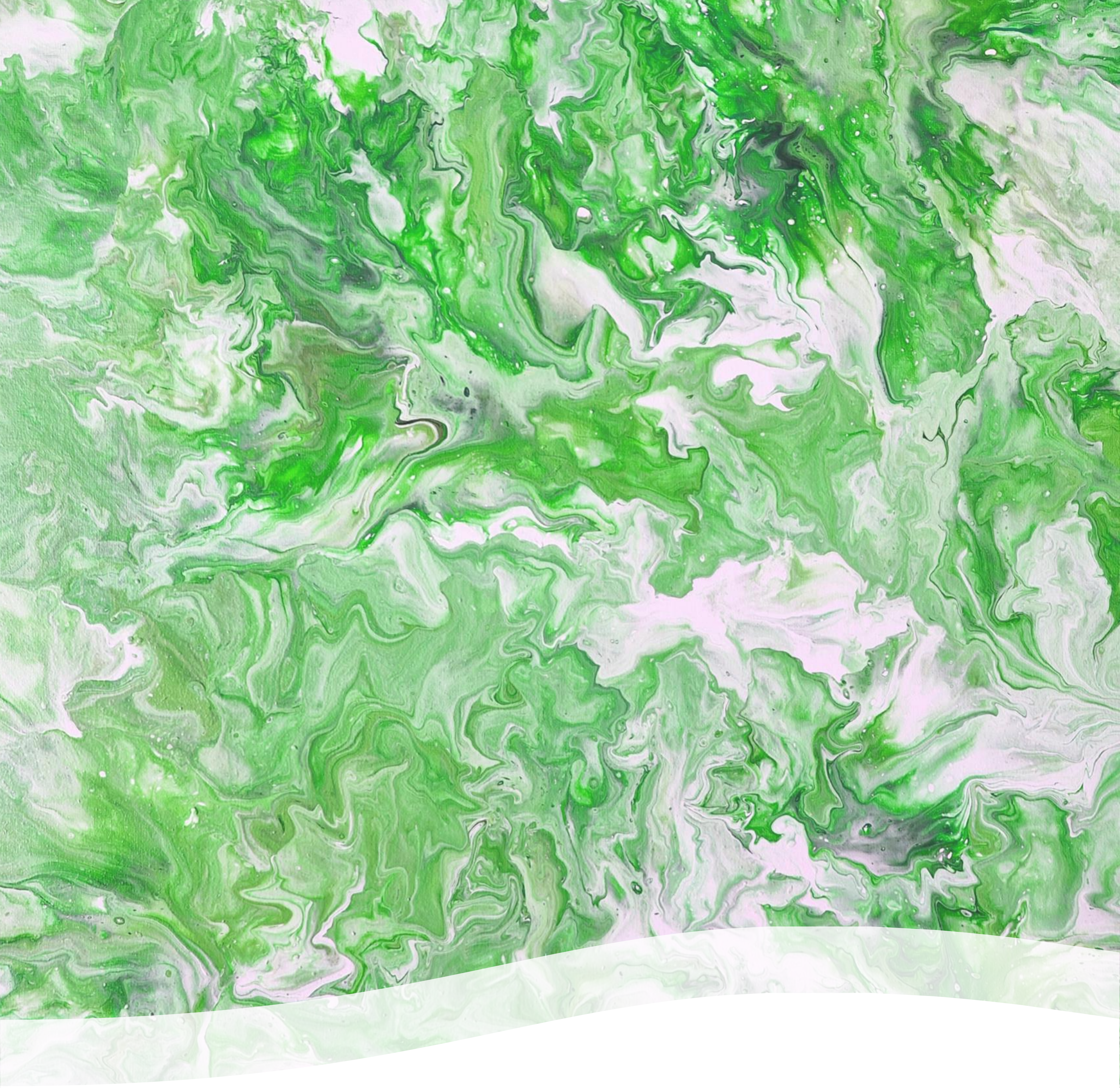

Introducing a lifecycle-based approach in energy-saving advice for utility buildings

The effect of global warming potential and cumulative energy demand on the decision-making process

Master Thesis Lisanne Hagen 3 July 2024

Introducing a lifecycle-based approach in energy-saving advice for utility buildings

The effect of global warming potential and cumulative energy demand on the decision-making process

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Colophon

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Preface

In front of you is the Master's thesis "Introducing a lifecycle-based approach in energy-saving advice for utility buildings; The effect of global warming potential and cumulative energy demand on the decision-making process". This research has been conducted for Antea Group and is written as part of the Civil Engineering and Management Master's programme at the University of Twente in Enschede.

