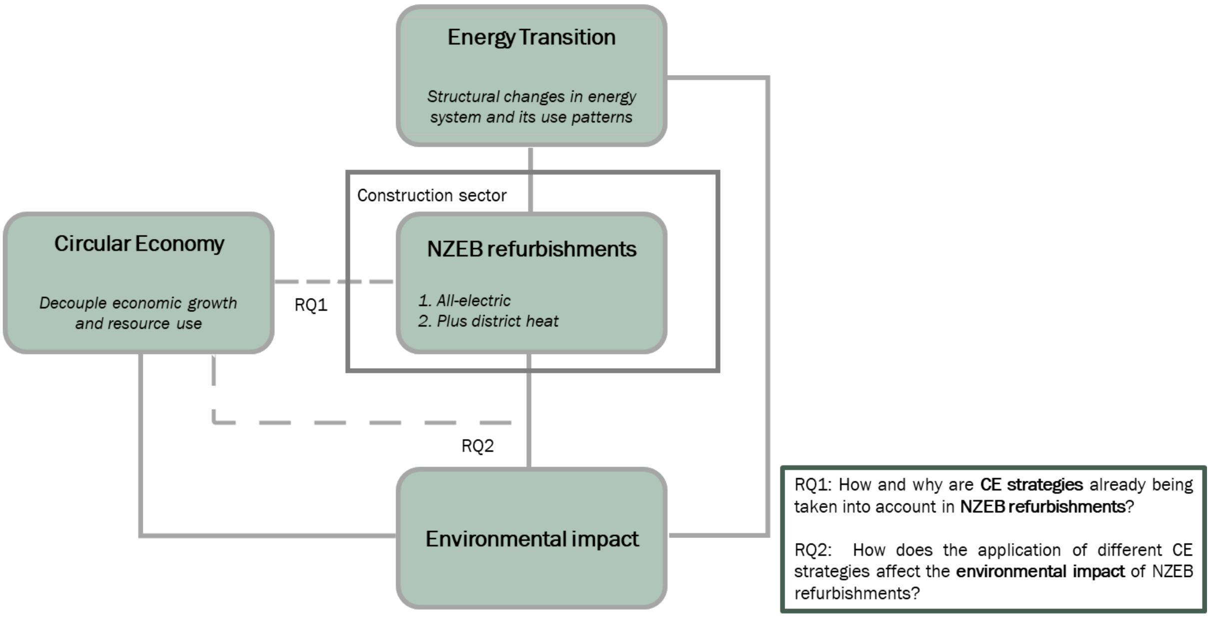
[21] Building Envelope Element Sample (BEES)

2.4 Theoretical Framework



RQ1: How and why are **CE strategies** already being taken into account in **NZEB refurbishments**?

RQ2: How does the application of different CE strategies affect the **environmental impact** of NZEB refurbishments?

Figure 6: Theoretical Framework.

The connecting lines shows the relationship between the goal (e.g. environmental impact reduction), paradigms and their measures (e.g. circular economy and energy transition) and solutions within the construction sector (NZEB all-electric and NZEB plus district heat refurbishments). The continuous lines show the known relationships, whereas the dotted lines show the unknown relationships. The D&C strategies as well as the VROs can be located at the Circular Economy square, whereas the technological measures are part of the Energy Transition square.

Figure 6 above shows the theoretical framework with the main aspects included that were discussed above, related to both research questions that will guide the rest of this study.

3. Methodology

3.1 Research Design

This study first, tried to understand the potential to adopt CE strategies in refurbishments to NZEB all-electric and NZEB plus district heat and second, explain how the application of different CE strategies affected the environmental impact of such refurbishment solutions.

An exploratory sequential mixed methods design was chosen and seemed most appropriate, since to answer research question 2, a qualitative understanding of the context of applying CE strategies within both solutions was required first. With this mixed methods approach, the researcher collects and analyses both qualitative and quantitative data, which can be done in several ways. In an exploratory sequential type, qualitative data was collected and analyzed first which guided the collection of quantitative data to test the findings empirically (Shorten & Smith, 2017). See figure 7 for a visualization of the research design.

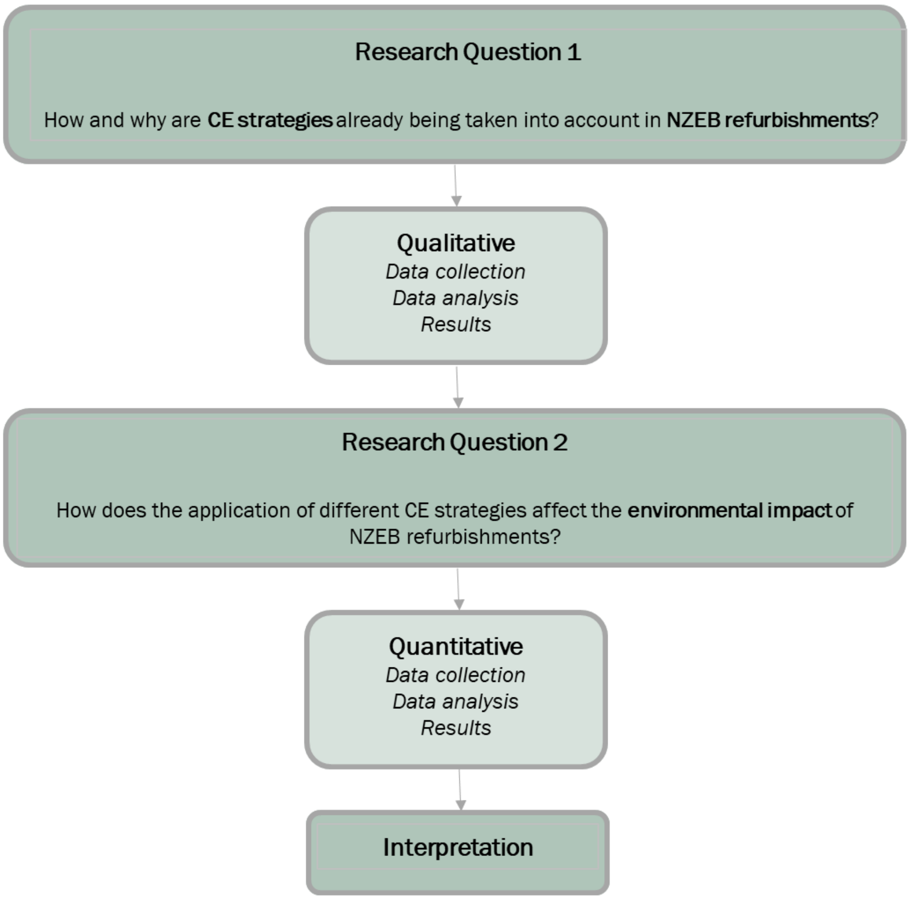


Figure 7: Research Design.

3.2 Research Question 1

3.2.1 Data Collection

To answer research question 1, seven semi-structured interviews were conducted in Dutch spoken language, composed of both closed and open questions. Furthermore, un-planned questions could be asked to obtain more depth of insights regarding their specific knowledge area. This method could be advantageous for exploratory research, since the flexibility allowed follow-up or how questions to obtain depth of insights which helped explore the context of this research (Adams, 2015). Because of the COVID-19 pandemic it would have been irresponsible to conduct the interviews in person. Therefore, they were remotely conducted through both Microsoft Teams in a video conference and phone calls. Since most of the interviews were conducted with a video application, it was still possible to notice body language. However, since they were remotely conducted, interviewees could have terminate sensitive questions more easily.

Regarding the sample selection, seven companies were chosen. This selection consisted of four construction companies that had a role as contractor within the supply chain and three companies that were more associated with a supplier of whole refurbishment solutions or separate products and, therefore, as partner of the construction companies. See table 4 for all participating companies. Furthermore, it was a precondition that these companies were involved or had been involved in NZEB refurbishments and that both solutions, e.g. NZEB all-electric and NZEB plus district heat, were represented by the interviewees. Therefore, company websites were carefully reviewed, so that they could provide sufficient data.

Interviewees were only chosen from Dutch construction companies, since Squarewise and Stroomversnelling are only active within The Netherlands and the construction sector differs between regions. Besides, they were selected based on their involvement in and knowledge of NZEB refurbishments within the company or when they had the power to influence decisions within the company. This resulted in a variety of different roles that interviewees adopted within their company. For example, three company directors were interviewed and one project manager. Furthermore, one manager of business development was interviewed and also two interviewees took a more specialist role, e.g. within energy, technology and monitoring.

Table 4: Interview organizations.

Interview Organizations
Hazenberg Bouw
Renolution
Dura Vermeer Onderhoud en Renovatie Midden West
Bébouw Midreth – VolkerWessels Group
BIK Bouw
Rc Panels
Factory Zero

Data were collected about the technological measures that are part of the ET in the construction sector and can apply in the refurbishment solutions (see theoretical framework). Furthermore, data were collected about the applied and possible CE strategies within their NZEB refurbishment solution as well as at other industry partners or other projects. Also, perspectives from the interviewees about the importance of the CE for their company as well as for the ET were relevant for the interpretation of the data.

To account for the diverse perspectives regarding CE strategies within businesses and help operationalizing the VROs, the prompt sheet in table 5 was shown during the interview in Dutch.[22] They were asked which activities they had consciously performed within their NZEB refurbishment solution and an explanation was asked for to account for misunderstandings. Furthermore, additional comments and scenarios to include CE strategies were asked for to obtain more depths of insights from the interviewees about CE strategies in NZEB refurbishments or at other projects.

Table 5: Prompt sheet CE activities.

Extract, reprocess and/or use valuable materials from landfills or waste plants	Use less materials per unit of production, i.e. dematerialize	Buy and or use processed materials from post-consumer products, 'secondary recycling'	Repair products or let them be repaired	Reuse products and adapt for another function, 'repurpose'	Design production processes to avoid waste or any virgin material
Buy and/or use recovered energy from waste treatment or biomass, i.e. waste-to-energy	Upgrade product by replacing or repairing components, while structure stays intact, i.e. refurbish	Refuse hazardous materials	Disassemble, clean, check, and/or replace or repair product in an industrial process	Buy, collect, inspect, clean and/or sell used products	Buy and or use processed materials from post-producer waste, 'primary recycling'

3.2.2 Data Analysis

To analyze the data, the interviews were manually transcribed rather than using digital automatic software, since this approach would help grasp their perceptions more successfully to increase validity. The transcripts had an average word count of 6300 words, which was the result of an average interview duration of 54 minutes.

After the transcripts were developed, they were added to and coded using Nvivo 12 Pro[23], which means that we "attach labels to segments of data that depict what each segment is about" (Charmaz, 2006, p. 3). Key themes were extracted by dividing the data into separate parts, e.g. whether it referred to the technological measures that were applied in NZEB refurbishments, barriers and drivers to apply CE strategies, application of different CE strategies and more contextual information regarding the company profile and perspective of the CE for the company

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[22] This study omits consumer-to-consumer applications, since producers and/or designers of the respective refurbishment solutions do not have direct influence on this.

[23] Nvivo 12 Pro is an qualitative data analyses software package developed by QSR International.

and ET. Furthermore, hierarchies were created within the coding framework to develop a clearer overview of the data that were to be analyzed. This helped to gather and structure all relevant data that were necessary to answer the research question. The coded data were carefully read through to find relevant relations between key themes and structure the results chapter. See Appendix B: Coding framework including hierarchies for the coding framework, including hierarchies.

So the interviews were coded to categorize relevant data that were necessary to achieve the research objective and answer the research question. Both an inductive approach and deductive approach was pursued. With an inductive approach, codes originate from what emerge frequently in the interview data, i.e. 'data-driven' (Thomas, 2003), whereas with a deductive approach the codes originate from preliminary research, i.e. 'a priori' (Stuckey, 2015). According to Seale (2004) such a hybrid approach helps the researcher to add knowledge to the topic. To operationalize this approach, codes were both pre-defined by the literature review, as well as derived from the interview data.

3.2.2.1 Interviewee codes

The interviewees' names and job roles were undisclosed in this study due to confidentiality. Furthermore, the results were encoded so that responses could not be traced to individual companies. The companies were encoded, based on whether they took the role of a contractor as a construction company, encoded as 'CC', or whether they took the role of a producer and supplier company of whole refurbishment solutions or separate elements and, therefore, position themselves as a partner company, encoded as 'PC'. Table 6 shows the codes of each interviewee.

Table 6: Interviewee codes.

Construction company	Partner company
CC1	PC1
CC2	PC2
CC3	PC3
CC4	

3.3 Research Question 2

3.3.1 Data Collection

To answer research question 2, one case study was analyzed in depth regarding an all-electric refurbishment solution. According to the systematic literature review of Hossain et al. (2020), more case studies of the entire building instead of the material level are required to evaluate CE actions within the construction industry, as well as to take into account the design by adopting circular materials, use- and end-of-life phases. Furthermore, the choice to only analyze a NZEB all-electric solution instead of a NZEB plus district heat solution had to do with several reasons. First, from the interviews it became clear that most of the companies were involved in NZEB all-electric solutions, which implies that all-electric solutions are more representative for the industry. Next, and related to the first reason it also became clear that NZEB plus district heat solutions are, therefore, often unique projects.

At the end of the interviews, the purpose of the rest of this study was explained and interviewees were asked whether they were willing to participate by sharing more detailed information on the specific refurbishment proposition. The case study was chosen based on several criteria. First, the willingness to participate was evaluated. Second, the expectation to what extent they could provide the required data was evaluated. Lastly, the application of CE strategies by the company case was evaluated, since without the application of any CE strategies too many assumptions had to be made.

Data was collected through a kick-off meeting at the company's office. Furthermore, documents of the NZEB refurbishment proposition were collected, which included architectural drawings, specifications and conditions and information regarding the materials used.

3.3.2 Data Analysis

To assess the environmental impact of applying different CE strategies in NZEB refurbishments, a LCA was conducted according to the European standard EN 15978 for LCAs on buildings. The Determination Method for the Environmental Performance of Buildings and Civil Engineering Works forms a coherent whole with the *Nationale Milieudatabase (NMD)*, translated in English as National Environmental Database and is managed by the *Stichting Bouwkwaliteit (SBK)*, translated in English as the Foundation for Building Quality. The basis for this method is EN 15804, for product-specific environmental product declarations (EPD), which in turn takes into account the ISO standards for LCA (Stichting Bouwkwaliteit, 2019). The EN 15804 and EN 15978 are part of the standards developed by the European Committee for Standardization (CEN). Although there are environmental performance requirements for new construction, the Building Decree[24] does not require specific environmental performances for refurbishments (Stichting Nationale Milieudatabase, 2020).

This LCA study was modelled with the help of the software One Click LCA, developed by Bionova Ltd. The software is compliant with the EN 15978 standard and is followed by EPDs, which are based on the EN 15804 and ISO 14044 standards. An EPD is a verified documentation of the environmental performance of a product, based on LCA calculations according to the standards ISO 14044, ISO 14040 and EN 15804 (Petrovic et al. 2019). The advantages of using the software is the time efficiency in calculating whole building LCAs as well as the possibility to simulate how to reduce carbon emissions by changing and choosing different materials of which you obtain the results immediately (Petrovic et al., 2019). Furthermore, it is validated by, and compliant with, all sorts of certifications and standards, e.g. *Milieuprestatie Gebouwen (MPG)* for The Netherlands, translated in English as Environmental Performance of Buildings, which is a measure often used in the Dutch context to determine the environmental performance of buildings due to its material use. It is measured in euros per square meter per year, where the monetary value represents the shadow costs explained further in this chapter. Since the energy performance of buildings is increasing, the environmental impact due to the material use become more important to measure its sustainability, while these measures can often conflict each other (RVO, 2020b).

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[24] The Building Decree consists of requirements regarding safety, health, usefulness, energy and the environment to which buildings have to comply (Rijksoverheid, 2020).

3.3.2.1 Goal and Scope

3.3.2.1.1 Goal of the study

The goal of this part of the study was twofold:

1. Identify and discuss how the different impact categories, life cycle stages as well as building elements contribute to the total environmental life cycle impact of a NZEB refurbishment (all-electric), while comparing a linear with a circular design.
2. Investigate how different CE strategies may affect the environmental life cycle impacts of NZEB refurbishments.

3.3.2.1.2 Function and functional unit description

The functional unit (FU) selected for this study was: *providing a climate-controlled space of a residential terraced house of 148,77 m^2 gross floor area with a maximum heat demand of 50 kWh / m^2 / year to be used over a period of 50 years under standard climate conditions within The Netherlands and standard use of the building according to Dutch standards.* The period of 50 years was chosen, since most of the structural building elements used in this study are expected to have theoretical service lives of 50 years. The multi-functionality of buildings has led to LCA studies not defining the functional unit properly, which posed inconsistent system boundaries (Bawden & Williams, 2015). According to a comprehensive literature review by Hossain & Ng (2018), most building LCAs use a functional unit of m^2 of living area or gross floor area over a certain period, often 50 years. This is also confirmed by others, such as Vilches et al. (2017). However, the amount of m^2 gross floor area of the entire building is a suitable alternative and is also taken into account in One Click LCA. Furthermore, with whole building LCAs, limiting the functional unit to a material or component level may lead to erroneous conclusions (Ingrao et al., 2018).

3.3.2.1.3 Description of system under study

The building to which both designs of a NZEB refurbishment proposition could apply to was a terraced house built between 1950 and 1980 within The Netherlands. The building had 2 floors, including the attic. Since this study was not focused on a specific project that was completed, but rather on a design proposition, the exact location was unknown, i.e. it could be anywhere in The Netherlands.

This study compared two different NZEB refurbishment propositions, a linear and circular design proposition. The linear design proposition functioned as the baseline scenario to which the circular design was compared to. The difference between the two designs was the use of a circular building envelope, i.e. external walls and façade, roofs and floors and windows and doors, which is in development by the construction company, rather than the more conventional building envelope. The linear building envelope consisted of structural insulated panels (SIP), which are sandwich panels with structural as well as insulating purposes. The circular design used a wooden frame construction, i.e. wooden skeleton of vertical and horizontal beams in which the insulation material was placed. See figure 8 for an example of the structure of both building methods. This is shown without the interior and exterior finishing.

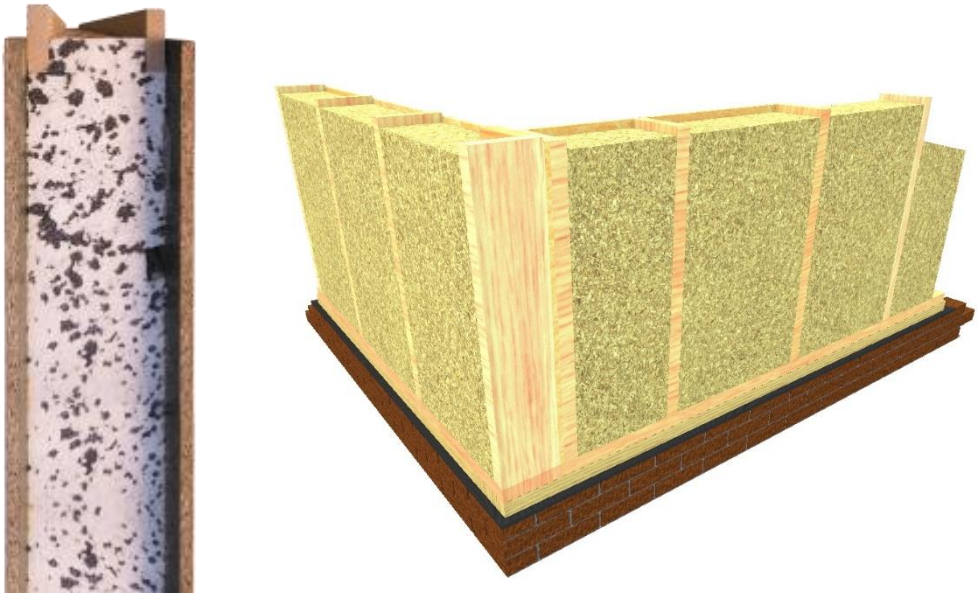

Figure 8: Example of a SIP construction (left) and wooden frame construction (right) (Rc Panels, 2020; Passiefhuismarkt, 2020).

Both designs reflected the use of different design and construction (D&C) strategies, including the use of different materials. Whereas the linear design included a building envelope that was difficult to disassemble due to the bonding techniques of the elements, the circular design used different material selections, such as bio-based and secondary materials, and bonding techniques, which is key to achieve a more sustainable construction sector (Ding, 2014). The detachability and substitutability of the elements extended the service lives of the elements. Together with the use of modular elements, it was expected that the circular design increased the reuse of elements and materials after the service life of the building. Also, both designs used prefabrication to reduce lead time and waste generation on site. For this study, it was assumed that no waste was generated on site, due to the prefabrication of building elements for both designs. This is an understatement since there probably will be some waste, however, data about this was not available. Therefore, the advantages in terms of environmental impacts of the circular design compared to the linear design were expected to be in the extended service life by reuse and the material selection. It was assumed that the installations and energy performance between both designs were equal.

3.3.2.1.4 System boundaries

Regarding the system boundaries, several Building Assessment Modules for LCA could be derived according to the standard EN 15804:2012 (Vilches et al., 2017). In this framework, refurbishment has its own module (B5), which can be further split up into several phases and extensions (see figure 9 and 10 below).

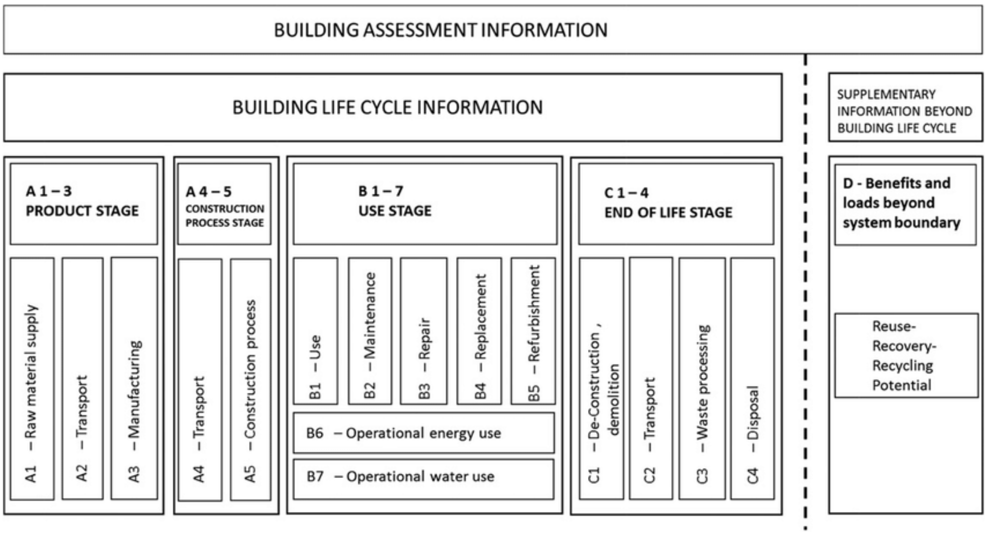

Figure 9: Building Assessment Modules for LCA according to EN 15804:2012 (Vilches et al., 2017).