During my Bachelor of Building Engineering, I became interested in the concepts of sustainability and circularity in the built environment. This interest grew during my Master's programme, where I followed courses related to these topics. For example, the courses related to conducting and interpreting Life Cycle Assessment (LCA) studies. Therefore, I wanted to direct my Master's thesis towards the subjects of sustainability and buildings. Despite this broad scope, the research assignment of Antea Group was a good match: the lifecycle impact of products implemented to reduce energy consumption in buildings. In addition to the LCA calculations, I wanted to challenge myself by taking the research one step further. I wanted to understand the effect of the results. Therefore, I conducted interviews and organised a brainstorming session. This provided me with insight, both personally and professionally.

I would like to express my gratitude to Antea Group for the opportunity to conduct my Master's thesis. In particular, Jan-Lucas Hof for his innovative mindset, which led to the main research question of this study, and for his enthusiasm for the subject throughout the thesis. This resulted in interesting discussions and ideas to include in the research as is now in front of you. Furthermore, I would like to thank Mats Wentholt for his support during the writing of my research proposal and the first part of my Master's thesis. He was always willing to help me with any questions. Unfortunately, he passed away on 19 May 2023 in an accident on one of the mountain peaks of the Swiss Alps. This had a huge impact on me and all the colleagues working with him, making it challenging to resume the thesis. Despite the difficult circumstances, Richard van Dijk and Jan-Lucas Hof were able to assume the role of Mats Wentholt. I am very grateful for their willingness to take on that role. I want to thank Richard van Dijk in particular for his continued support during this period and his trust in me. This gave me the confidence to resume.

I would also like to express my gratitude to Markus Berger, Rosalie Arendt, and Andreas Hartmann, my supervisors at the University of Twente, for their feedback and flexibility in allowing me the time I needed to complete the thesis. I would like to thank Markus Berger in particular for his passion for LCA studies during the course Sustainable Engineering and Integrated Water Management. This has inspired me to conduct my thesis in the field of LCA studies. Furthermore, I want to thank Rosalie Arendt for the meetings during the thesis in which she provided feedback and challenged me to bring the thesis to a higher level.

Finally, I would like to thank all clients and employees of Antea Group for their contributions during the interviews and the brainstorming session. The study would not have been possible without their input.

I wish you a lot of reading enjoyment.

Lisanne Hagen

Deventer, 3 July 2024

Summary

The building sector has a significant share in energy consumption and greenhouse gas (GHG) emissions worldwide. To reduce this, the energy consumption of buildings should be lowered by implementing energy-saving measures. Buildings receive an energy label indicating how energy efficient the building is. The higher the energy label, the less energy a building consumes. In the Netherlands, all utility buildings must have energy label A in 2030, and label Energy Neutral in 2050 (RVO, 2022). To achieve this, energy-saving measures should be implemented. These measures aim to reduce the energy consumption of a building. However, this approach only considers the energy reduction during the building's use phase, while energy is also consumed during the lifecycle of the products required for the energy-saving measures. Furthermore, this energy consumption results in GHG emissions over the lifecycle of energy-saving products.
To address this, the European Union has set a goal of having a net zero whole life carbon emission building stock in Europe by 2050 (WGBC, 2022). This means that the operational and embodied carbon emissions over the entire lifecycle of the building should reach a net zero level. Therefore, GHG emissions and energy consumption over the entire lifecycle of energy-saving products become of significant importance.

Antea Group is a significant player in the Netherlands, providing engineering and consultancy services for the built environment, including energy-saving advice for utility buildings. Therefore, they use the Vabi EPA-U software. This software enables the calculation of a building's energy performance, allowing the determination of the energy label and the energy-saving measures to achieve a higher energy label. However, the embodied energy and resulting emissions are not included in the Vabi EPA-U calculations and therefore not considered when advising on energy-saving measure packages. Therefore, Antea Group cannot advise its clients on energy-saving measures as comprehensively as they wish. To address this issue, the objectives of this research are 1) to determine the CO_2 equivalents and energy consumption over the lifecycle of the energy-saving measures and 2) to ascertain the effects of this knowledge on the decisions made by employees and clients of Antea Group.

First, the most commonly advised energy-saving measures by Antea Group are identified. These are insulation, glazing, heat pumps, PV panels, LED lighting, and mechanical ventilation. For each of these measures, conventional and alternative products are determined. This was achieved through ten interviews and a literature study, which resulted in 26 different products. For all these products, the lifecycle-based global warming potential (GWP) and cumulative energy demand (CED) are determined based on Environmental Product Declarations (EPDs). The results indicate that the production phase is the most significant for insulation and glazing, while the use phase is the most significant for the heat pumps, LED lighting, and mechanical ventilation. Only for PV panels, both the production and use phases are significant. This is in line with previous studies. The sensitivity analysis resulted in ranges for the GWP and CED. Values obtained in previous studies are within these ranges, although they also extend beyond them. This mainly depends on differences in goal and scope definitions.

The GWP and CED ranges are used to calculate the GWP and CED impact and payback periods per product for each building. In addition, the financial costs and payback periods are determined per product. To compute the GWP, CED, and financial costs and payback periods per measure package, it is necessary to select products per measure in the package. This is done based on three scenarios: the lowest GWP payback period, the lowest CED payback period, and the lowest financial payback period. It is found that the highest GWP, CED, and financial costs are associated with the transition from energy label E to label A or Energy Neutral. The lower outcomes of other label steps depend on the selected measures, products, and quantities of the products. Furthermore, it was concluded that only selecting the products with the lowest financial payback periods, leads to the highest GWP and CED impacts and payback periods of all label steps considered in this study.

The findings were presented to five clients and eight employees of Antea Group during interviews and a brainstorming session respectively. The interviews revealed that financial costs are considered the most important by clients when selecting energy-saving measures. Even after expressing confidence in choosing products with lower GWP and CED impacts in future projects. Because the respondents mentioned that the costs should remain within budget. During the brainstorming session, it was found that employees tend to focus on the client's demand. Consequently, the financial costs and energy-saving measures are accorded the highest priority, while environmental impacts are accorded a relatively low priority. As with the clients, the employees would also like to change their prioritisation in future projects.

To facilitate this change, several recommendations are proposed. First, it is recommended that employees should raise awareness of the lifecycle impacts to clients by means of an explanation. Even when clients do not initially request it. Because it is found that clients are more likely to select products with lower GWP and CED impacts after receiving in-person clarification. To provide this explanation, employees should be educated first.

When clients agree to include the GWP and CED in the advice, employees should calculate these impacts. A database with LCA results can be created to prevent conducting LCA calculations for each individual project. This database can be filled with the results of this study and expanded with data from other products. It is recommended to keep the database updated, and that additional impacts are added when employees are familiar with using the database. Because more impacts exist besides the GWP and CED.

When presenting the results to clients, it is advisable to use the three scenarios as included in this study to reduce time and costs. However, it is expected that clients want to create their own scenarios. Therefore, it is recommended to provide an overview of the GWP and CED results per functional unit in the advice. Thereby, it is important to mention to clients that products from different measures cannot be compared because of differing functional units per measure. In the longer term, it is recommended to create a dashboard in which clients can select products through a process of trial and error. This will enable clients to select products with the least GWP and CED impacts that still fit their budget.

Samenvatting

De bouwsector heeft wereldwijd een groot aandeel in het energiegebruik en de uitstoot van broeikasgassen. Om dit te reduceren, moet het energieverbruik van gebouwen worden verminderd door energiebesparende maatregelen toe te passen. Gebouwen hebben een energielabel dat aangeeft hoe energiezuinig het gebouw is. Hoe hoger het energielabel, hoe minder energie het gebouw gebruikt. In Nederland is het streven dat alle utiliteitsgebouwen in 2030 energielabel A hebben en in 2050 energieneutraal zijn (RVO, 2022). Om dit te bereiken moeten energiebesparende maatregelen worden toegepast. Deze maatregelen zijn gericht op het verminderen van het energieverbruik van een gebouw. Daarbij wordt echter alleen rekening gehouden met de gebruiksfase van het gebouw, terwijl er ook energie wordt gebruikt, en daarmee broeikasgassen worden uitgestoten, over de levensduur van energiebesparende producten.
Om dit te veranderen, heeft de Europese Unie een doel opgesteld waarbij alle gebouwen in Europa in 2050 netto nul emissies mogen hebben over de hele levenscyclus (WGBC, 2022). Dit betekent dat de operationele en materiaalgebonden emissies over de hele levenscyclus van een gebouw netto nul moeten zijn. Daarmee worden de broeikasgasemissies en het energiegebruik gedurende de hele levenscyclus van energiebesparende producten van groot belang.