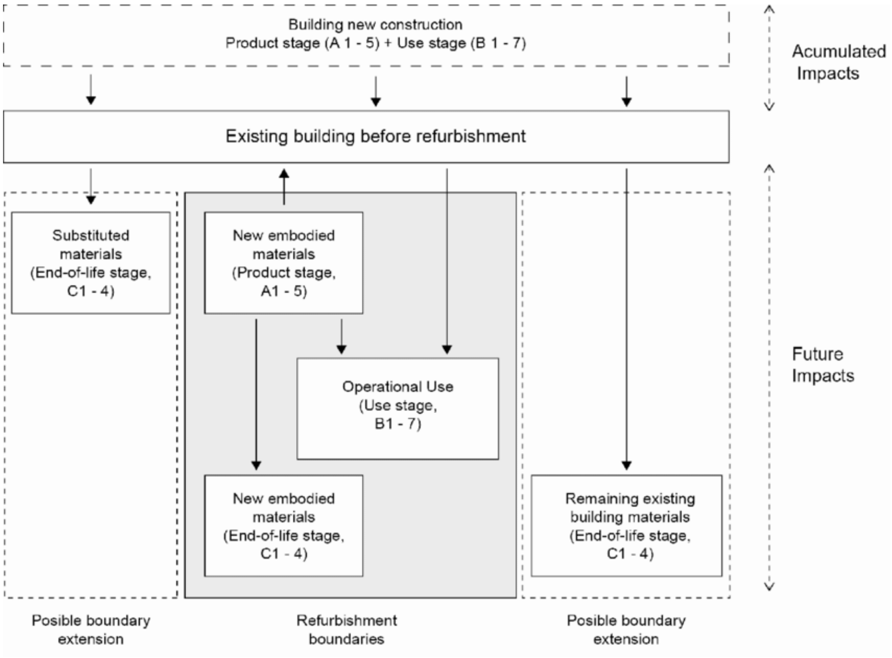

Figure 10: Building Refurbishment Boundaries (Vilches et al., 2017).

In this study, the possible boundary extensions were not taken into account, because it was assumed that these impacts will happen regardless of the refurbishment solutions and, furthermore, often the facades, floors, roofs and installations contribute most to the environmental impact of buildings, rather than the foundation and substructure (Stichting NMD, 2020). Therefore, this study encompassed all phases from cradle-to-grave[25] according to the EN 15978; manufacture of construction materials (A1-3), construction processes (A4-5), use (B1-7) and the end-of-life (C1-4). However, building assessment modules B6-7 were excluded, since it is assumed that a NZEB has a total energy use of zero on an annual basis and the study was focused on material-related impacts, i.e. life cycle embodied impacts. This energy use is related to the building-related and user-related energy use minus the generation of sustainable energy. To

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[25] Cradle-to-grave means all phases from the extraction of raw materials to the end-of-life of the product or service.

continue, the starting point and assumption of the studied refurbishment propositions was that the energy performances were equal, due to measures, such as insulation. Such consequences and dynamics are contextually dependent and should be further evaluated with, for example, dynamic thermal simulation.[26] However, this is beyond the scope of the study.

Furthermore, the net benefits and loads beyond the system boundary (D) due to materials recovery that had reached the end-of-waste state by reuse, recycle or energy recovery were also calculated, which can be more associated with a cradle-to-cradle approach (Bionova Ltd., 2018).[27] These end-of-waste state materials mainly originate from the construction stage (A4-5), use stage (B1-7) and end-of-life stage (C1-4). This approach results in that all benefits are to be allocated to the provider of these secondary materials. The standard EN 15978 refers to an attributional LCA[28] to which decisions could be based upon (Ramírez-Villegas et al., 2019). The reference flows refer to the total amount of added materials and energy required for each of the building designs to perform its function during the service life of 50 years, which are related to the life cycle inventories of table 7 and 8 for a composite product, such as a building.

3.3.2.1.4.1 Allocation procedures for reuse and recycling

Regarding the allocation of end-of-life modelling processes, the European CEN standards prescribe a cut-off approach according to the polluter-pays-principle. Therefore, loads from the production of materials were allocated to the primary user and secondary materials came, therefore, free of burden and should only bear the impacts of the recycling processes. Furthermore, providing materials for further use can result in credits to be voluntarily reported in module D, as described above, as net avoided impacts beyond the system boundary due to reuse, recycling and energy recovery after the end-of-waste state (Mirzaie et al., 2020). This provided transparency regarding the net environmental benefits or loads resulting from secondary materials. To avoid double counting, Mirzaie et al. (2020, p. 5) stated: “Net impacts due to recycling, recovery and reuse at EoL are deducted from those arising from recycled content in the production state”.

3.3.2.2 Life Cycle Inventory

The life cycle inventory (LCI) consisted of all collected data regarding the life cycle stages of the refurbishment proposition converted to the functional unit. In the selected software that was used, data was adopted from EPDs. If these were from the NMD, they were verified by the NMD assessment protocol and, therefore, coherent with the Determination method for the Environmental Performance of Buildings and Civil Engineering Works. EPDs were ISO 14040 or EN 15804 compliant and not older than 10 years. If data from the specific manufacturer was not available, products or materials from another local manufacturer were used or materials from the generic databases or neighboring areas. Products with technical similarities were then searched for, since often this determines the environmental impact of the product or material. If more than one EPD was available, the one that was most associated with the local market was chosen. One Click LCA has a local compensation feature which converts results to local manufacturing

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[26] By using a 3D model of a building, dynamic thermal simulation simulates the thermal behavior of the building regularly.

[27] The end-of-waste state is reached when materials fulfil the following criteria: it is commonly used for specific purposes, has an existing market or demand, fulfils technical requirements for specific purposes and its use will not lead to overall adverse effects (BRE Group, 2013).

[28] Calculating the environmental impact of a product or service, i.e. the share of global environmental burdens attributed to a product or service.

conditions according to CEN/TR 15941 to reflect the potential environmental impact within the selected country when data from other countries are used (Ramírez-Villegas et al., 2019). When EPDs were lacking, generic data from Ecoinvent and GaBi were used, as well as for upstream data. The data regarding building materials as well as installations were provided by the construction company. All the EPDs contained information regarding a cradle-to-grave, cradle to gate or cradle to gate with options[29] approach according to the standards EN 15804 and EN 15978.

To allow comparability and uniform results, some parameters were set beforehand within the software. Regarding transport distances and methods, default values were applied which reflected regional typical values for the product type and was set to European region. Default values were chosen, because of first, a lack of sufficient data and second, the study is focused on a design proposition instead of an actual project location. Transport methods were either 'trailer combination, 40 ton capacity, 100% filling rate' or 'large delivery truck, 9 ton capacity, 100% filling rate'. Other parameters include the service life values of materials or products, i.e. this determines how often the material or product will be replaced within the calculation period. The recommended technical service life was used as default value from the software manufacturer when specific service life values were lacking from the construction company. It represents how long the product or material lasts in good condition. Other options include a commercial service life, which is used for commercial construction and these are often shorter than the technical service life. Furthermore, product-specific service lives were also possible, which may vary by manufacturer (Bionova Ltd., 2020). The service lives of foundations and substructures were set as permanent, since these will not be replaced. The Netherlands was set as material manufacturing localization target for the local compensation feature. The end-of-life scenario was set on material-locked, which was the only option for the LCA tool with multiple impact categories and was mentioned as recommended. This material-locked end-of-life scenario option means that the end-of-life scenario, e.g. how waste is treated, is determined by what is most typical for that material type. Additional options include: market scenarios, which determines the end-of-life scenario that is most typical for that material or product in the specific market and EPD scenarios, which is determined by what is stated in the EPD. The latter two options are both user-adjustable, so include more possibilities to model the end-of-life scenario per material input. However, these options were not available with the LCA tool used for the chosen impact categories. But, for the sensitivity analysis explained further in section 3.3.2.4.1 Sensitivity analysis, the default parameter was set to market scenarios, since this option was available for the carbon footprint tool to determine the impact on climate change used for this analysis. Furthermore, the required user-adjustable options were possible for the sensitivity analysis and market scenarios represent the impact per material more realistically, since it represent the default end-of-life scenario within the Dutch context. See table 7 and 8 for the life cycle inventory of all main materials and products of each proposition.

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[29] Cradle to gate includes all life cycle phases from the extraction of raw materials until the product leaves the 'factory gates'. When options are included, additional information regarding the end-of-life (C1-4) is provided.

Table 7: Life cycle inventory of the linear NZEB refurbishment proposition.

Building elements	Linear design	Amount	Unit	Service life	Country
Foundation, sub-surface, basement and retaining walls	Concrete slab (for energy module)	0,24	m³	Permanent	The Netherlands
	80 mm EPS100 hard insulation	2,9	m²	Permanent	The Netherlands
External walls and façade	250 mm EPS100 insulation	43,32	m²	50 years	France
	Chipboard 11mm	293,28	kg	50 years	The Netherlands
	Mineral brick slips	21,16	m²	50 years	Germany
	Mineral façade plaster	21,16	m²	50 years	France
	80 mm rock wool insulation	3,54	m²	50 years	France
	Anchor rail construction	96,33	kg	50 years	Germany
Floors and roofs	270 mm GPS floor insulation	49,59	m²	50 years	Germany
	PIR insulation panels	67,26	m²	50 years	France
	Metal roof sheet	134,52	m²	50 years	Italy
Windows and doors	PVC-U window frames triple glazed	21,52	m²	50 years	Germany
	Skylight triple glazed 55x78cm	0,43	m²	50 years	Denmark
Building systems and installations	PV panels 7840 watt/building	24,5	unit	25 years	Vietnam
	Air-water heat pump	1	unit	15 years	Germany
	Buffer vessel	80	kg	15 years	Germany
	Heat recovery unit	1	unit	15 years	The Netherlands
	Inverter PV	1,70	unit	15 years	France
	Monitoring unit	1	unit	15 years	France

Table 8: Life cycle inventory of the circular NZEB refurbishment proposition.

Building elements	Circular design	Amount	Unit	Service life	Country
Foundation, sub-surface, basement and retaining walls	Concrete slab (for energy module) 80 mm EPS100 hard insulation	0,24 2,9	m^3 m^2	Permanent Permanent	The Netherlands The Netherlands
External walls and façade	150 mm non-virgin rock wool insulation in cavity Mineral brick slips Gypsum plasterboard 210 mm bio-based cellulose insulation in element 15 mm multiplex Wooden beams (non-virgin) 15% of façade element Steel L profile	43,32 43,32 43,32 43,32 43,32 1,36 0,014	m^2 m^2 m^2 m^2 m^2 m^3 m^3	50 years 50 years 50 years 50 years 50 years 50 years 50 years	The Netherlands Germany Turkey The Netherlands France The Netherlands The Netherlands
Floors and roofs	270 mm non-virgin GPS floor insulation 100 mm non-virgin rock wool insulation for cavity 300 mm bio-based cellulose insulation in elements Wooden beams 15% of roof element (non-virgin) 15 mm multiplex	49,59 67,26 67,26 3,03 134,52	m^2 m^2 m^2 m^3 m^2	50 years 50 years 50 years 50 years 50 years	Germany The Netherlands The Netherlands The Netherlands France
Windows and doors	Wooden window frames, triple glazed Skylight triple glazed 55x78cm	21,52 0,43	m^2 m^2	50 years 50 years	Sweden Denmark
Building systems and installations	PV panels 8540 watt/building Air-water heat pump Buffer vessel Heat recovery unit Inverter PV Monitoring unit	24,5 1 80 1 1,70 1	unit unit kg unit unit unit	25 years 15 years 15 years 15 years 15 years 15 years	Vietnam Germany Germany The Netherlands France France

3.3.2.3 Life Cycle Impact Assessment

For the life cycle impact assessment (LCIA), the impact assessment methodology CML – IA 2012 was used, developed by the University of Leiden. This method is required by the European EN 15978 and EN 15804 standards (Bionova Ltd., 2018). Furthermore, it suits well with the environmental impacts associated with buildings, which is documented by several studies (Ingrao et al., 2018). Impact categories that were used that could be modelled with One Click LCA were global warming potential (GWP)[30], acidification potential (AP)[31], eutrophication potential (EP)[32], ozone depletion potential (ODP)[33], photochemical ozone creation potential (POCP)[34] and total use of primary energy (TUPE)[35] (ex. used as raw materials), since these categories are mostly related to the total environmental impact of buildings (Ingrao et al., 2018) and were included in all EPDs used as data source.

Despite the calculation of mid-point indicator results, the conversion to shadow costs or Environmental Costs Indicator (ECI) was done by multiplying the results with a weighting factor expressed in a monetary value often used in the Dutch context, including the summation to one score. See table 9 for the weighting factors. This monetary value reflects the highest allowable costs (prevention costs) per unit of emission control by the government (Stichting NMD, 2020a). The values are developed by the Environment, Energy and Process Innovation part from *TNO*, the Dutch organization for applied scientific research. However, one difference was made by the Determination Method for the Environmental Performance of Buildings, whereas previously the total use of primary energy was set to 0€/kg equivalent (Stichting NMD, 2020a). Further conversion of the summarized ECI score to a functional equivalent of m^2 / gross floor area / year led to the Environmental Performance of Buildings (*MPG)* of both designs. Although the use of such weighting factors has limitations related to the subjectivity of the method, it could lead to clear recommendations for users of the results. Therefore, both results were communicated. See table 9 for the weighting factors.

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[30] GWP is a relative measure of how much heat a gas traps in the atmosphere, calculated in carbon dioxide equivalents and a time range of 100 years (Bionova Ltd., 2018).

[31] AP is described as the acidification of soils and waters by the ability of substances to build and release H+ ions. Is it measured in sulphur dioxide equivalents (Bionova Ltd., 2018).

[32] EP is described as the enrichment of nutrients in aquatic or terrestrial places and measured in phosphate equivalents (Bionova Ltd., 2018).

[33] ODP represents a relative measure of a substance to destroy ozone gas and is measured in chlorofluorocarbon-11 equivalents (Bionova Ltd., 2018).

[34] POCP represents smog formation due to the creation of ozone and measured in ethylene equivalents (Bionova Ltd., 2018).

[35] TUPE describes the total non- and renewable primary energy use, excluding the primary energy resources used as raw materials. It is measured in MJ.

Table 9: Weighting factors (based on Stiching NMD, 2020a).

Environmental impact category	Equivalent unit	Weighting factor (€/kg equivalent)
Global warming potential (GWP)	CO_2 eq.	€ 0,05
Acidification potential (AP)	SO_2 eq.	€ 4
Eutrophication potential (EP)	PO_4 eq.	€ 9
Ozone depletion potential (ODP)	CFC-11 eq.	€ 30
Photochemical ozone creation potential (POCP)	C_2H_4 eq.	€ 2
Total use of primary energy (TUPE)	MJ	€ 0,00008[36]

Several analyses were conducted to analyze both designs in depth according the goal and scope of the study. After having obtained the absolute characterized mid-point results, these results were converted to relative percentages to compare the linear and circular design by impact category and life cycle stage on one graph. The environmental impact of each category were shown on a scale of 100%, with the highest impact value of both designs set to 100%. The net benefits, i.e. negative values that were reported in module D, were kept outside the 100% range.

However, to state something about the relevance of each impact category, i.e. contribution of each impact category to the overall environmental impact, the results were weighted according to the weighting factors described above to determine the most contributing impact categories. A cut-off point of 80% cumulative impact was chosen to find the most relevant impact categories (Mirzaie et al., 2020). Afterwards, for each most contributing impact category, the most relevant life cycle stages (dominance analysis), building elements and materials were identified to obtain deeper insights into the different processes of each design at different levels of detail.

3.3.2.4 Interpretation

3.3.2.4.1 Sensitivity analysis

To increase the robustness of the results from the LCA, the quality of the interpretation of the results and to state something about the potential environmental impact reduction of different CE strategies, a sensitivity analysis was conducted. Besides the linear and circular baseline scenarios, this analysis included three additional scenarios, each applying different CE strategies. Furthermore, it was only focused on GWP in kg CO_2-eq./FU, because of the following reasons. First, as previously stated, GWP was the most relevant impact category and contributed for at least 56% to the weighted impact of both designs. Second, from a political and societal perspective, the Dutch government has clear and urgent objectives to reduce GHG emissions by 49% in 2030 relative to 1990, whereas the built environment has a central place in the Dutch Climate Agreement. It furthermore states that this societal transition affects everyday life, i.e. it is one of the biggest challenges nowadays that involves citizens, companies and government (Rijksoverheid, 2019).

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[36] Weighting factor is €0,16 / kg Sb eq. 0,000481 kg Sb eq. / MJ. Therefore, 0,16 * 0,000481 = € 0,00008 / MJ (Stichting NMD, 2020a).

Last, software restrictions posed limitations in modelling different scenarios for other impact categories than GWP.

The three additional scenarios included: (1) the use of bio-based materials, (2) use of secondary materials and (3) lifetime extension of the materials by reusing them at the end-of-life. The linear baseline is modelled the same as in previous analyses, whereas the circular baseline covers all three CE strategies. For example, in this baseline scenario, it was assumed that 50% of the rock wool insulation, GPS insulation and wooden beams are from secondary materials. Furthermore, due to the demountable construction, it was assumed that 100% of the wooden façade construction and roof element, including its insulation would be reused at the end-of-life. Furthermore, bio-based materials were used for some of the insulation materials. It should be noted that although building elements: foundation, sub-surface, basement and retaining walls and building systems and installations were included in the analysis, they were modelled equally between all scenarios. See table 10 and the subsequent paragraph for the differences of the scenarios in detail, including the end-of-life processes per material and additional assumptions.

Table 10: Differences between NZEB refurbishment scenarios, including end-of-life processes and assumptions.

Scenarios	Materials	EoL process	Assumptions
Linear BS	**Foundation, sub-surface, basement, retaining walls**		
	Concrete slab	Concrete to aggregate	
	EPS insulation	Plastic-based incineration	
	External walls and façade		
	EPS insulation	Plastic-based incineration	
	Mineral plastering	Cement/mortar use in backfill	
	Mineral brick slips	Brick crushed to aggregate	
	Chipboard	Wood incineration	
	Rail anchoring	Steel recycling	
	Rock wool insulation	Landfill (for inert materials)	
	Floors and roofs		
	GPS insulation	Plastic-based incineration	
	PIR insulation	Plastic-based incineration	
	Galvanized steel sheets	Steel recycling	
	Windows and doors		
	Skylight triple glazed	Glass recycling	
	PVC-U window frames triple glazed	Glass recycling	
	Building systems and installations		
	PV panels	Metal recycling	
	Air-water heat pump	Metal recycling	
	Buffer vessel	Metal recycling	
	Heat recovery unit	Metal recycling	
	Inverter PV	Metal recycling	
	Monitoring unit	Metal recycling	
Circular BS	**Foundation, sub-surface, basement, retaining walls**		
	Concrete slab	Concrete to aggregate	
	EPS insulation	Plastic-based incineration	
	External walls and façade		

	Mineral brick slips	Brick crushed to aggregate	*50% of rock wool insulation and wooden beams are from secondary materials. *Secondary materials free of burden. *No additional impacts for recycling processes from the use of secondary materials. *100% reuse of wooden façade element and insulation. Module D only includes the net benefits of avoided virgin production.
	Plywood	Reuse as material	
	Rock wool insulation	Reuse as material	
	Wooden beams	Reuse as material	
	Cellulose insulation	Reuse as material	
	Gypsum plasterboard	Gypsum recycling	
	Structural steel profile	Steel recycling	
	Floors and roofs		*50% of rock wool, GPS insulation and wooden beams are from secondary materials. *Secondary materials free of burden *No additional impacts for recycling processes from the use of secondary materials. *100% reuse of wooden roof element and insulation. Module D only includes the net benefits of avoided virgin production.
	GPS insulation	Plastic-based incineration	
	Plywood	Reuse as material	
	Wooden beams	Reuse as material	
	Cellulose insulation	Reuse as material	
	Rock wool insulation	Reuse as material	
	Windows and doors		
	Skylight triple glazed	Glass recycling	
	Wooden window frames triple glazed	Glass recycling	
	Building systems and installations		
	PV panels	Metal recycling	
	Air-water heat pump	Metal recycling	
	Buffer vessel	Metal recycling	
	Heat recovery unit	Metal recycling	
	Inverter PV	Metal recycling	
	Monitoring unit	Metal recycling	
Bio-based	**Foundation, sub-surface, basement, retaining walls**		
	Concrete slab	Concrete to aggregate	
	EPS insulation	Plastic-based incineration	
	External walls and façade		*Only bio-based insulation and façade facing
	Plywood	Wood incineration	
	Wooden beams	Wood incineration	
	Cellulose insulation	Landfill (for inert materials)	
	Structural steel profile	Steel recycling	
	Wooden façade facing	Wood incineration	
	Floors and roofs		*Only bio-based insulation
	Plywood	Wood incineration	
	Wooden beams	Wood incineration	
	Cellulose insulation	Landfill (for inert materials)	
	Windows and doors		