Antea Group is een belangrijke speler in Nederland die advies geeft voor verschillende projecten in de gebouwde omgeving, waaronder energiebesparingsadviezen voor utiliteitsgebouwen. De materiaal gebonden energie en de daaruit voortvloeiende emissies worden echter niet berekend in de berekeningen van Vabi EPA-U en dus ook niet meegenomen in de advisering over energiebesparende maatregelpakketten. Daardoor kan Antea Group haar klanten niet zo uitgebreid adviseren over energiebesparende maatregelen als zij wensen. Om dit aan te pakken, is dit onderzoek uitgevoerd. Daarbij zijn er twee doelstellingen: het bepalen van de CO2-equivalenten en het energiegebruik over de levenscyclus van de energiebesparende maatregelen; en het vaststellen van de effecten van deze kennis op de beslissingen die medewerkers en klanten van Antea Group maken tijdens het opstellen of kiezen van energiebesparende maatregelpakketten.

In dit onderzoek zijn de energiebesparende maatregelen bepaald die het vaakst worden geadviseerd door Antea Group. Dit zijn isolatie, beglazing, warmtepompen, PV-panelen, LED verlichting en mechanische ventilatie. Voor elk van deze maatregelen zijn conventionele en alternatieve producten bepaald door middel van tien interviews en een literatuurstudie. Dit resulteerde in 26 verschillende producten. Voor al deze producten zijn de global warming potential (GWP) en cumulative energy demand (CED) over de hele levenscyclus bepaald op basis van Environmental Product Declarations (EPD's). Uit de resultaten blijkt dat de productiefase leidt tot de meeste significante impact voor isolatie en beglazing. Voor warmtepompen, LED verlichting en mechanische ventilatie is dit de gebruiksfase. Bij zonnepanelen zijn zowel de productie- als de gebruiksfase significant. Deze resultaten komen overeen met eerdere studies.
Uit de sensitiviteitsanalyse zijn verschillende marges van de GWP en de CED naar voren gekomen. De berekende waarden van de GWP en CED uit eerdere studies liggen zowel binnen als buiten deze marges. Dit wordt voornamelijk veroorzaakt door de verschillende goal en scope definities.

De GWP- en CED-bereiken zijn gebruikt om de GWP- en CED-impact en terugverdientijden per product te berekenen voor elk gebouw. Daarnaast zijn de financiële kosten en terugverdientijden per product bepaald. Om de GWP, de CED en de financiële kosten en terugverdientijden per maatregelpakket te berekenen, moeten producten worden geselecteerd per maatregel in het pakket. Dit wordt gedaan op basis van drie scenario's: De laagste GWP-terugverdientijd, de laagste CED-terugverdientijd en de laagste financiële terugverdientijd.
Uit de resultaten blijkt dat de hoogste GWP-, CED- en financiële kosten geassocieerd zijn met de sprong van energielabel E naar energielabel A of Energieneutraal. De lagere uitkomsten van de andere

labelsprongen zijn afhankelijk van de geselecteerde maatregelen, producten en hoeveelheden van de producten. Ook is naar voren gekomen dat het selecteren van uitsluitend producten met de laagste financiële terugverdientijd resulteert in de hoogste GWP- en CED-impact en -terugverdientijden van alle labelsprongen die in deze studie zijn onderzocht.

De bevindingen van dit onderzoek zijn besproken met vijf klanten en acht medewerkers van Antea Group tijdens interviews en een brainstormsessie. Uit de interviews blijkt dat klanten de financiële kosten als belangrijkste criterium beschouwen bij het kiezen van energiebesparende maatregelen. Dit geldt nog steeds wanneer ze producten met een lagere GWP- en CED-impact toe willen passen in toekomstige projecten. Klanten geven namelijk aan dat de kosten binnen het budget moeten blijven. Tijdens de brainstormsessie is gebleken dat medewerkers de neiging hebben om de klantvraag als leidraad te nemen. Daardoor krijgen de financiële kosten en energiebesparende maatregelen de hoogste prioriteit en de milieu-impact een relatief lage prioriteit. Net als de klanten willen medewerkers in toekomstige projecten hun prioritering veranderen en meer aandacht geven aan de milieu-impact.

Om deze verandering mogelijk te maken, zijn een aantal aanbevelingen gedaan. Ten eerste wordt aanbevolen dat medewerkers hun klanten bewust maken van milieu-impact over de gehele levenscyclus van producten. Het is namelijk gebleken dat klanten eerder geneigd zijn om producten met een lager GWP- en CED-impact te kiezen nadat ze persoonlijk uitleg hebben gekregen. Om deze uitleg te kunnen geven, moeten medewerkers hierin eerst zelf worden bijgeschoold.
Als klanten ermee instemmen om de GWP en de CED in het advies op te nemen, zullen medewerkers deze impacts moeten berekenen. Om te voorkomen dat LCA-berekeningen voor elk individueel project moeten worden uitgevoerd, kan een database met LCA-resultaten worden gemaakt. Deze database kan worden gevuld met de resultaten van dit onderzoek en worden uitgebreid met gegevens van andere producten. Het is aan te raden om de database up-to-date te houden en extra milieu-impacts toe te voegen wanneer medewerkers bekend zijn met het gebruiken van de database. Er zijn namelijk meer milieu-impacts naast de GWP en CED.
Bij het tonen van de resultaten aan klanten is het raadzaam om de drie scenario's uit deze studie te gebruiken om tijd en kosten te besparen. Het kan echter voorkomen dat klanten hun eigen scenario's willen maken. Daarom wordt aanbevolen om in het advies een overzicht weer te geven van de GWP- en CED-resultaten. Daarbij is het belangrijk om klanten erop te wijzen dat producten uit verschillende maatregelen niet met elkaar vergeleken kunnen worden vanwege de verschillende eenheden per maatregel. Op de langere termijn is het advies om een dashboard te creëren waarin klanten producten kunnen selecteren door middel van een proces van trial-en-error. Zo kunnen klanten producten selecteren met de minste GWP- en CED-impact die toch binnen hun budget passen.

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Abbreviations

Abbreviation	Definition
CED	Cumulative Energy Demand
c-PCR	Complementary Product Category Rules
EoL	End of Life
EPD	Environmental Product Declaration
FU	Functional Unit
GHG	Green House Gas
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
PCR	Product Category Rules
Rc-value	Resistance Construction Value

Glossary

Term	Definition
Complementary product category rules c-PCR	A main PCR can have multiple complementary PCRs. These complementary PCRs contain additional rules for specific product categories. When a c-PCR is available, this must be used complementary to the main PCR.
Cumulative energy demand CED	The primary energy demand of a system or product over its entire lifecycle. The types of energy are both renewable and non-renewable.
End of life EoL	The last lifecycle phase of a system or product. For example, landfilling, recycling, or waste incineration, i.e. retrieving energy from waste.
Energy label	An indication of how energy efficient a building is. This is expressed in letters, where label A++++ is the most efficient and label G the least.
Energy neutral	A situation where a building's use of fossil fuels for energy is compensated by renewable energy. Therefore, an energy neutral building can still use fossil fuels as long as it is compensated.
Environmental impact	Changes in the environment which are caused by systems or products over their entire lifecycle.
Environmental product declaration EPD	The results of an LCA study after following specific PCR and c-PCR rules.