	Skylight triple glazed	Glass recycling	
	Wooden window frames triple glazed	Glass recycling	
	Building systems and installations		
	PV panels	Metal recycling	
	Air-water heat pump	Metal recycling	
	Buffer vessel	Metal recycling	
	Heat recovery unit	Metal recycling	
	Inverter PV	Metal recycling	
	Monitoring unit	Metal recycling	
Secondary materials	**Foundation, sub-surface, basement, retaining walls**		
	Concrete slab	Concrete to aggregate	
	EPS insulation	Plastic-based incineration	
	External walls and façade		*50% comes from secondary materials.
	Mineral brick slips	Brick crushed to aggregate	
	Plywood	Wood incineration	
	Rock wool insulation	Landfill (for inert materials)	
	Wooden beams	Wood incineration	
	Cellulose insulation	Landfill (for inert materials)	
	Gypsum plasterboard	Gypsum recycling	
	Structural steel profile	Steel recycling	
	Floors and roofs		*50% comes from secondary materials.
	GPS insulation	Plastic-based incineration	
	Plywood	Wood incineration	
	Wooden beams	Wood incineration	
	Cellulose insulation	Landfill (for inert materials)	
	Rock wool insulation	Landfill (for inert materials)	
	Windows and doors		*50% comes from secondary materials.
	Skylight triple glazed	Glass recycling	
	Wooden window frames triple glazed	Glass recycling	
	Building systems and installations		
	PV panels	Metal recycling	
	Air-water heat pump	Metal recycling	
	Buffer vessel	Metal recycling	
	Heat recovery unit	Metal recycling	
	Inverter PV	Metal recycling	
	Monitoring unit	Metal recycling	
Lifetime extension by reuse at EoL	**Foundation, sub-surface, basement, retaining walls**		
	Concrete slab	Concrete to aggregate	
	EPS insulation	Plastic-based incineration	
	External walls and façade		*100% reuse of materials. Module D only includes the net benefits of avoided virgin production.
	Mineral brick slips	Reuse as material	
	Plywood	Reuse as material	
	Rock wool insulation	Reuse as material	
	Wooden beams	Reuse as material	
	Cellulose insulation	Reuse as material	
	Gypsum plasterboard	Reuse as material	
	Structural steel profile	Reuse as material	
	Floors and roofs		*100% reuse of materials. Module D only includes the net benefits of avoided virgin production.
	GPS insulation	Reuse as material	
	Plywood	Reuse as material	
	Wooden beams	Reuse as material	

	Cellulose insulation	Reuse as material	
	Rock wool insulation	Reuse as material	
	Windows and doors		*100% reuse of materials. Module D only includes the net benefits of avoided virgin production.
	Skylight triple glazed	Reuse as material	
	Wooden window frames triple glazed	Reuse as material	
	Building systems and installations		
	PV panels	Metal recycling	
	Air-water heat pump	Metal recycling	
	Buffer vessel	Metal recycling	
	Heat recovery unit	Metal recycling	
	Inverter PV	Metal recycling	
	Monitoring unit	Metal recycling	

Next, the bio-based design (1) only used bio-based insulation and façade coverings, instead of also rock wool insulation and mineral brick slips. Furthermore, the default end-of-life scenarios per material in the specific market are used. For example, timber products will be incinerated with energy recovery at the end-of-life, whereas the cellulose insulation will be landfilled. For the design with secondary use of materials (2), it was assumed that all materials from the concerning building elements, i.e. floors and roofs, external walls and façade and windows and doors, are used from 50% secondary materials. Although the assumption of 50% secondary material use is somewhat arbitrary, it was chosen since first, this was also assumed for the circular baseline scenario and, therefore, other CE strategies could be isolated in this way. Last, this percentage could more or less reflect reality since with recycling often quality degradation of the materials takes place, which means that for example a percentage of 100% would not be realistic in that sense. According to the allocation method of the CEN standards, secondary materials come free of burden, since all impacts regarding the production are allocated to the first user according to the polluter-pays-principle. (Mirzaie et al., 2020). Therefore, the impacts from modules A1-3 were divided by 2. Although secondary materials should bear the impacts from recycling or other processing processes after the end-of-waste state, lack of data from recycled or reused materials forced to assume that no additional impacts were present from these processes. This was of course an understatement and something to be aware of. Also, default end-of-life scenarios per material were used, with credits allocated to module D divided by 2 to avoid double counting. For the scenario with lifetime extension by reusing all materials at the end-of-life (3), it was assumed that 100% of the materials will be reused. In reality, this percentage would be lower due to some material losses, however, due to the demountable design, lack of data and for the sake of this study it was assumed that 100% of the materials from the concerning building elements will be reused. This means that for scenarios, where secondary materials are used and provided at the end-of-life, both the impacts from modules A1-3 and D of these materials are divided by 2, since module D only accounts for net benefits or loads, i.e. this avoids double counting. During the study, problems within the calculation mechanics of the software to calculate module D by the reuse of materials as end-of-life scenario occurred, which meant that the author had to calculate that by hand. Due to the lack of data regarding processing steps and their impacts after the end-of-waste state, it was assumed that module D only included the net benefits of avoiding virgin material production. This probably lead to an overestimation of the benefits beyond the system boundary.

3.3.2.4.2 Life cycle gap analysis

Scholars state that the conventional cradle-to-grave approach, also when including credits for substituted materials is not completely suitable for LCA interpretation with a circular economy mindset (Dieterle et al., 2018). Circular economies require the closing of material loops, additional responsibility for producers and upcycling rather than down-cycling. This challenges the way LCAs are conducted and interpreted.

Therefore, Dieterle et al. (2018, p. 1) propose a life cycle gap analysis (LCG-A), which “highlights the theoretical circularity gaps with regard to the potential environmental impacts during a product’s life cycle in terms of system losses, the so-called life cycle gaps, between an ideal closed system and the status quo.” In other words, it visualizes the gap between an ideal closed system and the current system to interpret LCA results and support decisions in an additional way.

After having analyzed and compared the linear and circular design of a refurbishment proposition to NZEB all-electric, the results were interpreted with the complementary LCG-A. This was done by calculating the life cycle gaps (LCG) of both designs for a total score by using the weighting factors from table 9 above, i.e. the difference between the environmental impacts resulting from the materials and manufacturing processes (A1-3) of the product and the environmental benefits from its potential second life (module D). To calculate the LCG, equation 1 was used (Dieterle et al., 2018).

$$E_{LCG}(X_{old}) = \sum_{i=1}^{n} E_M(x_i) + E_P(X) - C_{EoL}(X; x_i) \rightarrow MIN! \rightarrow E_{LCG}(X_{new}) \qquad (1)$$

- $E_{LCG}(X_{old})$ is the life cycle gap of the old product X, which is in this study the linear NZEB refurbishment proposition. Therefore, it relates to the environmental impacts of the materials and manufacturing processes minus the environmental credits from module D.
- $E_m(x_i)$ relates to the environmental impacts of the product’s materials (M) related to the mass x and type of material i.
- $E_P(X)$ describes the environmental impacts of the manufacturing processes of product X.
- $C_{EoL}(X; x_i)$ relates to the environmental credits of the end-of-life activities of product X or product’s materials x_i.
- $MIN! \rightarrow E_{LCG}(X_{new})$ describes the search to minimize the LCG of the new product, i.e. the system losses regarding closing circularity gaps. The new product was in this study the circular NZEB refurbishment proposition.

Figure 11 below shows the interpretation of LCA results with the LCG approach, where the amount of environmental credits of the end-of-life phase are subtracted from the environmental impacts of the manufacturing phase to show the system losses. This approach allowed the quantitative results of the LCA to be interpreted in a way that it supports innovations to be related with the qualitative framework of CE, i.e. it highlights CE potentials.

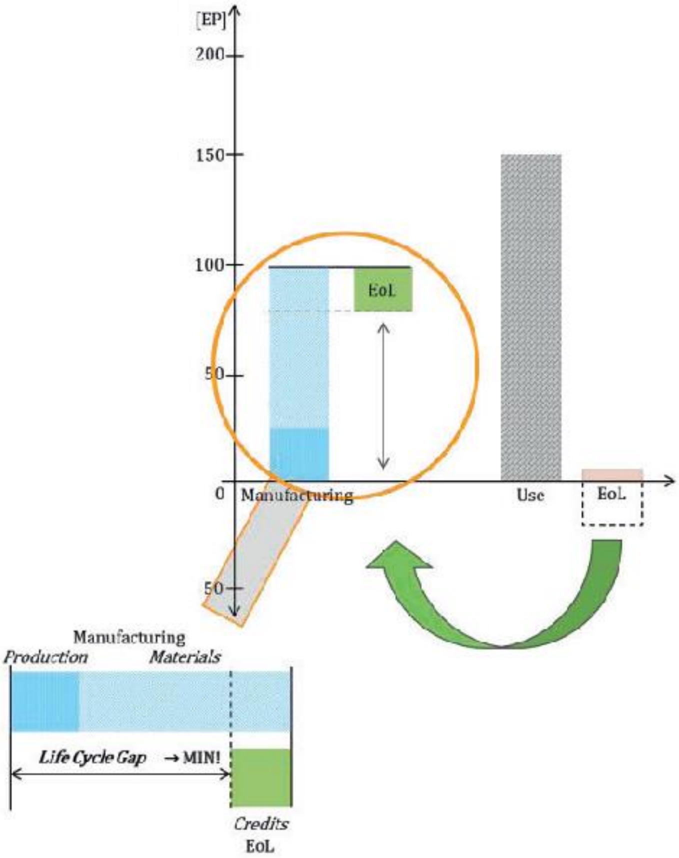

Figure 81: Interpretation of LCA results with a LCG-A approach (Dieterle et al., 2018).

3.4 Research Quality Indicators

This research took an onto-epistemological perspective that was related to critical realism.[37] This was well associated with the mixed methods research design chosen and therefore, the quality indicators of Maxwell (1992) were taken into account. To ensure descriptive validity[38], the interviews were manually transcribed so that no information was missed and asked to be checked by the interviewees when some parts were unclear. Furthermore, interpretive validity[39] was ensured by checking whether the researcher captured the meaning of the participants' perspectives correctly during the interviews by asking confirmation.

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[37] Critical realism is a philosophical branch, where it is believed that objective reality exists from an ontological perspective, but epistemologically that reality is understood through personal lenses and therefore individual perspectives are valuable to involve in research (Maxwell, 2012).

[38] Descriptive validity is about the accuracy and objectivity of the information gathered.

[39] Interpretive validity is about the meaning that is attributed to the behavior and perspective of the participant.

4. Results

This chapter elaborates on the findings of this study, first regarding the qualitative part from the interviews and subsequently the quantitative part. The qualitative part includes the findings of the seven interviews conducted, whereas the quantitative part includes the LCA from the case study.

4.1 Research Question 1

This section explains the insights from the seven interviews conducted, split between two major subsections: NZEB refurbishments and Circular economy in NZEB refurbishments. The first is split between four themes: 5.1.1.1 Measures of NZEB refurbishments, 5.1.1.2 Difference between NZEB refurbishment solutions, 5.1.1.3 Design and construction strategies in NZEB refurbishments and 5.1.1.4 Challenges of NZEB refurbishments. The latter is split between two themes: 5.1.2.1 CE strategies in NZEB refurbishments and 5.1.2.2 Barriers and drivers. In this section, I have translated all quotations from Dutch into English.

4.1.1 NZEB refurbishments

This subsection provides insights into the context of NZEB refurbishments. It sets out the applied measures relating to the building envelope and installations by the companies of the interviewees, to achieve a NZEB refurbishment. Furthermore, it explains the differences in measures of an all-electric or plus district heat solution. It also elaborates on the challenges that interviewees experience regarding such refurbishments and the different D&C strategies that are applied to implement these measures.

4.1.1.1 Measures of NZEB refurbishments

From the interviewees it is clear that many variations in measures are possible for the refurbishment of buildings in general and NZEB in particular, to stimulate the ET in the construction sector. Furthermore, it is evident that the interviewees have different approaches to offer their refurbishment proposition or products, i.e. the format in how they offer their product(s) differs. Whereas some offer a so called ‘menu’ with many options of measures to choose from, others provide a more ‘one size fits all’ approach. Regarding the first, (CC1) said:

> It is like an Ikea idea, where you have a rack with all kinds of packages and dependent on the corporation’s wish, the composition of the neighborhood, the social structure and the condition of the property, we decide together which packages we will open and merge into a proposition.

Regarding the latter, (PC1) said:

> I am a developer of propositions, so I develop a proposition and apply it like that. You should see it as a car, which you buy ready-made with all kinds of options included and excluded that you receive in three months including a warranty and that’s it. That’s me.

This difference is remarkable and could be first, a consequence of the different supply chain positions the companies are in. Whereas the first is positioned as a contractor, the latter is more positioned as partner company that develops and supplies refurbishment propositions. Second, the divergent policy perspectives of the corporations could be a reason for a flexible format.

However, to achieve a NZEB refurbishment all interviewees mentioned a combination of measures to the building envelope to increase insulation and ventilation and the replacement of installations. They all start with the building envelope, including the façade with windows, window frame and roof, to reduce the energy demand due to extra insulation. For example, (CC1) stated: “It is a little bit dependent on the ambition, but if you want to achieve a NZEB, then you should always have a complete envelope around it.” Since the requirement of a NZEB is that the energy use on a yearly basis equals zero, drastic insulation measures are required to achieve this.

Furthermore, regarding the installations to provide a comfortable indoor climate and sufficient energy, most interviewees mentioned an energy module with all the necessary installations. The general installations mostly mentioned were a heat pump for space heating and hot tap water, including a boiler. Besides, the energy module included heat recovery from the ventilation and the inverter for the PV panels, whereas the PV panels are installed on the roof. The type of heat pump varied, although most interviewees mentioned an air-to-water heat pump. Besides, a ground source heat pump and air-to-air heat pump were mentioned. Although these measures were commonly mentioned, many combinations of measures are possible and this also depends on the type of solution, e.g. NZEB all-electric or NZEB plus district heat.

4.1.1.2 Difference between NZEB refurbishment solutions

Regarding the type of refurbishment solution, most interviewees (5) have been involved in both solutions, e.g. NZEB all-electric and NZEB plus district heat. Only two of them have been only involved in all-electric solutions and no one was solely involved in NZEB plus district heat (see figure 12). However, one of the five interviewees (PC4) that were involved in both solutions only conducted a pilot project regarding NZEB plus district heat where they only did the monitoring instead of providing the installations. Another interviewee (CC2) mentioned that the NZEB plus district heat project in which the company was involved was quite an unique project. Therefore, from the interviews it could be derived that NZEB plus district heat solutions are less implemented than NZEB all-electric and that these are still in development. See figure 13 for a simplified visualization of both solutions.

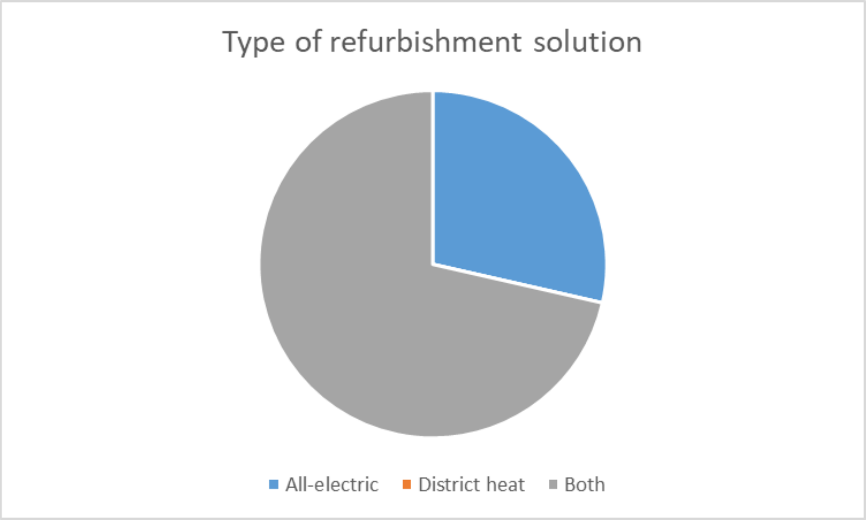

Figure 12: Pie chart showing the refurbishment solution the interviewees have been involved in.

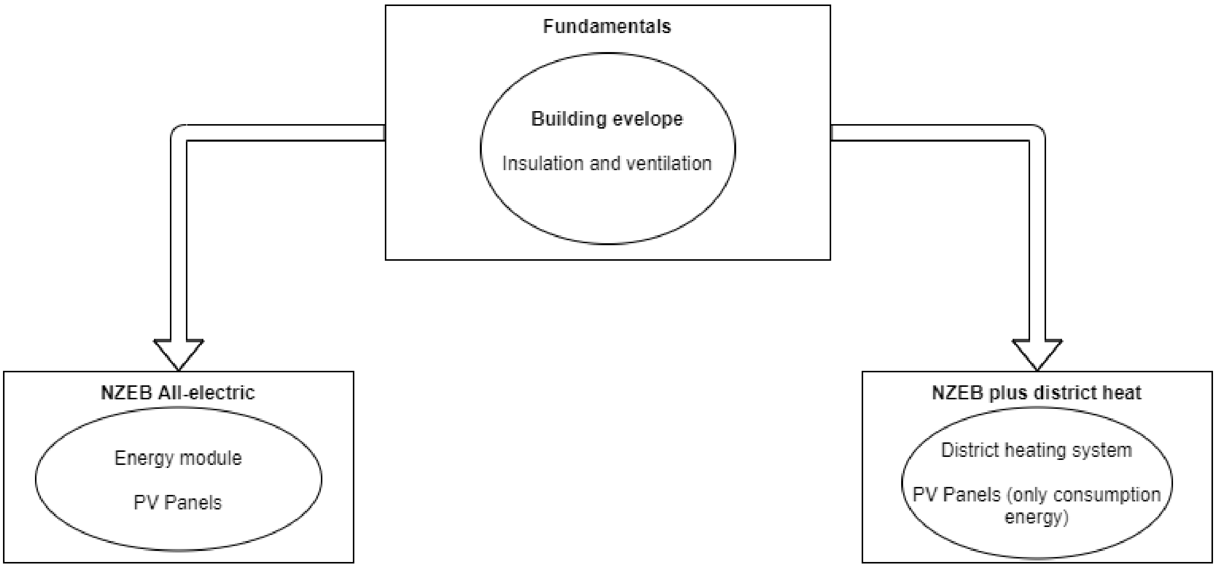

Figure 13: Simplified measures in NZEB refurbishment solutions.

The choice for NZEB all-electric or NZEB plus district heat depends on several factors. For example, amongst others, (CC3) said:

> Yes, what does the corporation wants? Is it already without natural gas? What is actually the kind of building? Because if you go to 10 floors high, you have a very small roof surface. Then you can try everything you want, but you can never install enough PV panels on the roof.

Furthermore, (CC2) stated:

> Because it is not an all-electric type, only the consumption energy of the residents, so for their TV, refrigerator, etc. is compensated by PV panels and the use of energy regarding space heating and hot tap water is compensated by demonstrable sustainable city heat.

This shows that the choice to go all-electric or plus district heat depends on multiple factors, such as the demand from the principal or corporation and the structure of the built environment. Furthermore, it shows that district heat is mainly used for stacked or high-rise buildings due to a lack of roof surface for PV panels, which results in a different origin of energy used for appliances and space heating and hot tap water. Therefore, most of the interviewees found it more difficult to refurbish stacked or high-rise buildings due to the extra challenges of energy generation.

In contrast to this, some interviewees did not care about the type of solution. For example, since (PC2) offers 2050-ready solutions by first insulating the building envelope severely, (PC2) stated:

> We actually ensure that the property, the building, will be packed with a new façade and roof, so it will use much, much less energy. Whether you then fill in the leftover all-electric, or with a heating network, that does not really matter to us. You just have to start using a lot less energy.

Besides, (PC1) said: “Look, at this moment we refurbish all kinds of buildings, even high apartment buildings. We already did a couple of high apartment buildings. A heating network happens to come as an idea when there is a heat network nearby.” It is noteworthy that these last two interviewees were both taking the role as partner company, instead of the traditional contractor as a construction company.

4.1.1.3 Design and construction strategies in NZEB refurbishments

Despite some common measures were applied by most interviewees, how these measures were applied varied, i.e. different D&C strategies for a CE could be derived from the interviews. Figure 14 shows how many of the interviewees mentioned the different D&C strategies.[40]

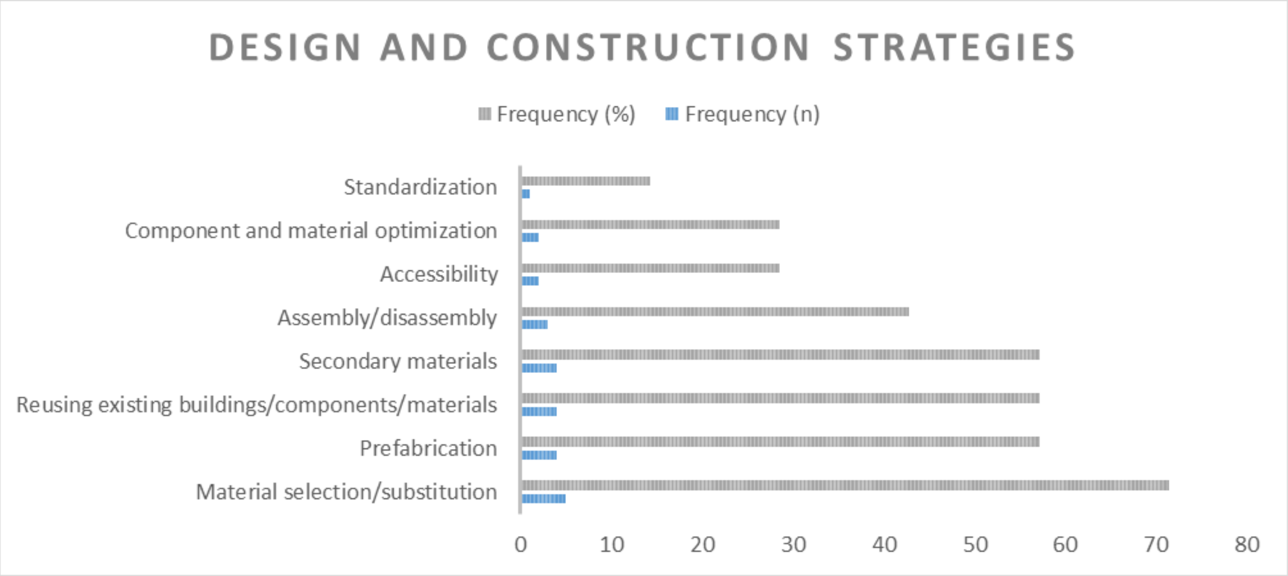

Figure 14: Bar chart showing how many interviewees spoke about the different design and construction strategies.

From figure 14 above it can be noted that interviewees mostly spoke about material selection/substitution, namely five out of seven interviews. This was followed by prefabrication, reusing existing buildings/components/materials and secondary materials, both four interviewees. However, since this taxonomy of D&C strategies was firstly developed for new construction projects, it is not surprising that reusing existing buildings/components/materials was mentioned a lot by the interviewees in relation to refurbishment projects. Furthermore, assembly/disassembly was mentioned by three interviewees, whereas accessibility and component and material optimization were mentioned by two interviewees. Optimized shapes/dimensions and standardization were only mentioned by one interviewee.