Term	Definition
Functional Unit **FU**	A quantified description of a system's function which serves as a reference basis for the LCA calculations. The calculated environmental impact will be expressed per functional unit, for example, the impact per m^2.
Global warming potential **GWP**	A measure of the contribution a system or product has to the greenhouse effect. This is expressed in CO_2 equivalents.
Greenhouse gas **GHG**	Gasses in the atmosphere that trap heat in the earth, leading to the global warming effect. Examples of greenhouse gases are carbon dioxide, water vapour, methane, nitrous oxide, and fluorinated gases.
Label step	The transition from the initial energy label to a new energy label.
Lifecycle assessment **LCA**	A method to identify and assess a system's or product's potential environmental impact over its entire lifecycle.
Lifecycle inventory **LCI**	An element of the LCA study that mainly includes collecting required data, presenting it in a flow diagram, and modelling it in LCA software.
Lifecycle impact assessment **LCIA**	An aspect of the LCA study after the data collection in the lifecycle inventory (LCA). The data of the LCI will be used to calculate the environmental impacts. For example, to assess the GWP and CED when using $1m^3$ of gas.
Payback period	The amount of time needed to repay the investments. This is mainly financial, however, in this study, it is also used in the way of GWP or CED payback periods.
Product category rules **PCR**	Specific rules on how to conduct an LCA for a particular product or system.
Sensitivity analysis	A method for investigating the robustness of the LCA results and to find the effects uncertain factors have on the results.
Thermal conductivity coefficient	The amount of heat a material can transfer. The lower this coefficient, the better the insulation capacity.
Thermal resistance coefficient **Rc-value**	The thermal resistance of an entire construction, instead of only one material.

1. Introduction

Greenhouse gas (GHG) emissions have increased significantly since 1900 and "GHG emissions from the building sector have more than doubled since 1970" (IPCC, 2014, p.78). In 2021, the share of buildings in global energy and process emissions was 37 per cent. This is a high share compared to the transport sector (22 per cent) and other industries (30 per cent) (UNEP, 2022).
GHG emissions have led to a rapid rise in global temperatures (Kumar & Pooja, 2020). To slow this down, parties around the world agreed to limit the rising temperature to 1.5 degrees Celsius compared to pre-industrial levels (United Nations, 2015). To achieve this, the UNEP identified critical actions for the building sector. These actions include 1) the requirement to label a building's energy performance with an energy label; 2) the implementation of energy efficiency refurbishment actions for existing buildings; 3) the use of low-carbon and biobased materials to reduce the long-term embodied carbon of buildings (UNEP, 2022). Therefore, energy-saving measures and their material choices play a large role in reducing GHG emissions in the construction sector.

An energy-saving advice is a combination of energy-saving measures to reduce the energy consumption of a building. Thereby, only the use phase of the building, i.e. the operational energy, is considered. However, energy is also consumed throughout the entire lifecycle of energy-saving products, which results in GHG emissions over this entire lifecycle. This is referred to as the embodied energy and embodied carbon of the building. The embodied carbon is the basis for the European Union's aim to have a net zero whole life carbon emission building stock in Europe by 2050 (WGBC, 2022). This means that the operational and embodied carbon over the whole lifecycle of a building should reach a net zero level. Emissions that cannot be eliminated should be neutralised through carbon removals (WGBC, 2022). Therefore, the building sector is challenged to consider GHGs over the entire lifecycle of a building. Accordingly, GHG emissions should be considered over the lifecycle of energy-saving products. Since GHG emissions result from energy consumption, it is also important to understand the energy consumption over the entire lifecycle of energy-saving products.

Antea Group is an international organisation that provides engineering and consultancy services for environmental, infrastructure, urban planning, and water projects. Currently, 1,500 engineers are working at Antea Group, making it a significant player in the Netherlands. Antea Group is dedicated towards sustainability, which can be recognised by its contribution to the Sustainable Development Goals (SDGs). The selected SDGs of focus are shown in Figure 1.

Figure 1 Selected SDGs of Antea Group (Antea Group, n.d.).

Antea Group's multi-year plan "Blauwdruk" translates these SDGs into four themes: Together, Client, Sustainability, and Digitalisation. Each department interprets these four themes. One of the five departments is called "Built environment". This department focuses on advising future-proof and energy-efficient building concepts based on its expertise in building engineering, installations, and building physics. One of the activities is advising clients on energy-saving measures for utility buildings.

These energy-saving measures contribute to a reduction in the building's energy consumption. The saved CO_2 emissions as a result of the building's energy reduction are added to the advice. Despite this addition, the focus remains on saving energy instead of reducing CO_2 emissions. Moreover, some employees have observed that the products required for the implementation of energy-saving measures consume energy and emit CO_2. To address this, Antea Group wants to include the lifecycle impact of energy consumption and corresponding emissions in their advice. In addition to raising awareness among clients and employees, this will help to take the first steps towards a net zero whole life carbon emission building stock in 2050.

1.1 Research problem

Antea Group uses the Vabi EPA-U software to calculate a building's energy performance. Thereby, the current energy label and the energy-saving measures to achieve a higher energy label can be determined. The embodied energy and resulting emissions are not included in the calculations of Vabi EPA-U and therefore not considered when advising on energy-saving measure packages. As a result, Antea Group cannot advise its clients on energy-saving measures as comprehensively as they wish. This indicates that in addition to the measure's energy-saving ability to achieve a higher energy label, the energy consumption and emissions over its lifecycle should also be considered.

The lifecycle energy consumption can be expressed in MJ of Cumulative Energy Demand (CED). Although CO_2 has been the largest contributor to the intensified temperature on Earth over the last century, it is not the only GHG (Kumar & Pooja, 2020). Other GHGs with a significant contribution to global warming are water vapour (H_2O), methane (CH4), nitrous oxide (N_2O), and fluorinated gases such as CFC-11 and CFC-12 (Khalil, 1999; IPCC, 2007; Kweku et al., 2017). As Khalil (1999) addresses, only focusing on CO_2 might lead to the rampant growth of other GHGs. Therefore, it would be better to look at the contribution to global warming. Hence, the Global Warming Potential (GWP) of the GHGs emitted over the lifecycle of the energy-saving measures. This can be expressed in CO_2-equivalents, a converted unit combining the GWP of CO_2, N2O, CH4 and fluorinated gases (IPCC, 1992). Additionally, Antea Group does not advise on materials or products for the proposed measures. However, it would like to have an overview of the commonly used products and their environmentally friendly alternatives. Therefore, the GWP and CED over the lifecycle of the products could be considered in the advice. This could lead to more comprehensive advice and it can make employees and clients more aware of the potential environmental impact of their choices. However, it is unclear whether this will lead to different advice and choices of energy-saving measures and packages.

1.2 Research objective

Antea Group wishes to make a well-considered decision about the environmental impact of their advised measure packages. Therefore, they want to investigate if other choices would be made if the environmental impact of their advice is known. Furthermore, Antea Group want to create awareness among its employees and clients about the measure packages and product choices. Therefore, the objectives of the research are to determine the CO_2 equivalents and energy consumption over the lifecycle of the energy-saving measures and to find out how this knowledge affects the decision-making process of clients and employees of Antea Group.

1.3 Research questions

To achieve the objective described in the previous section, the main questions are: What are the GWP and CED over the lifecycle of materials or products required for the energy-saving measures advised by Antea Group? And how could these results affect the advised and chosen energy-saving measures?

To answer the main question, the following four research questions are formulated.

1. What are the GWP and CED over the lifecycle of the conventional and alternative products that are currently being applied in practice for the most commonly advised measures by Antea Group?
2. How can the lifecycle GWP and CED of a measure package be implemented in the energy-saving advice?
3. How will the current prioritisation of criteria for selecting energy-saving measures, according to clients and employees of Antea Group, be affected by the introduction of the GWP and CED?

1.4 Outline

The background to this study is presented in Section 2, which describes the phenomenon of global warming and the construction sector's contribution to it. Furthermore, legislation to reduce global warming and Antea Group's method of advising on energy-saving measures will be elaborated. In addition, the LCA methodology and its application in the construction sector are outlined.

A detailed description of the applied methodology to answer the research questions is presented in Section 3. The results are provided in Section 4. The results consist of the most commonly advised measures and their conventional and alternative products, the GWP and CED results and payback periods of these products and measure packages, the financial costs and payback periods per product and measure package, and the results of the interviews with clients and the brainstorming session with employees. The methodology and results are discussed in Section 5 and conclusions are drawn in Section 6. The study is closed with a recommendation in Section 7.