However, it is surprising that standardization was only mentioned by one interviewee, since this is important for industrialization to reduce the costs of realizing NZEB refurbishments. It could be that standardization and component and material optimization were used interchangeably, where both focus on the minimization of different components or materials used. However, the first is more focused on ensuring materials recovery at the end-of-life. For the same reason, it seems conceivable that prefabrication was mentioned by four of the interviewees. Furthermore, from the interviews it could be derived that most interviewees thought well about the materials they have used, which can be seen in figure 14.

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[40] Strategies that were not mentioned at all were left out.

Regarding the building envelope, on the one hand, one interviewee mentioned the use of a steel frame, which relates to D&C strategies, such as material selection/substitution, accessibility and optimized shapes/dimensions. For example, (PC1) stated:

> An advantage is that it is very light weighted. Also, steel is dimensionally stable and accurate to the millimeter. … Another advantage of steel is the open construction, where I can incorporate installation techniques easily into the façade, so we do that.

On the other hand, some interviewees were using wood within the building envelope, since it captures CO_2 and besides the insulation properties of the panels, it also has construction possibilities. This relates to the D&C strategies of material selection/substitution and component and material optimization. For example (CC4) states about structural insulated panels (SIP): "So those are composite panels with a very high insulation value, which you can also use constructively, so where you can actually build with."

From the interviews it could be derived that this difference in material selection has to do, among other things, with different perspectives about the environmental sustainability of various materials and the difficulties that play a role in determining this. On the one hand, (CC3) said that more and more companies are going to apply wood, however, he states: "But if we do that for 100.000 houses only in the Netherlands, then we have to plant many, many trees." To continue on this, one interviewee (PC2) mentioned that they have been accused, merely on beliefs or feelings, by using a product that has its origin with fossil fuels, despite the fact they conducted a LCA that contradicts their statements. On the other hand, others stated that wood is preferable, since it captures CO_2. This shows the difficult discussions regarding material selection/substitution and their environmental impacts.

Furthermore, assembly/disassembly is mentioned by three interviewees. For example (PC2) stated: "Most of the construction companies that have a NZEB refurbishment proposition try to at least take into account the ability to demount components". However, this interviewee mentioned the difficulty of this with refurbishment projects in comparison with new construction. For example (PC2) said: "Regarding our refurbishment façade, that is less obvious, since those are developed with the exact measurements for that specific building." This shows the different challenges that can be experienced between new constructions and refurbishments.

Some interviewees mentioned that the biggest environmental benefits will be gained when you demolish as little as possible. However, one interviewee mentioned that demolition of the existing façades is sometimes required when there is 'gespikkeld bezit', translated in English as speckled possession. It refers to apartment buildings that are partly owned by corporations and partly by private actors. This can result in the refurbishment of some of the buildings. The demolition of some façades is then required, otherwise, the difference in thickness will be too noticeable.

Regarding the installations, accessibility is mentioned by two interviewees. For example (CC4) said: "Those are actually kept outside of the building envelope and also have a separate entry. So for maintenance and possibly a defect, the occupants do not even have to be home." This was in line with the perspective of another interviewee who stated that the social component of NZEB refurbishments is decisive in projects, i.e. the reduction of nuisance for the occupants. In contrast, other interviewees were searching for possibilities to integrate the installations within the building envelope to reduce the loads during the process of refurbishing and reduce the lead time.

4.1.1.4 Challenges of NZEB refurbishments

From the interviewees, several challenges to realize a NZEB refurbishment were noticeable. These can be allocated to three main challenges. Table 11 below shows the main challenges and their sub-challenges.

Table 11: Challenges of NZEB refurbishments.

Challenges	Sub-challenges
Economic	Difficult to market due to the high costs
	Different incentive between actors
	Lack of continuous workflow
Institutional	Inconsistent policies of corporations
	Misinformed corporations
	Uncertainties of future regulations
Social	Nuisance reduction

Most interviewees found it difficult to realize NZEB refurbishments due to financial aspects. For example (CC1) stated: "It turned out that it was quite difficult to market the refurbishment solution, because it was very expensive." Another interviewee (CC2) said: "Actually, the continuous flow of work is a precondition … If that does not work, one of the pillars is gone and the costs will increase rapidly." In this, he referred to the precondition for building a factory in relation to industrialization, which is required to reduce costs. Furthermore, one interviewee (PC2) mentioned that different incentives could exist between contractors and other actors, such as corporations, to go completely NZEB. This could reduce the workflow of the contractors by making the building future-prove immediately. However (PC2) also mentioned that there are progressive contractors as well that think along with the customer.

Next, regulatory challenges were also mentioned by the interviewees. First, some interviewees mentioned the inconsistent policies of corporations, i.e. divergent program requirements, which makes it more difficult to realize NZEB refurbishments since it hampers industrialization. For example, (CC3) said to a couple of corporations: "You totally disagree with each other. How can you ask one product from me?" Also, (CC1) said: "Well, if you look at the customer's wish, then it varies in between. They want it cheap, fast, customized and flexible." Another interviewee (PC1) stated that corporations are misinformed and think refurbishing to NZEB is still too expensive and not worth it. He said: "most of the corporations are unknown and unknown makes unloved, fear and so on." Lastly, (PC2) noticed that some contractors are reactive to go for NZEB, since they are uncertain about future regulations.

Regarding the social aspects, some interviewees mentioned the importance of nuisance reduction when refurbishing to NZEB. One interviewee stated that lead time and associated nuisance reduction is more important than sustainability during refurbishments, (CC3) said:

> If you notice to where the attention is with NZEB refurbishments in the existing residential sector, then it is not about technique, not about heat, it is all about how much nuisance do you create to the occupant and how do you reduce this? So, the social component much more decisive than the whole energetic discussion in the end.

4.1.1.5 Summary and further interpretation

- A NZEB refurbishment can include several combinations of (technological) measures, however, it is always a combination of measures to the building envelope for increased insulation and installations.

- A NZEB all-electric solution is more commonly realized than a NZEB plus district heat solution.
    - This can be a consequence of the fact that most interviewees experience more difficulties with stacked and high-rise buildings, where NZEB plus district heat is more suitable than NZEB all-electric, due to fewer possibilities for energy generation.
    - The main difference in (technological) measures between both solutions is the amount of PV panels installed on the roof, with fewer PV panels for the NZEB plus district heat solution.

- Various D&C strategies are applied by the interviewees, with material selection/substitution mostly mentioned, followed by prefabrication, reusing existing buildings/components/materials and secondary materials.
    - Divergent perspectives on the environmental sustainability of materials result in different material selections and other D&C strategies.

- The main challenges experienced by the interviewees with NZEB refurbishments are economic, institutional and cultural. Institutional and economic challenges can influence and strengthen each other.
    - The inconsistent policies of corporations result in various formats of NZEB refurbishment propositions. The flexibility in offerings due to this can hamper industrialization, which in turn increases the costs. Due to these high costs, it can be difficult to market the refurbishment proposition, which can reduce the continuous work flow of the companies. Furthermore, the continuous work flow is a precondition for industrialization and, therefore, this process can be seen as a positive feedback loop. See figure 15 for a visualization.

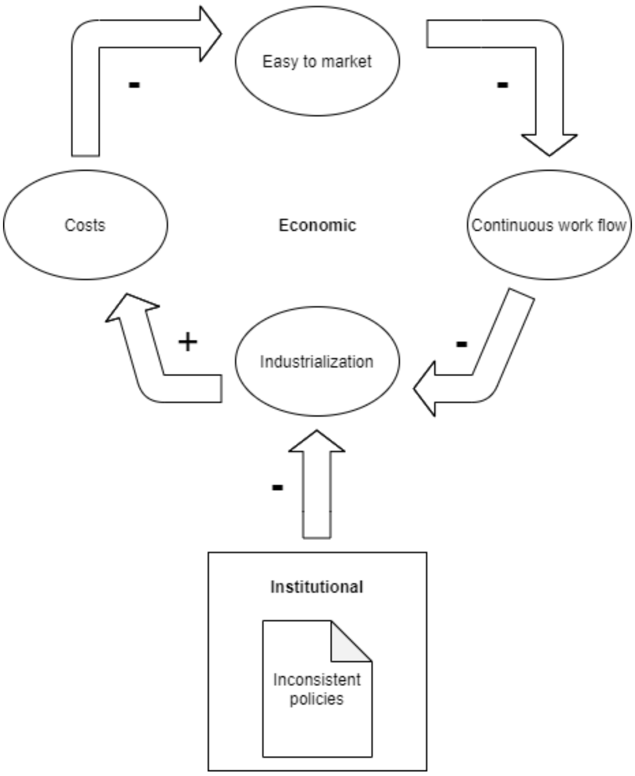

Figure 15: Positive feedback loop of challenges NZEB refurbishments.

4.1.2 Circular economy in NZEB refurbishments

This subsection provides insights into the different CE strategies, operationalized by the value retention options (VROs), that were applied by the interviewees in NZEB refurbishments and other projects. It also goes beyond the value retention options by highlighting other CE developments within the sector. It further highlights the perspective of the interviewees about the importance of the CE to accelerate the ET and their view on a circular construction economy (CCE). It ends with the results regarding the experienced drivers and barriers to apply CE strategies in NZEB refurbishments.

4.1.2.1 CE strategies in NZEB refurbishments

Several CE strategies, operationalized as VROs, have been implemented within NZEB refurbishments by the interviewees. Figure 16 below shows the percentage of interviewees that implemented CE strategies by VRO. It shows the percentage for NZEB refurbishments as well as when only implemented in other projects.

From the interviewees, it seems that shorter loop and higher order VROs predominate the implementation of CE strategies. Whereas (R4) refurbish (71%) has been mostly implemented. On the one hand, this can be a result of that buildings are in fact refurbished or upgraded after such a project. On the other hand, interviewees also mentioned the upgrade of separate products or components, such as wood to increase its service life. Besides, interviewees mentioned the further development of energy modules that are already installed or the district heating system that has been refurbished. Next, (R7) recycle (57%) is also implemented by the interviewees. However, one interviewee mentioned that the waste trade is not transparent. For example (CC3) said: “Yes, if someone could tell me where the recycled resources come from. No idea. I think that everything ends up in one pile. The whole waste trade is not transparent, including the recycling of it.” Furthermore, (CC4) said: “That happens actually at the producers from which we buy products. You should ask them about this." This confirms the fact that most interviewees have a lack of overview and details about the recycling of their products and materials, both at the end-of-life of products as well as at the beginning-of-life as secondary products. Next, (R1) reduce, (R2) reuse and (R3) repair are all implemented by 43% of the interviewees. Relating to (R1) reduce, (PC2) stated: "We use the materials very carefully and also not too much. So it is also a very light weighted panel and without a frame." However, not all interviewees were convinced about the relevance of (R1) reduce in relation to circularity and NZEB refurbishments. For example, (CC2): stated: "A wall is a wall with a certain size and if you refurbish that, you still keep the same size and thickness. …. I do not think it is relevant, less is not always better." (R2) Reuse is for example applied, by reusing the packaging of the supplied products. Regarding (R3) repair, some interviewees mentioned the responsibility of the service they have over their products. For example, (PC3) said: "If components are not working anymore, we first try to fix the problem at the location before we replace the component." Next, (R0) refuse and (R5) remanufacture were both implemented by 29% of the interviewees, whereas (R6) re-purpose and (R8) recover were only implemented by 14% of the interviewees. The fact that (R8) recover was barely implemented could be an outcome of the non-transparent waste trade, since interviewees mentioned they have little insight into that from waste processors. It is noticeable that (R9) re-mine was not implemented in NZEB refurbishments.

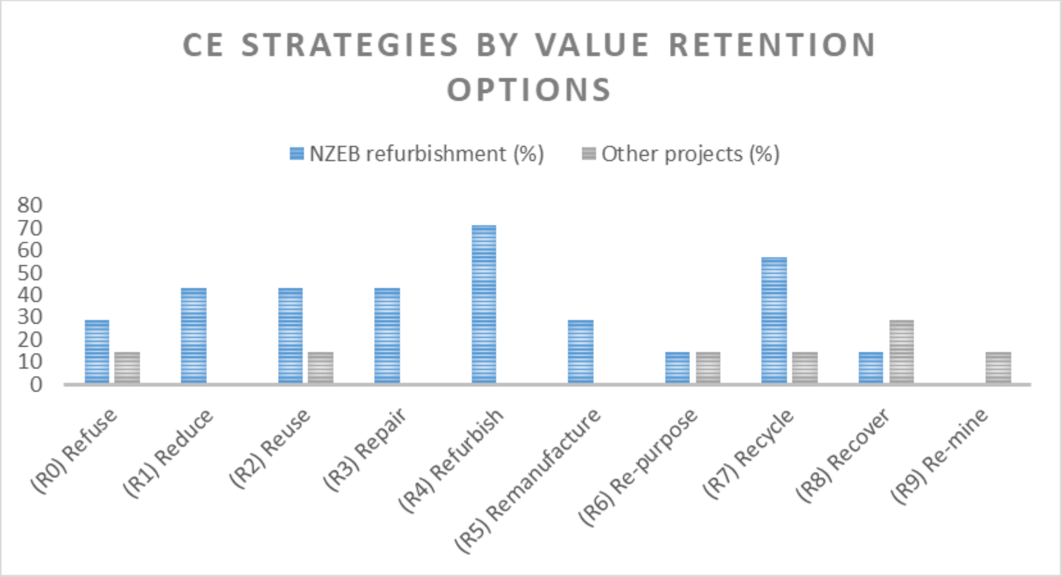

Figure 16: Bar chart showing the percentage of interviewees implementing CE strategies by value retention option (VRO) in NZEB refurbishments as well as only in other projects.

One interviewee mentioned the difficulty regarding (R2) reuse and (R5) remanufacture in the Dutch construction sector, due to the rapid developments in changes of norms and standards in relation to the long service life of buildings and components. For example (CC2) stated:

> Doors that were built in the 50s, 60s were 2,10m high. Nowadays, the standard is 2,30m high. … This happens with many products, such as the thickness of insulation that changes. Part of the reason is that, in contrast with a car, buildings have long service lives. In many instances it is outdated by the time.

Figure 16 also shows that some VROs were only applied in other projects than NZEB refurbishments (see grey color). From the interviewees, it was noticeable that these projects were done separately, e.g. circular projects and NZEB refurbishments. For example (CC4) said:

> We are also working on circularity. That is true. We have not yet combined it, if I am honest. … We are working on a large refurbishment/transformation project, really high level refurbishment. … where we also apply circular materials. However, that is not NZEB. We are doing everything, I have to say, but we have not combined it yet, that we put circularity and NZEB in one project.

To continue on this, two interesting insights could be derived from the interviewees. First, more than half of the interviewees think the CE slows down the process of achieving the ET, especially on the short term. However, they acknowledge that on the long term circularity is important to achieve the ET by reducing energy use and other resources and thereby the emissions of greenhouse gases. But in the coming decade(s), it only slows down the process due to increasing costs and being too long in the R&D phase for circularity. For example (CC1) said: "If you look at the coming 10 years and you want to accelerate the energy transition … then circularity will only slow [it] down, because the cost price will increase and therefore [it will] certainly not accelerate it." Besides, (PC2) continued: "That way you stay longer in the study phase and you won't enter the 'doing phase', the climate doesn't wait for us." In this, (PC2) referred to the complexity of the ET, which could lead to postpone action when circularity comes to play a role. This could distract companies to act on the ET. Lastly, most interviewees could not be clear and agree on what a CCE meant. Some interviewees mentioned a material passport, others mentioned CO_2 capturing or renewable materials. Besides, the elimination of the word 'waste' and demountable construction were mentioned. It seems that no clear perspective on the meaning of a CCE exists within the industry. These reasons may affect and delay the coupling of projects regarding the CE and ET, i.e. keep these two paradigms separate from each other.

Furthermore, most of the interviewees mentioned that the CCE is slowly developing and therefore we cannot expect too much of it yet. Especially the installations sector is lacking behind, mentioned an interviewee (CC2). Another interviewee (PC2) stated that circularity is discussed a lot within the sector, but the implementation is lacking. According to the same interviewee, there is also not yet consensus on the circularity of different materials, e.g. EPS versus wood insulation materials.

Despite the slow development within the sector, current developments are noticeable besides the implementation of different VROs. For example, one interviewee (CC3) was involved in a material passport by coding all the materials of a building to create value for future use. The same interviewee mentioned the measurement of circularity within the company. Another interviewee (PC3) mentioned the search for different suppliers that are willing to take action on the CE or developing partnerships for R&D on circular projects.

Although these current developments play a role in stimulating a CCE, most interviewees think that future developments will go step-by-step. For example, (CC3) stated: "I think the slogan 'think big, start small', definitely applies to circularity." One reason for this slow development could be the many challenges the interviewees have experienced.

4.1.2.3 Barriers and drivers

Many drivers and barriers to apply a CE in the construction sector in general and NZEB refurbishments in particular were experienced by the interviewees. Tables 12 and 13 show the different drivers and barriers, allocated to three different themes, e.g. market, institutional and cultural. Furthermore, it also shows how many of the interviewees mentioned the same driver or barrier and they are clarified by an example quote.

Table 12: Drivers that were experienced by the interviewees to implement a CE.

Category	Drivers	Frequency (n)	Example quote
Market	Demand from the market	2	CC4: "If I am honest ... the market demands it."
	First mover advantages	1	CC4: "If we start doing it right now ... we will be leading, get more customers, a better image and company."
	Unsustainable practices costs money	1	PC2: "Of course there is a driver in that producing waste is not free."
Total		**4**	
Institutional	Subsidies to stimulate innovation	2	PC2: "In general there are incentives to achieve the climate goals, subsidies for innovation."
Total		**2**	
Cultural	Internal motivation towards sustainable development	2	CC1: "We are at ... actual sustainability men."
	Mindset towards sustainability	1	CC1: "But it is also mindset."
Total		**3**	

Table 10: Barriers that were experienced by the interviewees to implement a CE.

Category	Barriers	Frequency (n)	Example quote
Market	Traditional products cheaper than circular products	4	CC1: "But the problem is that if you want to be fully circular, it increases the costs ... A new brick is cheaper than a circular brick."
	Availability of products on the market	3	CC4: "Well, a difficulty is the availability of materials."
	Lack of standardization of products	2	CC2: "So from the start, we have to work with more standardization."
	Lack of circular supply chains	2	CC1: "The supply chain in not equipped to that, we are not yet used to it."
	Lack of application options for circular products	1	CC4: "The application area is quite limited. It just has to fit into the project."
	Lack of economies of scale	1	PC2: "If you do something for the first time and on a small scale ... than it is relatively expensive."
Total		**13**	
Institutional	Inconsistent policies of principals	3	CC1: "Then we soon found out that circularity at corporations, really goes from 0 to 100."
	Restraining government regulations and standards	2	PC2: "You do something that is socially desirable ... but then you are punished by extra rules, because you fit into a different company category."
	Lack of stimulating government regulations	1	PC2: "The lack of [norms and standards] can be a barrier."

	NZEB refurbishments already have too many requirements	1	CC2: "The biggest challenge is that actors already find it too difficult to realize NZEB … Circularity is experienced as an extra load."
	Optimal responsibilities unclear for reclamation of products	1	PC2: "What should you recycle or make circular in your own process and what on sector or national scale?"
	Performance guarantee towards the principals	1	CC3: "If I choose to use circular products, which could be fine as well. However, nobody could provide a certificate on that."
Total		**9**	
Cultural	Lack of commitment from all (supply chain) actors	4	CC3: "Most important … is that everyone is fully committed. You actually see that these are merely fashionable words."
	Lack of priority within principals	3	CC2: "It is often low on the list of requirements."
	Lack of priority within company	1	CC3: "If you look at where most of the attention goes to, it is social safety, social hygiene."
	Mindset towards sustainability	1	CC1: "But it is also mindset."
Total		**9**	

Regarding the drivers, it was noticed that market drivers were mentioned 4 times by the interviewees, institutional drivers 2 and cultural drivers 3 times. From the market drivers, interviewees mostly mentioned that the market demands new innovations for circular applications, i.e. the market is challenged to develop new innovations. Regarding the institutional drivers, only financial incentives were mentioned by the use of subsidies. Furthermore, cultural drivers mainly relate to the internal motivation towards sustainable development of the companies' employees. Although there were some drivers experienced by the interviewees, one interviewee (CC2) stated: "No, there are no drivers to combine circularity and NZEB." This was mainly due to the low priority of CE within corporations and the misalignment of the demand for project specific solutions by corporations and offering a product by contractors. This misalignment between the supply and demand was also experienced as a challenge for a NZEB refurbishment in itself, due to inconsistent policies of principals (see section 4.1.1.4 Challenges of NZEB refurbishments).

Regarding the barriers, it can be noticed that more barriers were experienced by the interviewees to implement circular practices within NZEB refurbishments than drivers. Market barriers were mentioned 13 times by the interviewees, whereas both institutional and cultural barriers were mentioned 9 times. Regarding the market barriers, most interviewees mentioned the high prices and availability of circular products. Furthermore, the inconsistent policies of the principals and restraining government regulations and standards were mostly mentioned as institutional barriers. For the cultural barriers, interviewees mainly mentioned the lack of commitment by other (supply chain) actors and the lack of priority from the principals.

4.1.2.4 Summary and further interpretation

- Shorter loop and higher order VROs predominate the implementation of CE strategies by the interviewees.
    - (R4) Refurbish (71%) and (R7) Recycle (57%) are mostly implemented, whereas and (R8) Recover (14%) and (R9) Re-mine (0%) are least implemented in NZEB refurbishments.
- Interviewees had divergent perspectives on the relevance of (R1) Reduce in NZEB refurbishments
- The CCE is slowly developing and CE implementation is lacking, despite the many discussions within the sector.
- The CE and ET are often kept separate in projects. Reasons for this could be:
    - Negative or neutral perspectives on the importance of the CE for accelerating and achieving the ET. There is a difference between the long and short term.
    - No consensus on the meaning or definition of a CCE.
- More barriers than drivers to apply CE strategies within NZEB refurbishments are experienced by the interviewees.
    - Regarding the drivers, the market category predominates.
    - Regarding the barriers, the market category predominates.

4.2 Research Question 2

This section explains the insights from the life cycle assessment (LCA) that was conducted. It explains the environmental life cycle impacts of a linear and circular NZEB refurbishment proposition in six impact categories: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP) and total use of primary energy (TUPE).[41] These impact categories were chosen, since they represent most of the impact for building constructions as identified in several studies explained in the theory chapter and, besides, these are all included in the EPDs used as data sources within the modelling software. It should be noted that the results refer to embodied impacts, since direct emissions due to the use phase are excluded as explained in section 3.3.2.1.4 System boundaries. Furthermore, it identifies the most dominant life cycle stages, building structures and materials within the most contributing impact categories. It also explains the effect of applying different CE strategies on the environmental impact of NZEB refurbishments according to the most contributing impact category, GWP. For additional data tables regarding the figures, the author refers to Appendix C: Additional data tables research question 2.

4.2.1 Life cycle impacts at the complete refurbishment level

Table 13 below shows the characterized life cycle impacts per functional unit (FU) (see section 3.3.2.1.2 Function and functional unit description) in the six impact categories for two scenarios: a linear, i.e. baseline scenario, and a circular NZEB refurbishment design. It should be noted that the first LCA analysis of the circular design is solely based on the different materials used in comparison with the linear design, instead of the application of different CE strategies, such as the use of secondary materials and lifetime extension by different end-of-life modelling approaches. In other words, only the effect of alternative materials will be analyzed first according to the LCA methodology, before the analysis of different CE strategies. From table 13 it becomes clear that

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[41] Excluding primary energy used as raw materials.

the linear design has higher impacts in all impact categories when all values per life cycle stage of each impact category are added up (see column ‘Total excl. D). For example, the linear design emits 45100 kg CO_2-eq./FU, whereas the circular design emits 36200 kg CO_2-eq./FU due to the use of different materials. Module D is reported separately according to the CEN standards, since these are the net loads or benefits beyond the system boundary due to reuse, recycling and energy recovery. Reporting them separately increases transparency, because the burdens and benefits are reported separately, instead of cancelling each other out. However, adding them all as one module reduces insights about the sources of the benefits or loads (Mirzaie et al., 2020). Although table 14 shows the characterized life cycle impacts as absolute values to increase transparency of the report, it makes it difficult to compare both designs in each impact category.

Table 14: Characterized life cycle impacts of a linear and circular NZEB refurbishment per functional unit (FU).

Characterized life cycle embodied impacts	**Life-cycle stage**	**A1-3**	**A4**	**A5**	**B1-5**	**C1-4**	**D**	**Total (excl. D)**
Global warming potential (kg CO_2-eq./FU)	Linear	2,48E+04	7,91E+01	4,51E+03	1,48E+04	8,72E+02	-4,23E+03	**4,51E+04**
	Circular	1,62E+04	1,03E+02	4,51E+03	1,48E+04	5,78E+02	-3,34E+03	**3,62E+04**
Acidification potential (kg SO_2-eq./FU)	Linear	1,45E+02	3,49E-01	1,63E+01	9,28E+01	3,63E-01	-1,44E+01	**2,55E+02**
	Circular	9,94E+01	4,58E-01	1,63E+01	9,28E+01	1,17E+00	-6,16E+00	**2,10E+02**
Eutrophication potential (kg PO_4-eq./FU)	Linear	3,56E+01	7,56E-02	9,90E+00	2,36E+01	6,96E-02	-1,44E+00	**6,92E+01**
	Circular	1,88E+01	9,94E-02	9,90E+00	2,36E+01	6,05E-01	-9,69E-01	**5,30E+01**
Ozone depletion potential (kg CFC_{11}-eq./FU)	Linear	2,20E-03	1,55E-05	6,45E-04	1,96E-03	3,76E-06	-4,48E-05	**4,82E-03**
	Circular	2,18E-03	2,02E-05	6,45E-04	1,96E-03	3,26E-06	-4,56E-05	**4,81E-03**
Photochemical ozone creation potential (kg C_2H_4-eq./FU)	Linear	2,03E+01	5,22E-03	5,53E-01	9,20E+00	2,61E-02	-1,92E+00	**3,01E+01**
	Circular	1,36E+01	6,56E-03	5,53E-01	9,20E+00	7,39E-02	-7,76E-01	**2,34E+01**
Total use of primary energy (MJ/FU)	Linear	3,06E+05	2,24E+03	8,43E+04	2,16E+05	1,08E+03	-5,00E+04	**6,10E+05**
	Circular	2,57E+05	2,91E+03	8,43E+04	2,16E+05	2,51E+03	-5,62E+04	**5,63E+05**

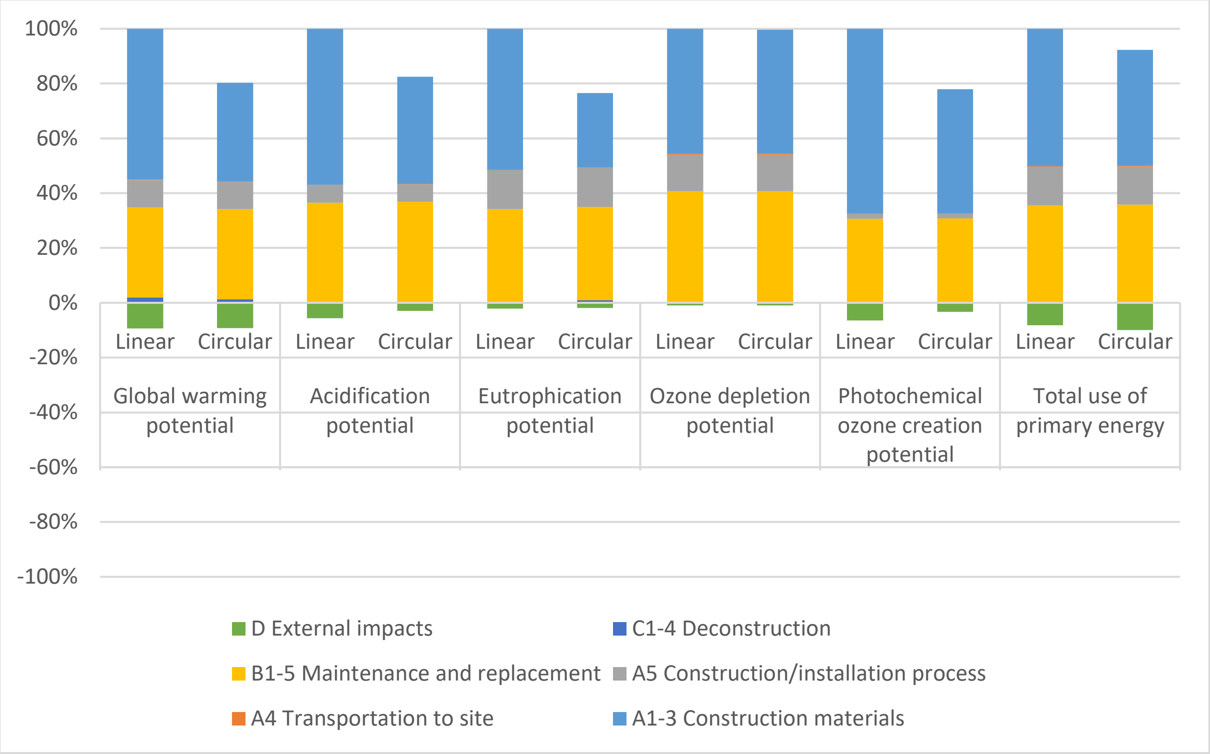

Figure 17: Relative comparison of characterized life cycle impacts of a linear and circular NZEB refurbishment per functional unit.

Therefore, figure 17 shows the relative comparison of characterized life cycle impacts of the linear and circular design of a NZEB refurbishment per functional unit in percentages. For the data table, the author refers to Appendix C: Additional data tables research question 2. Each environmental impact category is shown on a 100% scale to compare all categories on one graph, with the highest impact value of both designs set to 100%. The net benefits beyond the system boundary, i.e. the negative values from module D are also shown, but as previously stated reported separately outside the 100% range. The graph shows that the linear design, i.e. baseline scenario, has higher impact values in all impact categories than the circular design, although the difference is significantly small for ozone depletion potential (ODP) in kg CFC11-eq./FU, namely 0,3%. This small difference is due to the fact that most emissions that result in ODP originate from building systems and installations and construction site scenarios, 79% and 13% respectively for both designs, which are modelled equal in this study. The biggest difference is noticeable in eutrophication potential (EP) in kg PO_4-eq./FU (23%), which is followed by photochemical ozone creation potential (POCP) in CFC_{11}-eq./FU (22%) and global warming potential (GWP) in kg CO_2-eq./FU (20%). The least difference is noticed in the total use of primary energy (TUPE) with only 8%. The difference in EP is mainly due to the construction materials within the building elements: external walls and façade and floor and roofs, which include galvanized steel for the roof sheets and mortar for the external façade wall in the linear design. However, further differences in building elements and materials will be discussed later in section 4.2.2 Life cycle impacts at the building element and material level.

Besides the total impacts per category, figure 17 shows the impact per life cycle stage as well, which provides the following insights. First, cradle-to-gate impacts (A1-3) due to the extraction of raw materials, transport of these materials and manufacturing processes cause the main difference in impacts between both designs and they are the highest in each impact category of each design, except for EP in the circular design. In this design and category, 'B1-5 Maintenance and replacement' causes the highest impact, which is first, due to the fact that most of these impacts are caused by building systems and installations (70%), which have shorter service lives than the rest of the building elements and, second, less materials are used that lead to eutrophication. For example, the production of galvanized steel for the roof within the linear design results in nitrogen oxides (NO_x) which is the main cause for eutrophication to occur (World Steel Association, 2018). Furthermore, the biggest difference between the designs for construction material impacts is found to be in POCP due to the higher use of expanded polystyrene (EPS) and polyisocyanurate (PIR) insulation within the linear design. Second, maintenance and replacement causes the second highest impacts in the rest of each design and category and their contribution is equal in each of them, due to the fact that these impacts are only caused by building systems and installations which are the same in both designs. Third, the contribution of impacts caused by 'A5 Construction/installation process' are equal in each design, since construction site scenarios were used based on climate zone averages, instead of project-specific site impacts due to the lack of data and the subject of the study being a design or proposition. Furthermore, wastage was set to zero, because of the prefabrication of both designs as explained in section 3.3.2.1.3 Description of system under study. Lastly and surprising is that benefits beyond the system boundary due to reuse, recycling and energy recovery ('D External impacts') are higher in each impact category for the linear design, except for ODP and TUPE. This can be a result of the default end-of-life scenario for each material, however, more differences are to be expected in further analyses when additional CE strategies are modelled for the circular design. Later in this chapter, additional differences in building elements and materials between both designs will be explained.

Although figure 17 shows the relative comparison of both designs in each impact category, a comparison between the impact categories, i.e. the contribution of each impact category to the overall environmental impact cannot be explained by this figure. For this, the characterized results should be weighted according to the weighting factors stated in section 3.3.2.3 Life Cycle Impact Assessment, i.e. the shadow costs. This ensures the comparability of impact categories, based on a monetary value often used in the Dutch context.

Figure 18 shows the weighted life cycle impacts of the linear and circular NZEB refurbishment in euros per functional unit. For the data table, the author refers to Appendix C: Additional data tables research question 2. The aggregated weighted environmental impact, i.e. the Environmental Costs Indicator (ECI), over its 50-year service life equals more or less €3715/FU and €3013/FU, according to the linear and circular design, respectively.[42] This makes a difference of 19% in weighted impact according to the ECI when the linear and circular design are compared and results in an Environmental Performance of Buildings score (*MPG)* of €0,50/m^2/year for the first and €0,41/m^2/year for the latter, which is a difference of 18%.[43]

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[42] ECI is measured, including the net loads or benefits 'D External impacts' (Stichting NMD, 2020a).

[43] It should be noted that the MPG and ECI are in this case only measures, including the six impact categories that are part of this study.

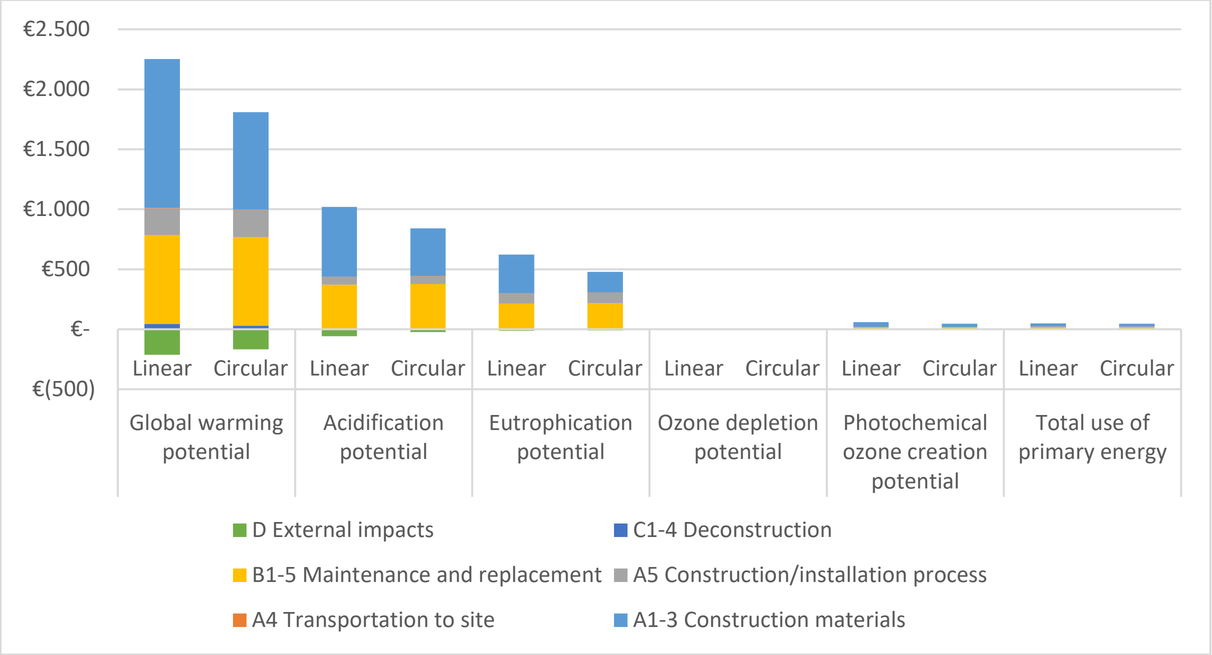

Figure 18: Weighted life cycle impacts of a linear and circular NZEB refurbishment in €/functional unit.

The NZEB refurbishment emits 45100 [kg CO_2-eq/FU] when the linear design is applied in comparison with 36200 [kg CO_2-eq/FU] when the circular design is applied, a difference of 20% (excluding credits from external impacts). When credits from external impacts are included, the difference becomes 19%, therefore, in- or excluding these end-of-life benefits from module D does not make a significant difference between the total weighted impacts in this case. However, it does show that when the differences of module D between both designs become higher, it can positively contribute to the life cycle impact from a cradle-to-cradle perspective, due to the avoided impacts of reuse, recycling and energy recovery, which could stimulate innovations associated with a CE.

From figure 18 it becomes clear that GWP is by far the most contributing impact to the overall life cycle impact of both designs, followed by acidification potential (AP) and EP. On the one hand, the substantial contribution of GWP can be caused by the fact that it is a highly valued category. For the weighting factors the author refers to section 3.3.2.3 Life Cycle Impact Assessment. On the other hand, the choice of construction materials and maintenance and replacement rates of the building systems and installations, due to lower service lives causes the high contribution of GWP. The high contributions of these life cycle stages show comparable results in other impact categories, such as AP and EP. However, when we apply the cut-off criteria of at least 80% cumulative contribution to the life cycle impacts of both designs as from the article of Mirzaie et al. (2020), it becomes clear that GWP and AP are the most relevant impact categories, with GWP contributing for at least 56% to the total weighted impacts for each design. Both designs have a cumulative contribution of GWP and AP of around 82%. Therefore, the analysis focusing on the building elements and materials will be conducted for these two impact categories.

4.2.2 Life cycle impacts at the building element and material level

From the previous analysis, it was found that GWP and AP were the most contributing categories to the overall environmental life cycle impacts of a linear and circular NZEB refurbishment, according to the shadow costs weighting factors. The subsequent analysis will focus on the contribution of different building elements and materials to the weighted life cycle impacts of both designs in these two impact categories.

Figure 19 below shows the weighted contribution of the different building elements to the life cycle impacts of a linear and circular NZEB refurbishment. Besides the impacts within the product system, also the net benefits are shown that can be credited in module D as external impacts beyond the system boundary. From the figure, it becomes clear that building systems and installations contribute significantly to the total environmental impact of both GWP and AP. 60% of the GWP and 64% of AP is caused by building systems and installations for the linear design, compared to 75% of GWP and 78% of AP for the circular design. Since, building systems and installations are modelled equal, the absolute values are equal for both designs. It is interesting to notice that although building systems and installations cause the highest impact, the external impacts that can be credited in module D are relatively low compared to other building elements. This could mean that for this building element the benefits due to reuse, recycling and energy recovery are low compared to the loads or that few options are available to provide reusable and recyclable materials to be further used in product systems. The results also show that foundation, sub-surface, basement and retaining walls barely contribute to GWP and AP in both designs, which is due to the fact that few materials related to that building element are included in such refurbishments. The biggest differences are to be seen in building elements: floors and roofs, external walls and façade and slightly less in windows and doors, which was already expected due to the differences in these building elements for both designs. To obtain more insights into those differences, the next analysis will solely focus on these building elements and their materials.

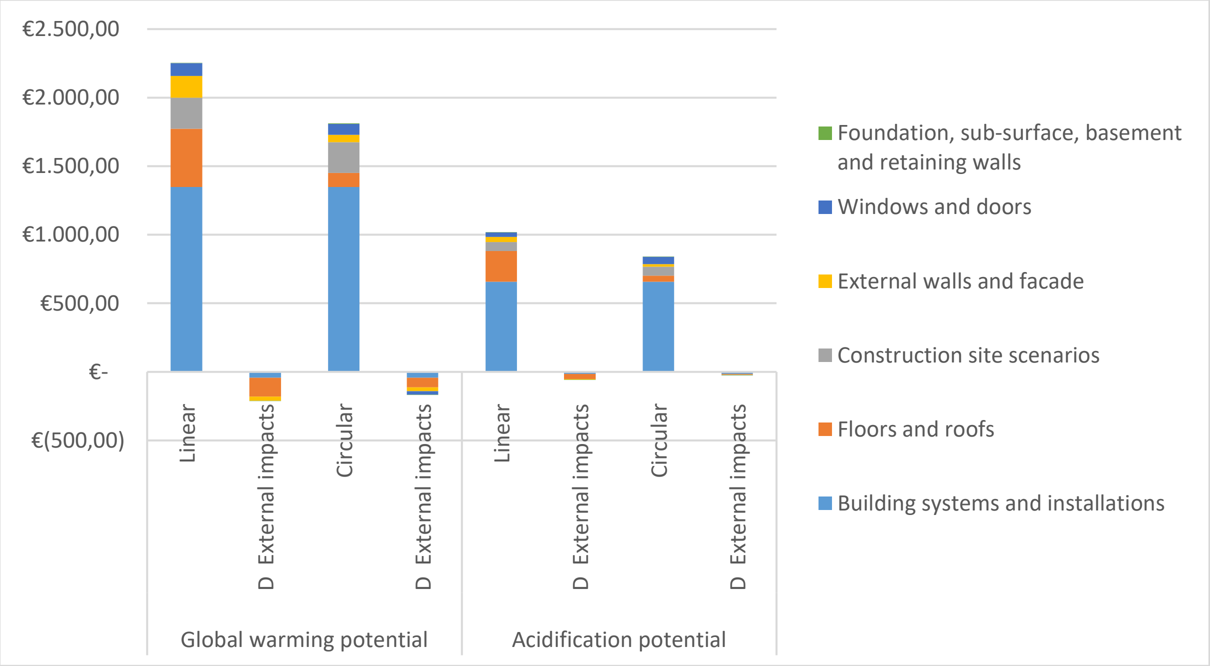

Figure 19: Weighted contribution of building elements to the most contributing life cycle impacts of a linear and circular NZEB refurbishment.

Figure 20 shows the weighted contribution of materials to the different building elements according to the most contributing impact categories: GWP and AP. In other words, the results of each impact category are added up for each design according to the differentiation in building elements.

Regarding the floors and roofs, a substantial difference in impact can be noticed between the linear and circular design, where the impact of the linear design is nearly 5 times higher than the circular design when module D is excluded, €650/FU and €148/FU, respectively. When module D is included in the impact the difference between the two designs becomes slightly less, due to the credits that could be provided in the linear design by steel recycling. This shows that the use of materials that can be further used in subsequent product systems can have a positive impact on the environment. Important to note is that the difference is only due to the different roof construction and insulation, since both designs use graphite polystyrene (GPS) as floor insulation. GPS is an expanded polystyrene (EPS) product manufactured in the same way, however, graphite beads are added to increase the R-value, i.e. insulating performances. The high impact from the roof of the linear design is caused by materials, such as galvanized steel and PIR insulation. Due to steel recycling, benefits beyond the system boundary could be credited for galvanized steel, however, polyisocyanurate (PIR) does not have these recycling options yet and could only be incinerated with lower avoided impacts, which is also confirmed by Duijve (2020). In contrast, the circular design uses materials for the roof construction and insulation with significantly lower impacts, such as the bio-based materials: plywood, timber and cellulose insulation and other materials, such as rock wool insulation. These insulation materials replace PIR within the linear design, which result in lower impacts. Furthermore, the use of plywood and timber could result in avoided impacts beyond the system boundary as can be seen from the figure. For the external walls and façade, the impacts of the linear design are more than double compared to the impacts of the circular design when module D is excluded, €195/FU and €73/FU, respectively. When module D is included, this difference becomes also less as for the floors and roofs. The highest impact in the linear design is caused by EPS insulation and other steel/iron, used to mount the façade to the existing wall. However, benefits beyond the system boundary could be credited due to avoided impacts by steel recycling and plastic-based incineration with energy recovery. From the results, it becomes clear that the circular design has lower impacts mainly due to the use of cellulose and rock wool insulation, which replaces the EPS insulation from the linear design. The impacts of the windows and doors does not differ substantially between the designs, although the linear design has slightly lower impacts than the circular design when module D is excluded, €128/FU and €134/FU. However, when module D is included, the circular design has lower impacts due to the use of wooden window frames which result in credits due to avoided impacts beyond the system boundary compared to PVC window frames. These credits originate from wood incineration with energy recovery processes, substituting energy production.

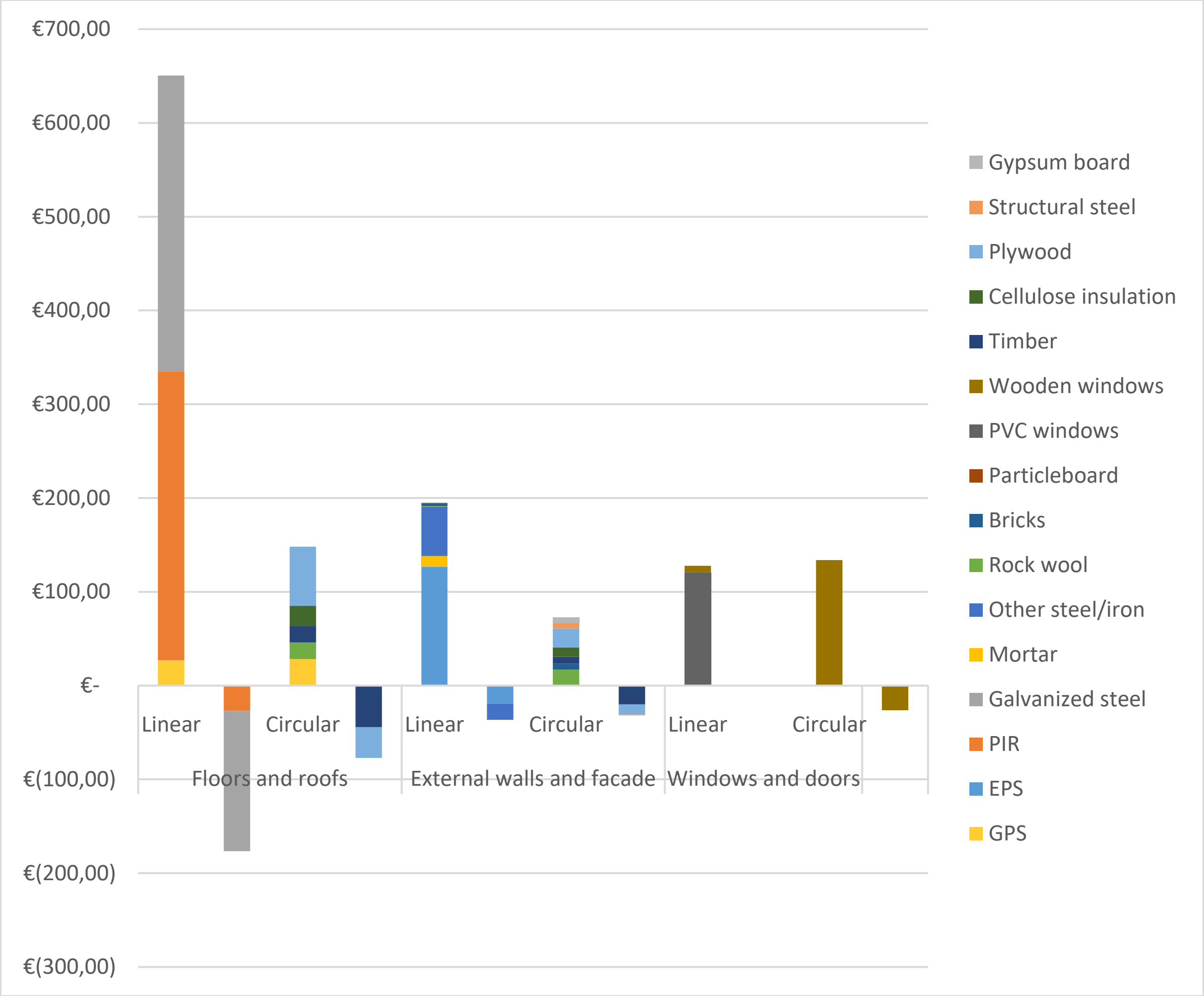

Figure 20: Weighted contribution of materials to the building elements according to the most contributing impact categories for a linear and circular NZEB refurbishment.

4.2.3 Interpretation and sensitivity analysis

Previous analysis was only based on two designs, whereas the circular design was solely modelled with different materials, instead of additional CE strategies. Besides, from the previous analysis, it was found that most differences between the two designs exist due to different materials used within building elements: floors and roofs, external walls and façade and windows and doors. Also, it was found that the impact category GWP contributed most to the overall weighted impact of both designs.

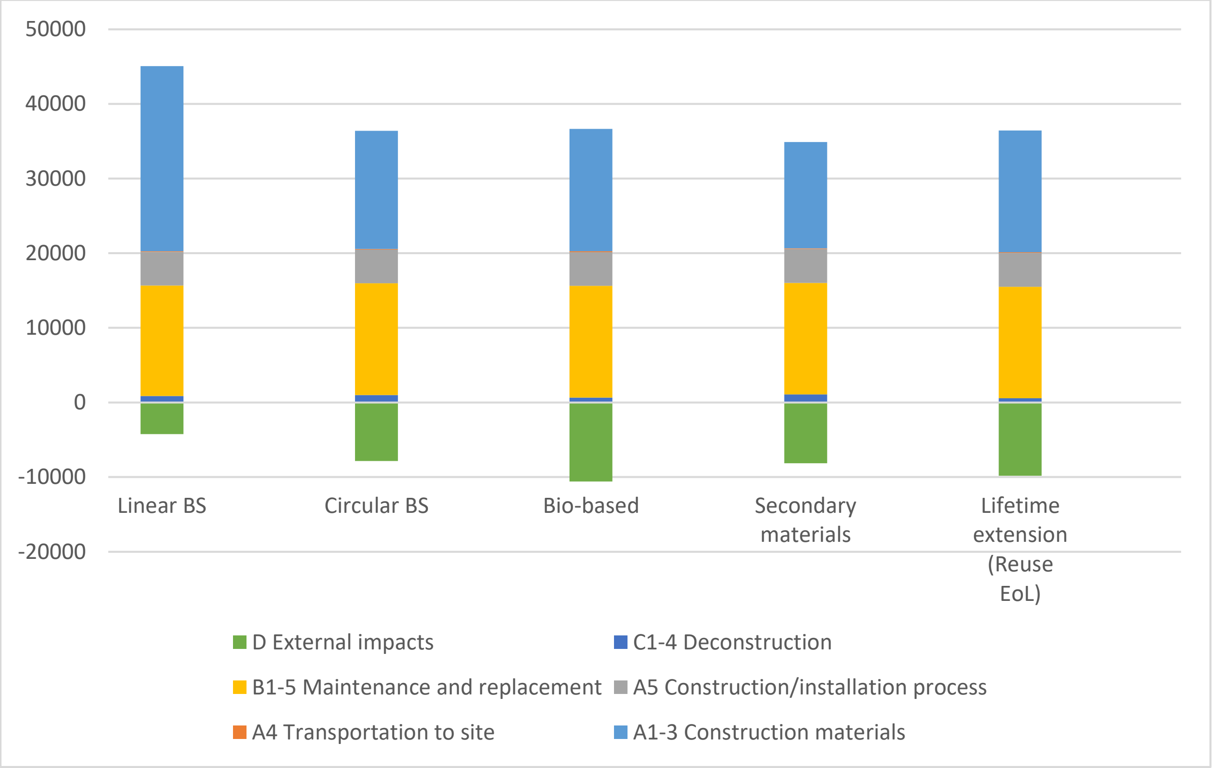

Figure 21: Characterized life cycle impacts of a NZEB refurbishment according to different CE scenarios [kg CO2-eq./FU].

Figure 21 shows the characterized life cycle impacts of a NZEB refurbishment according to different CE scenarios in kg CO_2-eq./FU compared to a linear baseline scenario. The following insights could be derived from this analysis. First, all circular scenarios have lower impacts than the linear baseline scenario, which was expected from the analyses in section 4.2.1 Life cycle impacts at the complete refurbishment level and 4.2.2 Life cycle impacts at the building element and material level. This difference is mainly caused by different impacts in 'A1-3 Construction materials', due to the replacement of PIR and galvanized steel by lower impact materials for the roof construction and EPS for the external walls and façade. Second, the difference in impact between all circular scenarios is small when module D is excluded and only impacts within the product system are taken into account (cradle-to-grave approach). Whereas the circular baseline scenario emits around 36400 kg CO_2-eq./FU (19% lower impacts than the linear scenario), the (1) bio-based, (2) secondary materials and (3) lifetime extension by reuse at the end-of-life scenarios emit around 36600 (19% lower than linear), 34900 (23%) and 36400 (19%) [kg CO_2-eq./FU], respectively. Therefore, compared to the linear baseline scenario, the use of secondary materials (with 50% secondary material use) reduces the environmental impact of GWP the most. However, as stated previously, it was assumed that no additional impacts were allocated due to recycling and other processing processes, because of a lack of data within the used databases and product system information. In reality, the impacts according to the use of secondary materials will be higher. To continue on this, the difference is further caused by the allocation method prescribed by the CEN standards (Mirzaie et al., 2020), where secondary materials come free of burden due to the polluter-pays-principle, visible in 'A1-3 Construction materials'. The influence of different allocation methods will be further discussed in section 5.2.2 Research question 2. Also, the difference does not seem that significant at first, which is due to the fact that building systems and installations are also still included in the analysis. Third, to compare the circular scenarios, differences in impact are noticeable within deconstruction processes. For example, the scenarios (1) bio-based materials and (3) lifetime extension by reuse at the end-of-life have significantly smaller impacts than the circular baseline and (2) secondary materials scenario (see figure 22). This is mainly due to the waste processing phase (C3) of plastic-based material incineration of GPS insulation. In the scenario with lifetime extension, this GPS insulation is directly reused (instead of incinerated), whereas in the bio-based scenario the material is substituted by cellulose insulation. Last, the differences of module D, i.e. net external benefits due to avoided impacts beyond the system boundary, between the scenarios is worth noting. When a cradle-to-cradle approach is taken into account and, therefore, impacts that occur in subsequent product systems are included by pursuing a circular economy mindset, environmental benefits are highest by the bio-based scenario. On one hand, this can be explained by the fact that wood incineration at the end-of-life causes energy to be recovered, which substitutes energy production by natural gas in this study. The substitution method, as prescribed by the CEN standards can provide substantial different results based on the substitution assumptions, i.e. what is being substituted and how efficiently this is being done (Salehi & Shahabaldin, 2020; Suter et al., 2017). On the other hand, the cut-off approach for secondary materials input lead to a reduction in benefits beyond the system boundary to avoid double counting. Therefore, the scenario with secondary use of materials has lower benefits in the future, although the current impacts within the concerning product system are lower. This incentivizes companies to currently use secondary materials, which will be further discussed in section 5.2.2 Research question 2.

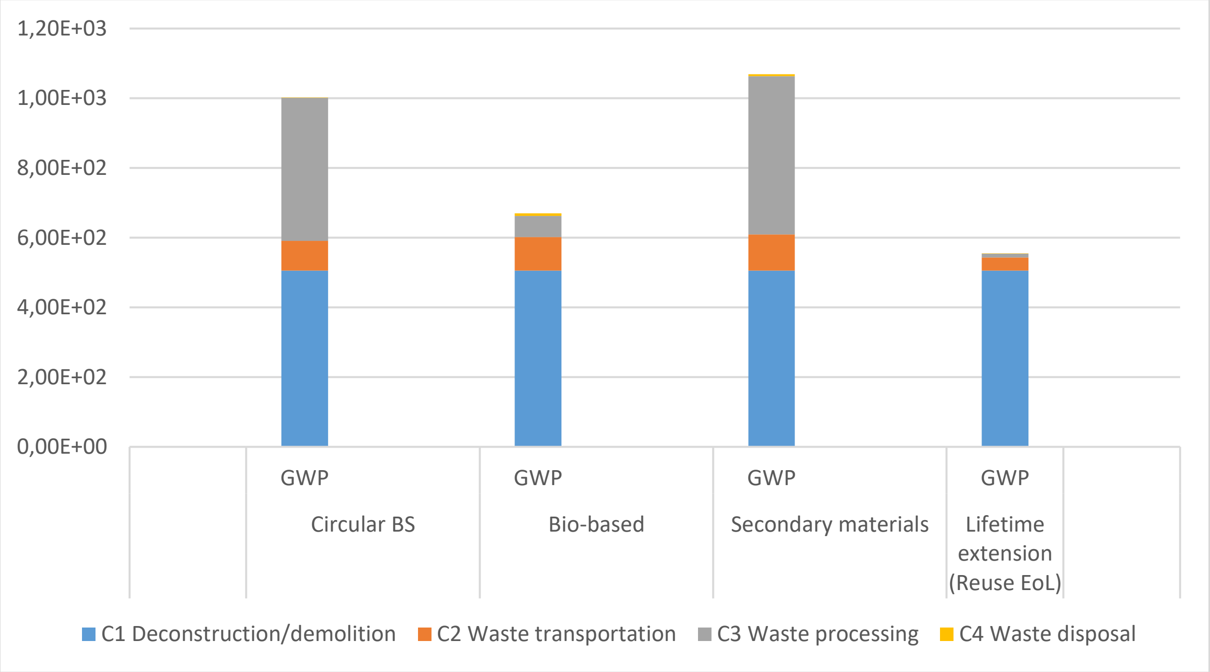

Figure 22: Characterized impacts of deconstruction processes for a NZEB refurbishment according to different CE scenarios in kg CO2-eq./FU.

Although the above analysis is mainly focused on the environmental impact, this cradle-to-grave approach, including credits by avoided impacts, is not completely suitable for LCA interpretation with a circular economy mindset, since it does not really goes into the theoretical system losses of resources (Dieterle et al., 2018). Therefore, Dieterle et al. (2018) propose the life cycle gap analysis (LCG-A) as complementary interpretation approach to account for this by determining the life cycle gap of a product system, which is explained in section

3.3.2.4.2 Life cycle gap analysis. In figure 23 the life cycle gaps of the different scenarios are shown for GWP in kg CO_2-eq./FU, i.e. the environmental impacts caused by the production of the materials minus the environmental benefits beyond the system boundary allocated to module D. It becomes clear that the linear baseline scenario results in the highest system losses as how they are modelled in this study, with 20570 [kg CO_2-eq./FU]. Although the secondary materials scenario had the least impact within the product system due to burden free materials, it is not the most suitable scenario from the interpretation with a life cycle life gap approach, since from a broader perspective it results in overall system losses of 13694 [kg CO_2-eq./FU]. In contrast, the scenario with bio-based materials results in the least system losses of 5772 [kg CO_2-eq./FU],

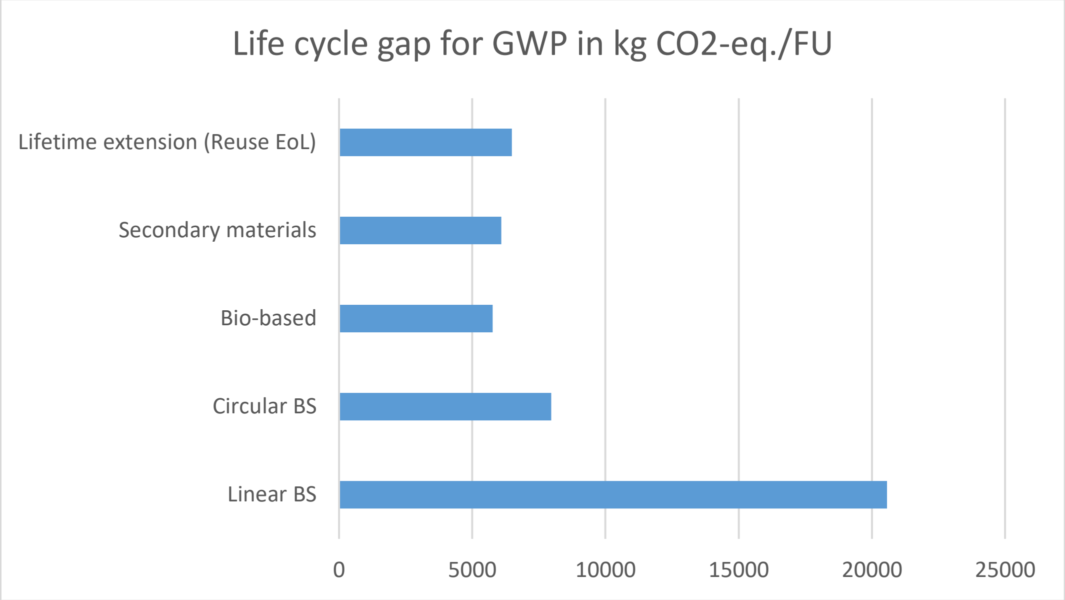

Figure 23: Life cycle gap of a NZEB refurbishment according to different CE scenarios for GWP in kg CO_2-eq./FU.

From the results of section 4.2.1 Life cycle impacts at the complete refurbishment level and 4.2.2 Life cycle impacts at the building element and material level, that compared a linear and circular NZEB refurbishment, solely based on a different material selection, the following concluding remarks can be provided. First, the circular design had lower impacts in all categories with the greatest difference in EP between both designs, which is due to the use of galvanized steel for the roof and mortar for the external façade within the linear design. Second, cradle-to-gate impacts (A1-3) contributed most in almost all categories of both designs, with the biggest difference in POCP due to the use of EPS and PIR in the linear design. External impacts due to the avoided emissions beyond the system boundary were found highest for the linear design, which was surprising at first. However, this was due to the default end-of-life scenarios per material type, instead of additional CE strategies. Still, the total impacts were lower for the circular design. Third, there was a difference of 19% between both designs according to the overall weighted impacts. When impact categories were aggregated, GWP and AP contributed most to the overall environmental impact, with a contribution of 56% and 26%, respectively. Fourth, although building systems and installations contribute significantly to the most contributing categories, the benefits beyond the system boundary were rather low relative to other building elements, which could be due to the fact that little benefits could be derived from reuse, recycling and energy recovery or that few end-of-life options are yet available to provide materials for further use for this building element. Lastly, the biggest differences between both designs were found within the roof, due to the use of galvanized steel and PIR insulation, which is replaced by bio-based and low impact materials within the circular design that also have additional benefits beyond the system boundary. Furthermore, for the external walls and façade, EPS insulation versus bio-based and rock wool insulation led to the difference between both designs.

However, to state something about the effect on the environmental impact due to different CE strategies, a sensitivity analysis was conducted based on GWP, which led to the following insights. First, the environmental impact of the CE scenarios, excluding module D, did not differ significantly, although the secondary materials scenario had slightly less impact than other scenarios. This means that using secondary materials would reduce the environmental impact in the current product system, due to the fact that they come free of burden. However, it should be remembered that it was assumed that no impacts for recycling processes were included due to a lack of data, i.e. an underestimation of the impacts. Second, impacts due to deconstruction processes were highest within the circular baseline and secondary materials scenario, because of the plastic-based material incineration of GPS, instead of reuse or the substitution by bio-based insulation. Third, the effect of different CE strategies was mostly noticeable depending on the scope of the analysis, i.e. whether to include reporting net external loads or benefits. It showed the importance of reporting the environmental benefits of module D to state the effect of different CE strategies with a broader perspective and to stimulate innovations for a CE. The use of bio-based materials with wood incineration at the end-of-life led to the greatest environmental benefits beyond the system boundary, although extending the lifetime of materials by reuse was a close second. However, from the LCG-A, the bio-based scenario was preferable and, therefore, fit better into a CE perspective according to the allocation method used. To conclude, the potential environmental impact reductions are to be found highest by the use of secondary materials within the current product system, i.e. cradle-to-grave approach, however, when a cradle-to-cradle approach is used and credits for avoided production are taken into account, the use of bio-based materials with energy recovery by wood incineration at the end-of-life leads to the highest environmental impact reduction. For the limitations and recommendations of this part of the study, the author refers to section 5.2.2 Research question 2 and 6.2 Managerial and policy implications, respectively.

5. Discussion

This chapter reflects on the research methods and results that were found by first, explaining the theoretical implications of the results from research question 1 and 2 separately as well as the linkage between both research questions and, second, setting forth the limitations of the research. Also, it provides innovative avenues for further studies to explore.

5.1 Theoretical implications

5.1.1 Research question 1

Although various design and deconstruction (D&C) strategies are applied by the studied companies and higher order value retention options (VROs) predominate the CE implementation within NZEB refurbishments, it is clear that standardized methods and practices for CE implementation are lacking (Benachio et al., 2020). The presence of higher order VROs is in line with the development of implementing preventive measures rather than end-of-pipe solutions (Eberhardt et al., 2020). Despite the many discussions of CE applications, actual implementation is lacking, especially within the installations sector. This also shows the clear separation of paradigms, e.g. circular economy (CE) and energy transition (ET) within the sector.

This can be explained by several reasons. First, part of this can be explained by the ambiguous understanding of a circular construction economy (CCE) by the interviewees, as well as the negative or neutral perspectives on the importance of the CE for reaching the objectives of the ET, especially on the short term. Second, the fact that no consensus exists between the interviewees about the environmental benefits of applying certain CE strategies could also explain the slow uptake of the CE (Eberhardt et al., 2020) and separation of paradigms.

Last, from the experienced barriers of implementing NZEB refurbishments in general and the application of CE within these solutions in particular, it seems that institutional, market and cultural barriers can influence each other. For example, the misalignment between demands from corporations in the form of divergent policies and demanding project-specific solutions and offering one product by the contractors (institutional barrier), as explained in 4.1.2.3 Barriers and drivers, could result in a lack of standardized products (market barrier). Consequently, this could lead to a lack of commitment from supply chain actors to CE implementation (cultural barrier). Besides, interviewees mentioned the lack of quality assurance and warranty procedures regarding circular products as a barrier to choose these over conventional products, since they are required to provide warranties towards corporations. Important to note that these circular or innovative products may include several CE strategies in this case, such as recycled, reused, etc. However, for reused products which are not completely processed to the core materials as with recycling, this is particularly problematic. Overall, it thus seems that the different barriers are not experienced in isolation, but rather have an effect on each other.

This provides signs that strategic or inter-organizational collaboration between relevant actors, e.g. supply chain partners, is lacking. However, this has a critical role for transitioning to a CE in general and the reuse of materials in particular within the construction sector according to Trabulsi & Sofipour (2020), since CE implementation in itself requires a systems perspective that goes beyond the boundaries of single organizations and, furthermore, given the fragmented nature of the construction sector with many different actors involved, such collaborations become particularly important. Besides, they found that real estate developers have key roles in stimulating inter-organizational collaboration, which are in this study the corporations. They found, among other things, that the lack of clear responsibilities for logistics and recovery facilities as well as procedures for quality assurance and warranties hamper such strategic collaboration and, therefore, CE implementation. Different incentives as well as a market demand for circular or reused products has to be established in order to create responsibilities regarding logistics and recovery facilities (Trabulsi & Sofipour, 2020). The corporation could play a role in this, by for example to design and plan for reuse at the end-of-life from early on and create conditions for reuse or other CE strategies by formulating their requirements and demands differently towards contractors. To continue, besides collaboration between corporations and other market actors, close collaboration amongst corporations could also increase the application of CE strategies by other market actors, since the inconsistent programs of requirements is experienced as a hampering factor. This could also increase the commitment of supply chain partners to work together towards CE implementation, which was mentioned as a barrier by multiple interviewees. See figure 24 for a visualization of the interaction between barriers for CE implementation, strategic collaboration and the corporations as described above.

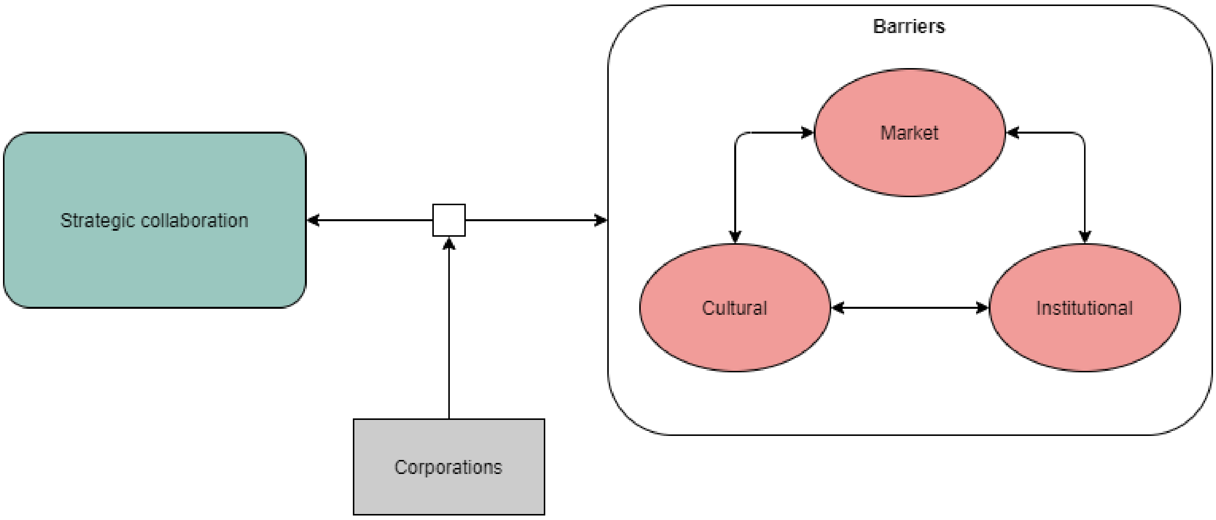

Figure 24: The interaction between barriers for CE implementation, strategic collaboration and corporations.

5.1.2 Research question 2

From the results of research question two, it becomes clear that the implementation of CE strategies within NZEB refurbishment could reduce the embodied environmental life cycle impact of these solutions. However, the preferred strategies, i.e. most potential strategies, depend on the scope of the LCA chosen, i.e. cradle-to-grave or cradle-to-cradle. With the allocation method chosen described by the CEN standards, cut-off approach and credits for avoided impacts beyond the system boundary reported separately, it was found that the use of secondary materials results in the most environmental impact reduction from a cradle-to-grave approach. However, when credits for the avoided production in subsequent product systems are taken into account, the scenario with bio-based materials and wood incineration at the end-of-life results in the highest potential for environmental impact reduction, which is also confirmed by the LCG-A from section 4.2.3 Interpretation and sensitivity analysis. This finding is interesting and should have some extra attention, since it contrasts the theoretical literature about the hierarchy of value retention options (VROs), explained in section 2.2 Circular Economy in the Construction sector. From theory, it is stated that energy recovery by for example incineration at the end-of-life is less preferable than, e.g. reuse or recycle. A possible explanation for this controversial finding is the fact that the substitution approach applied in the allocation method prescribed by the CEN standards, can provide substantially different results depending on the substitution assumption, i.e. what is being substituted and how efficiently (Salehi & Shahabaldin, 2020; Suter et al., 2017). In this case, energy production by natural gas, a fossil based source, is being substituted in the bio-based scenario. This could have led to the high credits and is confirmed by studies from Salehi & Shahabaldin (2020) and Suter et al. (2017). For example, Suter et al. (2017) found that benefits are especially high for replacing heat by oil or gas and that particularly wood products result in high benefits, since these are often directly incinerated and result in low GHG emissions to be emitted. Furthermore, the study from Saheli & Shahabaldin (2020) that compared the end-of-life stages by use of the CEN standards with the Product Environmental Footprint (PEF) for several construction material groups, found that benefits beyond the system boundary were by far the highest for wood incineration with energy recovery with the CEN standards. This is due to the fact that the CEN standards provide extra credits for the incineration of products that provide 'greener fuels' than conventional fossil-based fuels, which is not the case with the PEF. However, since these 'benefits' will be retrieved in the future, but are credited now (with the current technologies), it is questionable whether this approach is most desirable due to developments regarding more sustainable productions of energy in the future. Therefore, whether the use of this allocation method by the CEN standards and, therefore, this finding is justifiable from a CE perspective is, however, questionable.

To continue on this, the use of this allocation approach from a CE perspective, where loops are to be narrowed, slowed and closed now and in the future, is also debatable due to following additional reasons. Since most of the impacts are allocated to the first user cycle, companies have great incentives to use 'burden free' secondary materials, however, design for disassembly to ensure long-term future retrieval is less incentivized by this approach (Eberhardt et al., 2020a). The inclusion of module D credits tries to tackle this, however, according to Eberhardt et al. (2020a) it does not promote designing for a system perspective with multiple product cycles. This can be explained by the scenario with bio-based materials and wood incineration at the end-of-life, where the product system obtains credits in module D by energy recovery. However, it only incentivizes the approach for one cycle ahead, since the material only has one final use, e.g. incineration, instead of additional future purposes. So with this in mind, companies should be incentivized to design for multiple cycles by, e.g. designing for disassembly, to fit the future perspective of a CE.

Regarding the potential use of secondary materials, a study by EIB and Metabolic (2020) found that the demand for materials is larger than the offer from refurbishment and demolition in the Dutch construction sector. This means that the use of secondary materials could only provide part of the materials required for future building adaptation projects, theoretically 41% in 2014 and 59% in 2030 (EIB & Metabolic, 2020). However, in reality the actual implementation percentage will be lower. To continue, differences between types of materials exist. For example, the possible offer of glass and insulation materials will be less than average due to stricter norms and standards, which is relevant for this study. Therefore, additional strategies are required to apply CE strategies within NZEB refurbishments to the full potential, which include the use of bio-based materials and design applications to extend the lifetime of building materials, studied in this research.

Furthermore, it was also found that building systems and installations represent the majority of the impacts, despite the little contribution to the overall mass (EIB & Metabolic, 2020). However, end-of-life applications for these building elements are lacking or the benefits compared to the loads are low relative to other building elements, found in this study. Both reasons seem probable, because of the complexity of these products, composed of many interdependent and connected materials, in contrast to other products, such as a wooden beam or rock wool insulation which is only composed of a few materials. Furthermore, alternative building systems and installations with lower environmental impacts are also still not yet available to tackle the high impacts. Therefore, without commitment of the installations sector to a CE, the potential for environmental impact reduction of NZEB refurbishments will lack a crucial component, especially due to the shorter service lives of these elements.

5.1.3 Link between research question 1 and 2

Until now, the results of research question one and two were discussed separately, however, insights could be derived from the linkages between them. First, it was found from the interviews that the installations sector is lacking behind in developments within the playing field of CE, despite the majority of the impacts from a NZEB refurbishment is caused by these building elements. For example, (CC2) stated regarding the developments of a circular construction sector: "There are many ongoing developments. However, within the installations sector very few." The fact that there are few developments to reduce the environmental impact by CE implementation in such a crucial sub-sector, could have led to the lack of data within databases required to assess this impact. In comparison with other products used for building LCAs, EPDs regarding several alternative building systems and installations as well as from different manufacturers are lacking behind. It is expected that if this sub-sector would be more stimulated to be actively involved in the developments regarding CE implementation in the construction sector, that data creation would also improve.

From research question two, it was found that the reuse of materials or components, either as input or output, could reduce the environmental impact of NZEB refurbishments. However, many interviewees mentioned the lack of standardized components to be a barrier to CE implementation in general and the reuse of components in particular. This is confirmed by a study from Finch et al. (n.d.), where the lack of standardized spatial geometries of components results in virgin materials to be more economically attracting. This is also strengthened by the fact that refurbishments require specific measurements, since there is already an existing situation. In other words, the possible applications for direct redeployment of products or materials are less than with new construction. Furthermore, flexibility was often strived for by the interviewees in offering their NZEB refurbishment solution to comply with the inconsistent policies of corporations. It seems that there is a contradiction between on the one hand, pursuing flexibility to fit multiple requirements from corporations and on the other hand, to require standardization for better CE implementation.

5.2 Limitations

5.2.1 Research question 1

Although this study has provided relevant societal as well as scientific insights, it was also subject to some limitations worth reflecting upon. These can be described as follows. First, the exploratory sequential mixed methods design chosen, as described in section 3.1 Research Design, led to a clear order of process where the qualitative research was conducted first. This resulted in the fact that the interviews were already conducted before all relevant information was gathered that could be used for the interview. Besides, the strict time frame did not allow additional interviews to be conducted. For example, the theoretical information regarding design and construction (D&C) strategies was gathered after the interviews were conducted, which forced the author to deduce this information from the interviews, rather than gathering it from explicit statements. This could influence the validity of the research as described in section 3.4 Research Quality Indicators. However, information regarding the CE strategies by value retention options (VROs) was explicitly asked for during the interview, which helped to deduce the applied D&C strategies. Second, validity of the research could also be influenced by the fact that barriers and drivers were analyzed and asked for based on counts, rather than importance. It could be that some barriers or drivers were mentioned less than others, but influenced the application of CE strategies more than others. Third, semi-structured interviews are often prone to problems regarding reliability, since each interview is unique in its own way, which could pose problems of consistency of interview data and biases (Abd Gani et al., 2019). This can lead to different results when the study is repeated. However, the clear structure of the interview guide (see Appendix A: Interview guide), as well as the deductive part of the data analysis by developing the coding framework, based on previous literature, could increase the reliability of this part of the study.

5.2.2 Research question 2

The limitations regarding research question two, i.e. the LCA study that was conducted, could be explained as follows. A couple of aspects that led to uncertainty of the results were first, that the chosen allocation method could influence the results significantly, as previously described. To increase the robustness of the results, another sensitivity analysis can be conducted using different allocation methods that fit better CE needs. For example, different allocation methods could probably led to a different valuation of the impacts by CE strategies, which could lead other strategies to be preferable than was found in this study. In a recently published article by Eberhardt et al. (2020a) which shows that the topic of allocation and CE is on the forefront of science, it was found that the four allocation approaches studied: EN 15804/15978 cut-off approach, Circular Footprint Formula (CFF), 50:50 and linearly degressive (LD) approach showed substantially different impact distributions for the products that were studied. In other words, the incentive to apply different CE strategies depends on the allocation method chosen, as explained in section 5.1.2 Research question 2. Furthermore, they found that most of the approaches do not incentivize taking into account subsequent cycles and their use for the assessment of multi-cycling systems was debatable, which is preferred to fully assess the benefits of a CE (Eberhardt et al., 2020a). Although the LD approach was found preferable in this context, which “uses a discounting principle allocating impacts from virgin material production and disposal in a linearly degressive manner to all use cycles, allocating the highest share of impact to the cycle where the impact happens”, they developed a CE LD approach to increase the applicability, better align it with CE principles and create incentives for CE within the industry (Eberhardt et al., 2020a, p. 3-4).

Although this approach is in its infancy, it would be relevant to include it in the sensitivity analysis to better create incentives for CE implementation within the construction sector.

Second, the lack of data posed limitations to this study. For example, the lack of data regarding the impact of recycling processes of reused or recycled materials undermined the impacts of using secondary materials. Besides, quality degradation of materials due to these processes also increased the uncertainty of the impact of these materials. Therefore, the Foundation of the National Environmental Database (Stichting NMD, 2020b) intends to include many environmental profiles of reused construction products and materials, to help modelling LCAs pursuing a CE. Besides, data within the databases of the software regarding building systems and installations were also lacking, despite these building elements represent the majority of the environmental impacts. The lack of data can be also a result of the fact that the software only allows to use externally certified data points, that are voluntarily provided by commercial companies. According to Mirzaie et al. (2020), LCA studies are often prone to two types of data gaps: the lack of product system information and lack of input/output flows of the products. Although this study was confronted with both types, the latter was more noticeable regarding the lack of EPDs. The construction sector should be stimulated to improve and provide more data regarding these building elements. Third, it was found during this study that One Click LCA had a commercial intend. Although this brought the possibility of performing a detailed LCA with limited data and to see changes in the model immediately, since it is cloud-based (Ramírez-Villegas et al., 2019), it also resulted in limitations for research purposes. Few options regarding data manipulation were possible, for example the origin of materials could not be changed. To solve this problem, One Click LCA has a so called local compensation feature, which is based on statistical data regarding energy intensity of the concerning country. However, calculation mechanics behind this feature lack transparency towards users of the selected software. Fourth and to continue on the aspect of transparency, reporting the aggregation of all avoided emissions beyond the system boundary in module D, as the CEN standards prescribe result in transparency by keeping the burdens and benefits separately, however, it also hides the sources of benefits in terms of life cycle modules (Mirzaie et al., 2020). For example, having multiple sub-module D's would solve this problem to communicate results more transparently. Last, building components are often only replaced when it is absolutely necessary (Ramírez-Villegas et al., 2019), which lead to a reduction in energy performance during the service life of the building. In this study, it was assumed that energy performances were equal among the different scenarios. However, since this is contextual dependent and, therefore, the robustness of the results would be increased if a detailed energy analysis would have been performed.

5.3 Further research

Although this study provided relevant insights, it has also opened up avenues to further explore within the scientific domain. First, this study has provided insights regarding the barriers to implement CE strategies within the construction sector in general and NZEB refurbishments in particular and the importance of strategic collaboration between relevant supply chain actors to overcome these barriers. However, it would be interesting to further study the potential of strategic collaboration from a circular supply chain (CSC) perspective within the construction sector and also include additional supply chain partners within as well as beyond their own boundaries in the study, such as suppliers and waste managers. Namely, it is argued by De Angelis et al. (2018, p. 432) that "CSCs are enabled by close supply chain collaboration with partners within and beyond their immediate industrial boundaries, including suppliers product designers and regulators”. Due to the fragmented nature of the construction industry, such a study could provide the insights to improve the strategic collaboration within the industry.

Second, this research solely studied the environmental impacts of NZEB refurbishments and its various CE scenarios, instead of going into depth of their circularity performance and the three pillars of sustainability, i.e. the environmental performance, economic prosperity and social equity. However, in order to use the full potential of the decision-making function of LCA, it would also be relevant to complement the analysis with a life cycle cost (LCC) assessment in order to assess the most desirable scenarios to include CE strategies within NZEB refurbishments according to the life cycle costs or a life cycle sustainability assessment (LCSA) to further include social aspects as well.

Last, in order to make well-thought decisions about the potential of implementing CE strategies within NZEB refurbishment to reduce the environmental impact as well as achieving the ET, more research should be conducted regarding CE implementation within the building systems and installations sector. Since the majority of the impact of these refurbishments is caused by these building elements, more insights regarding potential CE applications is required. For example, it could be studied how the service life of these elements could be extended by different supply chain relationships or business models or research could focus on more environmentally friendly end-of-life scenarios. The expected globally installed PV is 4500 GW by 2050 in comparison with 400 GW in 2017, which will potentially lead to enormous hazardous waste streams (Chowdhurry et al., 2020). Although, Chowdhurry et al. (2020) state that many countries intend to extend the responsibilities of PV manufacturers to better anticipate the end-of-life of their products, however, R&D needs acceleration they state to improve the research on this topic.

6. Conclusion

6.1 Concluding remarks

This research intended to understand the potential coupling of the circular economy (CE) and energy transition (ET) in the context of the built environment in general and building adaptation projects in particular. In other words, it tried to provide insights in the achievement of the ET's objectives by the implementation of different CE strategies in so called NZEB refurbishments. It therefore explored the application of different CE strategies within such solutions as well as the experienced barriers and drivers, which resulted in an epistemology of contextual perceptions and experiences by the interviewees. Seven semi-structured interviews were conducted by interviewing construction companies and suppliers and coded using a combined deductive-inductive approach. Furthermore, it studied the potential environmental impact reduction of applying different CE strategies in NZEB refurbishments by comparing a linear and circular design according to the LCA methodology. Therefore, this study can be framed as an exploratory sequential mixed methods study, where qualitative data analyses are followed by quantitative data analyses. This allowed the following research questions to be answered:

RQ1*: *How and why are CE strategies already being taken into account in NZEB refurbishments?

To answer this research question, it was split in two parts: whether and how certain CE strategies are implemented in NZEB refurbishments and the motives behind this implementation. First, from the interviews, it was found that although the CE is intensively discussed, actual implementation is often lacking, especially regarding installations. This is particularly true for the combination of CE applications within building adaptation projects fitting the ET, such as NZEB refurbishments. Potential reasons for this will be explained later in this section.

Despite CE practices are slowly developing, it was still found that various design and construction (D&C) strategies were applied by the construction companies and their suppliers, which can relate to the implementation of a CE. For example, companies were actively involved in selecting the right materials for their refurbishment proposition, such as materials with lower environmental impacts and are easier to assemble and disassemble, using prefabrication techniques and secondary materials, either by direct reuse or recycling. However, there was no consensus regarding the environmental benefits of the selected materials and other D&C strategies. Furthermore, when interviewees were asked directly about the applied CE strategies by value retention options (VROs), it was found that focus lies on preventive measures versus end-of-pipe solutions, since higher order value retention options were mostly mentioned. This seems that action is being taken upon CE applications, but that is going step-by-step.

Reasons for the slow uptake of CE implementation in NZEB refurbishments could be due to the fact that no consensus between interviewees was found regarding the understanding of a circular construction economy (CCE), as well as the neutral or negative perspective of it towards achieving the ET. Next, many market, institutional and cultural barriers were experienced by the companies that could influence each other, where market barriers predominate the experiences. It seemed that better strategic collaboration amongst corporations and between corporations and other supply chain actors could reduce these barriers by better aligning their requirements and needs and incentivizing supply chain actors to actively be involved in CE solutions.

RQ2: How does the application of different CE strategies affect the environmental impact of NZEB refurbishments?

To answer this research question, the Life Cycle Assessment (LCA) methodology was used according to EN 15804/15978 from the CEN standards to compare a linear and circular NZEB refurbishment design (all-electric). The differences between both designs were the use of a circular building envelope, consisting of a timber frame construction, instead of a more conventional building envelope by the use of structural insulated panels (SIP). Furthermore, different design and construction (D&C) strategies were applied, such as a different material selection, as well as bonding techniques for (dis)assembling. The LCA focused on six impact categories over a calculation period of 50 years: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP) and total use of primary energy (TUPE). The study had two goals: (1) identify and discuss how the different impact categories, life cycle stages as well as building elements contributed to the total environmental life cycle impact of a NZEB refurbishment (all-electric), comparing a linear and circular design and (2), investigate how different CE strategies affected the environmental life cycle impacts of NZEB refurbishments.

When comparing the linear and circular NZEB refurbishments solely based on the different material selection used, it was found that the circular design had substantial environmental improvements in all impact categories, except for POCP since these emissions are mainly caused by building systems and installations which were modelled equally in this study. Most of the differences in impacts between both designs were caused by cradle-to-gate (A1-3) impacts, due to the different materials selected, which was also the most dominant life cycle stage in most categories. Impacts due to maintenance and replacement (B1-5) represented the second most dominant life cycle stage, due to the shorter service lives of the building systems and installations. GWP and AP contributed most the overall weighted life cycle impacts according to the shadow costs method, around 56% and 26% for both designs, respectively. Although building systems and installations represented the majority of the impacts in these impact categories for both designs, net benefits at the end-of-life due to avoided production in subsequent life cycles were relatively low compared to other building elements. This indicates either low benefits compared to the loads of the end-of-life scenarios or few available options for subsequent use. From a circular economy perspective, where loops are to be narrowed, slowed and closed, this should be worrying, since these building elements are prone to high impacts with a relatively short service life. Next, the materials used for the roof causes the highest environmental improvements of all building elements between the circular and linear design, followed by the external walls and facade. For example, galvanized steel sheets and PIR insulation causes relatively high impacts compared to the bio-based materials for the construction and insulation and rock wool used for the circular design.

To investigate how different CE strategies affected the environmental life cycle impacts of NZEB refurbishments (goal 2), a sensitivity analysis was conducted for GWP, which compared a linear and circular baseline scenario with three additional scenarios: (1) bio-based, (2), secondary materials use and (3) extending the lifetime by reuse and the end-of-life. From a cradle-to-grave perspective, it was found that the use of secondary materials results in the highest environmental improvements, due to the fact that these materials come free of burden with the cut-off allocation approach used. However, the analysis showed the importance of reporting module D to see the environmental effects from a cradle-to-cradle approach, and, therefore, to stimulate innovations for a CE. From this perspective, it showed that the bio-based scenario resulted in the greatest environmental benefits due to avoided production of energy in subsequent product systems by wood incineration. However, the reuse of materials at the end-of-life was a close second and, therefore, the effect of different allocation methods should be further investigated as described in section 5.2.2 Research question 2, since the use of the allocation method prescribed by the CEN standards is debatable for the purpose of assessing multi-cycling product systems and taken into account future technology developments, which is important to assess the full potential of a CE and for stimulating companies to innovate towards CE implementation.

6.2 Managerial and policy implications

From the introduction of this study (section 1.1 Context of the Internship Organization), it was explained that the organizations Stroomversnelling and Squarewise believe that further CE implementation within the construction sector is required to achieve the objectives of the ET and that this research could provide insights in the context of this statement. Therefore, the findings of this study provide important managerial and policy implications for them to stimulate the CE implementation within the sector in general and NZEB refurbishments in particular.

One of the shortcomings of this research was the data availability, in the form of EPDs, submitted to the databases, e.g. the National Environmental Database (NMD). Data provision by construction companies and their suppliers is a voluntary activity, which means that not all the important data that is 'out there' is available to use, especially data regarding building systems and installations that is particularly important given their large impact contribution. Lacking data, for example about innovative or circular building materials and products, reduces the potential for LCA practitioners to fully grasp the potential of CE practices in terms of objectives of the ET and further environmental impact. Therefore, it would be relevant that construction companies and other manufacturers are incentivized to first, assess the impacts of their materials and products and, second, to submit the results to different databases. Regarding the first, not only activities and impacts within the product system should be assessed, but also aspects beyond the system boundary, since these reveal the potential to apply CE principles, as found in this study as well as by Mirzaie et al. (2020). Stroomversnelling could play a crucial role in this, since it consists of several relevant actors and members, such as corporations, construction companies, suppliers, governmental organizations and more. Therefore, knowledge dissemination about the relevance of knowledge creation and sharing within the sector could be further taken into account, for example in close collaboration with the foundation that manages the NMD to increase credibility.

To continue on the aspect of collaboration, this study found that better strategic collaboration amongst corporations and between corporations and other supply chain actors could reduce market, institutional and cultural barriers to apply CE strategies within NZEB refurbishments, especially the aspect of quality assurance and warranty procedures as well as circular supply chain factors, e.g. logistics and recovery responsibilities. In this study, corporations are found critical actors in creating incentives for innovative CE solutions. Besides, since the lacking of circular supply chains as well as procedures for quality assurance and warranties could hamper strategic collaboration and, therefore, CE implementation, Stroomversnelling could also play a more active role in satisfying these needs. For example, by incentivizing companies to explore the innovative functions of software tools, such as building information modelling (BIM) to fit CE needs, quality assurance processes of circular products could be improved, which was a major barrier for construction companies to apply recycled or reused products.

Furthermore, to use the full potential of CE strategies to reduce the environmental impact of NZEB refurbishments and construction sector in general, it is important that the focus of CE applications is broadened and shifted. First, given the major impacts of building systems and installations, compared to their CE potential in subsequent life cycles, it is relevant to stimulate the sector to take more action regarding circular applications for these building systems. Stroomversnelling could more actively involve these actors, such as manufacturers of building systems and installations. Second, is was found that the use of the allocation method, the so called EN 15804/15978 cut-off approach, mostly provide incentives for construction companies to use secondary materials as input, which is also stimulated by policy, and that the use for assessing multi-cycling product systems is questionable, also found by Eberhardt et al. (2020). Regarding the latter, high benefits could be provided at the end-of-life by the use of bio-based materials, despite the material only had one final use in the case of wood incineration. Also, the report from EIB & Metabolic (2020) that emphasized the discrepancy between the supply and demand of secondary materials, reveals the importance to additionally focus on different CE strategies. Despite focusing on secondary materials as input is important in light of narrowing material loops, it is also important that construction companies see potential in designing for future use in subsequent life cycles, e.g. by reuse, to slow and close loops. The use of this European standard for allocation is questionable in serving this purpose.

Although the circular economy is intensively discussed within the Dutch construction sector, standardized practices for circular economy implementation are developing slowly in combination with NZEB refurbishments, despite the urgent global risks of climate change and policy objectives coming closer. Furthermore, the two paradigms of the circular economy and energy transition are still found to be two separate worlds, despite the presence of clear signs of the importance to treat materials differently as being currently done to achieve the objectives of the energy transition in particular and global environmental sustainability in general. Relevant actors within and beyond direct supply chains have to collaborate more closely to make circular economy implementation more attractive to them, instead of pursuing a fragmented short-term competition oriented culture. Although this study has far from taken away all doubts regarding overcoming the challenges of refurbishing the enormous existing Dutch building stock in a responsible way to achieve both the policy objectives of a circular economy and energy transition, it has provided insights in the right direction to further explore.

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8. Appendix

Appendix A: Interview guide

Interview guide:

The potential of coupling the circular economy and energy transition in the built environment.

Before starting:

Ask permission to audio-record the interview

Introduction:

OK Hello. Thank you for making some time to conduct this interview with me today. First, I will shortly explain the theme and aim of this study before we start. Stroomversnelling is exploring circular construction within their program called 'Koppelkansen', translated in English as Couple Opportunities. Within this program, the contribution of the circular economy to the acceleration of the energy transition is explored as well as how this can shape different refurbishment solutions. As a first step, I will do research to the application of circularity within different NZEB refurbishments by answering the following question:

"How and why are CE strategies already being taken into account in refurbishments to NZEB all-electric and NZEB plus district heat?"

The aim of answering this question is to map the measures currently applied, including the treatment of materials as well as identifying the enablers and barriers for applying these measures.

(Name organization) is involved in such renovation solutions and therefore, you are a relevant actor to take part in this interview.

Start interview:

1. What is your role in this organization?

Questions regarding NZEB refurbishment solutions:

2. To what extent is your organization involved in NZEB housing refurbishment?
    a. All-electric and including a connection to a heat network.

3. What are the current developments of NZEB refurbishment solutions in your industry?
    a. All-electric and including a connection to a heat network.

4. What does a NZEB housing refurbishment entails?
    a. If involved in both all-electric and including a connection to a heat network, explain both refurbishments, otherwise one of the two.

   b. Building type (e.g. building year, low-rise vs high-rise, household composition, etc.)
   c. How does the process look like?
   d. Which measures/modifications? → e.g. envelop and installations.
   e. Do you have insights in what materials are mainly used? If so, which ones?

Questions regarding the circular economy:

Research regarding the opportunities that circular construction can provide to accelerate the energy transition is increasing. Materials have a certain environmental impact. Many housing refurbishments related to energy efficiency lower the impact of the use of the house, however, the share of environmental impact regarding materials increases. The circular economy can play a role in this.

5. What current developments do you see in the circular construction economy?

6. What does your organization mean by a circular construction economy?
   a. To what extent are you involved in activities regarding the circular economy?

7. To what extent is the circular construction economy important for your organization?

8. What is your perspective regarding the importance of the circular construction economy for accelerating the energy transition?

9. What activities has your organization carried out in accordance with the circular construction economy?

10. What activities related to the circular construction economy does your organization apply in your NZEB refurbishment solution?
    a. All-electric and including a connection to a heat network.
    b. Ask examples

11. Can you provide me further examples of activities that can be applied in the future?
    a. What do you need to take these steps? In other words, why are you not applying these yet?
    b. [Provide suggestions based on the prompt sheet regarding circular strategies if these are not yet mentioned in question 10]

12. Why does your organization not apply additional circular strategies in your NZEB refurbishment solution?
    a. In other words, which enablers and barriers do you experience?
    b. All-electric and including a connection to a heat network.
    c. Ask examples

13. [At this point, the prompt sheet can be shown with circular economy strategies, so that the interviewee could state which activities they have performed, including a short explanation.]

Closing interview:

14. Is there something that has not been said and you want to add?

15. Whom or which organization do you think is relevant to interview for further data collection?

16. Can I contact you if I need clarification on any issue?

17. [Explain the second part of the study and ask whether they are willing to participate by sharing detailed data about a certain case study. Obtain free insights in the materials and environmental impact of the NZEB refurbishment solution.]

    a. Offer them the choice regarding sending the data:
        i. Let them send raw data, whereby I send a list of relevant data required.
        ii. Send a questionnaire prepared by myself, so that they can fill it out.

18. *Thank them for participating in the interview and ask whether they are interested in the final research paper*

Appendix B: Coding framework including hierarchies

Name	**Description**
Barriers and drivers to apply CE strategies	Barriers and drivers to apply CE strategies, experienced by the interviewees.
Barriers to a circular construction economy (CCE)	Barriers to a circular construction economy (CCE) to apply CE strategies.
Availability of circular products on market	Availability of circular products on market.
CCE requires commitment from all supply chain actors	CCE requires commitment from all supply chain actors.
CCE requires culture change	CCE requires culture change.
CCE requires design for the future	CCE requires design for the future.
CCE requires institutional change	CCE requires institutional change.
CCE requires more studies	CCE requires more studies.
CCE requires standardization	CCE requires standardization.
CCE requires technical innovations	CCE requires technical innovations.
CE low priority within company	CE low priority within company.
CE low priority within corporations	CE low priority within corporations.
Current economy hampers CCE	Current economy hampers CCE.
Demands from corporations or principals	Demands from corporations or principals.
Financial barriers	Financial barriers.
Lack of application options for circular products	Lack of application options for circular products.
Mindset	Mindset towards sustainable development by applying CE strategies.
No circular supply chains	No circular supply chains.
No economies of scale	No economies of scale.

NZEB difficult enough to realize	NZEB difficult enough to realize.
Optimal responsibilities unclear	Optimal responsibilities to apply CE strategies unclear.
Path dependency of production processes	Path dependency of production processes.
Performance guarantee towards corporations	Performance guarantee towards corporations.
Project-specific solution	Project-specific solution hampers industrialization and the implementation of CE strategies.
Trade-off circularity and industrialization	Trade-off circularity and industrialization.
Drivers to a circular construction economy (CCE)	Drivers to a circular construction economy (CCE) experienced by the interviewees.
Demand from the market	Demand from the market to apply CE strategies.
Financial incentives	Financial incentives to apply CE strategies.
Internal motivation towards sustainable development	Internal motivation towards sustainable development.
Mindset	Mindset towards sustainable development and its implementation by CE strategies.
No drivers to combine circularity with NZEB refurbishments	No drivers to combine circularity with NZEB refurbishments mentioned by the interviewees.
Company profile	Information regarding the company profile derived from the interviews.
Current and past NZEB projects	Current and past NZEB projects of the company
Partnerships with other actors in supply chain	Partnerships with other actors in the supply chain, mentioned by the interviewees.
Role of the company	Role of the company within the industry.
Role within the company	Role of the interviewee within the company.
Implementation of CE strategies	Experiences with a circular construction economy (CCE) by the interviewees.
CCE in other projects	CE implementation in other projects besides NZEB refurbishments.
Current developments of CE in industry	Current developments of CE in the industry, experienced by the interviewees.
Future developments of CE in industry	Future developments of CE in the industry expected by the interviewees.
Importance of CCE for company	
Importance of Circular Economy (CE) for Energy Transition (ET)	Importance of the Circular Economy (CE) for the Energy Transition (ET) by the interviewees' perspective.
Short term vs. long term	Difference in short and long term perspective.
Meaning of circular construction economy (CCE)	Perspectives by the interviewees on the meaning of a circular construction economy (CCE).
Other circular developments within company	Other circular developments within the company besides the value retention options (ROs).
Material passport	Experiences with a material passport by the interviewees.
Measurement of circularity	Measurement developments of circularity within the company.
Partnership with waste processors	Partnership with waste processors by the company.

Partnerships for R&D	Partnerships for R&D by the company.
Search for alternative suppliers	Search for alternative suppliers by the company.
Value retention options (ROs)	Value retention options (ROs) implemented or not implemented by the interviewees.
(R0) Refuse	Value retention option: (R0) Refuse.
(R1) Reduce	Value retention option: (R1) Reduce.
(R2) Reuse	Value retention option: (R2) Reuse.
(R3) Repair	Value retention option: (R3) Repair.
(R4) Refurbish	Value retention option: (R4) Refurbish.
(R5) Remanufacture	Value retention option: (R5) Remanufacture.
(R6) Re-purpose	Value retention option: (R6) Re-purpose.
(R7) Recycle	Value retention option: (R7) Recycle.
(R8) Recover	Value retention option: (R8) Recover.
(R9) Re-mine	Value retention option: (R9) Re-mine.
Measures in NZEB refurbishments	The (technological) measures within the company's refurbishment proposition which the interviewees mentioned.
Challenges of NZEB refurbishments	Challenges of NZEB refurbishments, experienced by the interviewees.
Different incentives to invest between actors	Different incentives to invest between actors, such as corporations, private owners, construction companies and suppliers.
Different ratio in Trias Energetica	Challenges of finding the right balance in the Trias Energetica.
Difficult to have continuous flow of work	Difficult to have continuous flow of work.
Difficult to market NZEB	Difficult to market NZEB
Difficult to standardize NZEB	Difficult to standardize NZEB.
Doubts of corporations	Doubts of corporations.
Inconsistent demands from corporations or principals	Inconsistent (policy) demands from corporations or principals
Misinformed corporations	Misinformed corporations regarding the relevance of NZEB.
New construction vs. refurbishment	Different challenges between new construction and refurbishment
Social component in NZEB important	Social component in NZEB important
Uncertainties regarding regulations	Uncertainties regarding (future) regulations.
Design and construction (D&C) strategies	Design and construction (D&C) strategies derived from literature and interviews, i.e. how the (technological) measures are applied, mentioned by the interviewees.
Accessibility	Accessibility.
Assembly and disassembly	Assembly and disassembly.
Demolition	Reasons to demolish parts of the existing building
Design for the future	To design for future demands.
Integration of energy module and envelope	Integration approaches to integrate the energy module into the building envelope.
Material selection or substitution	Material selection or substitution.
Prefabrication	Prefabrication.
Use existing building or components	Use existing building or components.

Format refurbishment solutions	Format of the refurbishment solutions, i.e. menu of different options, mentioned by the interviewees.
NZEB all-electric vs. NZEB plus district heat	Differences in (technological) measures between refurbishment types, such as NZEB all-electric and NZEB plus district heat.
Type of refurbishment solutions	Involvement in different refurbishment solutions, i.e. NZEB all-electric and NZEB plus district heat by interviewees.

Appendix C: Additional data tables research question 2

Relative characterized life cycle impacts	**Impact categories (%/FU)**											
	Global warming potential (kg CO_2-eq./FU)		**Acidification potential (kg SO_2-eq./FU)**		**Eutrophication potential (kg PO_4-eq./FU)**		**Ozone depletion potential (kg CFC11-eq./FU)**		**Photochemical ozone creation potential (kg C2H4-eq./FU)**		**Total use of primary energy (MJ/FU)**	
Life cycle stage	Linear	Circular	Linear	Circular	Linear	Circular	Linear	Circular	Linear	Circular	Linear	Circular
A1-3	55,04%	35,95%	56,90%	39,01%	51,41%	27,15%	45,60%	45,19%	67,48%	45,21%	50,20%	42,16%
A4	0,18%	0,23%	0,14%	0,18%	0,11%	0,14%	0,32%	0,42%	0,02%	0,02%	0,37%	0,48%
A5	10,01%	10,01%	6,40%	6,40%	14,30%	14,30%	13,37%	13,37%	1,84%	1,84%	13,83%	13,83%
B1-5	32,84%	32,84%	36,42%	36,42%	34,08%	34,08%	40,63%	40,63%	30,58%	30,58%	35,43%	35,43%
C1-4	1,94%	1,28%	0,14%	0,46%	0,10%	0,87%	0,08%	0,07%	0,09%	0,25%	0,18%	0,41%
D External impacts	-9,39%	-9,23%	-5,65%	-2,93%	-2,08%	-1,83%	-0,93%	-0,95%	-6,38%	-3,31%	-8,20%	-9,99%
Total (excl. D)	**100,00%**	**80,32%**	**100,00%**	**82,46%**	**100,00%**	**76,55%**	**100,00%**	**99,67%**	**100,00%**	**77,89%**	**100,00%**	**92,31%**

Weighted life cycle embodied impacts	**Impact categories (€/FU)**											
	Global warming potential		**Acidification potential**		**Eutrophication potential**		**Ozone depletion potential**		**Photochemical ozone creation potential**		**Total use of primary energy**	
Life-cycle stage	**Linear**	**Circular**	**Linear**	**Circular**	**Linear**	**Circular**	**Linear**	**Circular**	**Linear**	**Circular**	**Linear**	**Circular**
A1-3	1.240,00	810,00	580,00	397,60	320,40	169,20	0,07	0,07	40,60	27,20	24,48	20,56
A4	3,96	5,15	1,40	1,83	0,68	0,89	0,00	0,00	0,01	0,01	0,18	0,23
A5	225,50	225,50	65,20	65,20	89,10	89,10	0,02	0,02	1,11	1,11	6,74	6,74
B1-5	740,00	740,00	371,20	371,20	212,40	212,40	0,06	0,06	18,40	18,40	17,28	17,28
C1-4	43,60	28,90	1,45	4,68	0,63	5,45	0,00	0,00	0,05	0,15	0,09	0,20
D External impacts	-211,50	-167,00	-57,60	-24,64	-12,96	-8,72	-0,00	-0,00	-3,84	-1,55	-4,00	-4,50
Total (incl. D)	**2.041,56**	**1.642,55**	**961,65**	**815,87**	**610,25**	**468,32**	**0,14**	**0,14**	**56,33**	**45,31**	**44,77**	**40,52**
Total (excl. D)	**2.253,06**	**1.809,55**	**1.019,25**	**840,51**	**623,21**	**477,04**	**0,14**	**0,14**	**60,17**	**46,87**	**48,77**	**45,02**

Weighted life cycle impacts per building element	**Global warming potential (€/FU)**				**Acidification potential (€/FU)**			
Building elements	**Linear**	**D External impacts**	**Circular**	**D External impacts**	**Linear**	**D External impacts**	**Circular**	**D External impacts**
Building systems and installations	1.348,59	-41,70	1.348,59	-41,70	656,53	-13,76	656,53	-13,76
Floors and roofs	424,27	-139,00	101,76	-71,00	226,09	-37,20	44,84	-6,08
Construction site scenarios	225,71	-	225,71	-	65,32	-	65,32	-
External walls and facade	159,33	-29,85	53,32	-29,10	35,64	-6,68	19,31	-2,70
Windows and doors	93,63	-	79,87	-24,10	34,18	-	54,05	-2,05
Foundation, sub-surface, basement and retaining walls	3,65	-0,68	3,65	-0,68	0,67	-0,09	0,67	-0,09
Total	**2.255,17**	**-211,23**	**1.812,90**	**-166,58**	**1.018,44**	**-57,73**	**840,72**	**-24,68**

Relative characterized life cycle impacts per building element	**Global warming potential (%/FU)**				**Acidification potential (%/FU)**			
Building elements	**Linear**	**D External impacts**	**Circular**	**D External impacts**	**Linear**	**D External impacts**	**Circular**	**D External impacts**
Building systems and installations	59,80%	19,74%	74,39%	25,03%	64,46%	23,83%	78,09%	55,75%
Floors and roofs	18,81%	65,81%	5,61%	42,62%	22,20%	64,44%	5,33%	24,64%
Construction site scenarios	10,01%	0,00%	12,45%	0,00%	6,41%	0,00%	7,77%	0,00%
External walls and facade	7,06%	14,13%	2,94%	17,47%	3,50%	11,57%	2,30%	10,92%
Windows and doors	4,15%	0,00%	4,41%	14,47%	3,36%	0,00%	6,43%	8,31%
Foundation, sub-surface, basement and retaining walls	0,16%	0,32%	0,20%	0,41%	0,07%	0,16%	0,08%	0,37%
Total	**100,00%**	**100,00%**	**100,00%**	**100,00%**	**100,00%**	**100,00%**	**100,00%**	**100,00%**

Characterized life cycle impacts per material type	Floors and roofs (€/FU)				External walls and façade (€/FU)				Windows and doors (€/FU)			
	Linear		**Circular**		**Linear**		**Circular**		**Linear**		**Circular**	
GPS	27,02		28,35									
EPS					126,70	-19,07						
PIR	307,62	-26,92										
Galvanized steel	315,80	-149,54										
Mortar					11,64							
Other steel/iron					52,54	-16,62						
Rock wool			17,69		0,74		17,08					
Bricks					2,96	-0,08	6,05	-0,17				
Particleboard					0,34	-0,79						
PVC windows									120,67			
Wooden windows									7,14		133,91	-26,14
Timber			17,23	-44,33			7,73	-19,91				
Cellulose insulation			21,74				9,81					
Plywood			62,94	-32,95			20,29	-10,64				
Structural steel							5,66	-1,09				
Gypsum board							6,03					
Total	**650,43**	**-176,46**	**147,95**	**-77,28**	**194,91**	**-36,57**	**72,65**	**-31,81**	**127,81**		**133,91**	**-26,14**

Characterized life cycle embodied impacts	Scenarios (eq./FU)									
	Linear BS		**Circular BS**		**Bio-based**		**Secondary materials**		**Lifetime extension (Reuse EoL)**	
Life-cycle stage	**GWP**		**GWP**		**GWP**		**GWP**		**GWP**	
A1-3	2,48E+04		1,58E+04		1,64E+04		1,42E+04		1,63E+04	
A4	7,91E+01		1,03E+02		1,19E+02		1,03E+02		1,03E+02	
A5	4,51E+03		4,51E+03		4,51E+03		4,51E+03		4,51E+03	
B1-5	1,48E+04		1,50E+04		1,50E+04		1,50E+04		1,50E+04	
C1-4	8,72E+02		1,00E+03		6,70E+02		1,07E+03		5,54E+02	
D External impacts	-4,23E+03		-7,84E+03		-1,06E+04		-8,16E+03		-9,81E+03	
Total (excl. D)	**4,51E+04**		**3,64E+04**		**3,66E+04**		**3,49E+04**		**3,64E+04**	
Total (incl. D)	**4,08E+04**		**2,86E+04**		**2,60E+04**		**2,68E+04**		**2,66E+04**	

Relative characterized life cycle embodied impacts	**Scenarios (%/FU)**									
	Linear BS		**Circular BS**		**Bio-based**		**Secondary materials**		**Lifetime extension (Reuse EoL)**	
Life-cycle stage	**GWP**		**GWP**		**GWP**		**GWP**		**GWP**	
A1-3	55,04%		35,08%		36,33%		31,62%		36,17%	
A4	0,18%		0,23%		0,26%		0,23%		0,23%	
A5	10,01%		10,02%		10,02%		10,02%		10,01%	
B1-5	32,84%		33,22%		33,22%		33,22%		33,22%	
C1-4	1,94%		2,22%		1,49%		2,37%		1,23%	
D External impacts	-9,39%		-17,40%		-23,52%		-18,10%		-21,77%	
Total (excl. D)	**100,00%**		**80,76%**		**81,32%**		**77,46%**		**80,86%**	

Characterized life cycle embodied impacts	**Scenarios (eq./FU)**							
	Circular BS		**Bio-based**		**Secondary materials**		**Lifetime extension (Reuse EoL)**	
Life-cycle stage	**GWP**		**GWP**		**GWP**		**GWP**	
C1 Deconstruction/demolition	5,06E+02		5,06E+02		5,06E+02		5,06E+02	
C2 Waste transportation	8,49E+01		9,63E+01		1,03E+02		3,72E+01	
C3 Waste processing	4,10E+02		5,99E+01		4,54E+02		1,06E+01	
C4 Waste disposal	6,83E-01		7,95E+00		5,52E+00		2,46E-01	