2. Background

The starting point of this research is global warming and the impact of the building sector towards this phenomenon (Section 2.1). Global warming can be limited by implementing legislation to reduce GHG emissions (Section 2.2). Building owners need to comply with this legislation. For example, by implementing energy-saving measures. Antea Group advises clients about these measures according to the process as described in Section 2.3. Currently, this process only focuses on the building's use phase, while the entire lifecycle of the energy-saving products should also be considered. An LCA study considers this whole lifecycle. Therefore, the LCA method (Section 2.4) and the application of LCAs in the construction sector (Section 2.5) are also included in the research's background.

2.1 Global warming and the building sector's impact

The average temperature on Earth is rising which should be limited as soon as possible. The increasing temperature is caused by the greenhouse effect which is dominated by greenhouse gases (GHG) in the atmosphere. As presented in Figure 2, GHGs allow solar radiation to pass from space to the Earth's surface inducing the surface to warm up. Besides, the surface partly reflects radiation into space. However, GHGs hinder part of this radiation from escaping. Hence, it is reflected back to the Earth, causing the surface to warm up even more (Kumar & Pooja, 2020; Kweku et al., 2017; Khalil, 1999; EIA, 2022).

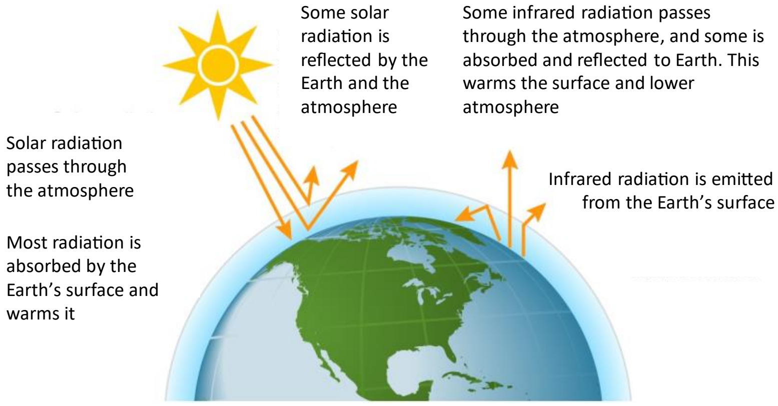

Figure 2 The greenhouse effect, adapted from (EIA, 2022).

This natural process creates a habitable environment with liveable temperatures and is therefore critical for life on Earth (Kweku et al., 2017). However, the concentration of GHGs, especially CO_2, has rapidly increased over the last century and more than doubled since 1970 due to a growing population, industrialization, and social and economic development (Kumar & Pooja, 2020; Khalil, 1999; IPCC, 2014). Therefore, more radiation is reflected on Earth, leading to rapidly increasing temperatures. This is also called global warming and has alarming effects on the climate. Examples are sea level rise, heat waves, wildfires, drought, intense rainfall, storms, ocean acidification, and permafrost degradation (Kumar & Pooja, 2020). These effects should be prevented by reducing GHG emissions worldwide, as well as in the building sector.

The global building sector uses 30 per cent of global energy and emits 27 per cent of global operational-related CO_2 emissions. When adding the production of concrete, steel, aluminium, glass, and bricks, the CO_2 emissions of the use and production phases of the building sector result in approximately 37 per cent (UNEP, 2022). In the Netherlands, the built environment is responsible for 38 per cent of the Dutch CO_2 emissions. This is divided into 27 per cent of operational emissions and 11 per cent of embodied carbon (DGBC, 2021). This indicates that the building sector plays a significant role in the emission of GHGs. Therefore, a reduction of GHGs in this sector is needed.

2.2 Legislation to reduce GHG emissions in the building sector

To reduce GHG emissions worldwide, the Paris Agreement has been signed by 196 parties in 2015. Its main goal is to restrain the average temperature on the earth to rise by 1.5 degrees Celsius compared to pre-industrial levels (United Nations, 2015). This agreement also applies to the building sector in Europe and the Netherlands. This section covers the main legislations about reducing GHG emissions in these regions, namely energy labelling (Section 2.2.1) and lifecycle emissions (Section 2.2.2).

2.2.1 Energy labelling

To reduce GHGs, it is important to have insight into the energy use of products. Therefore, labelling of energy consumption is mandatory in Europe since 2002 (European Parliament, 2018). Specific to labelling buildings, the EPBD (Energy Performance of Buildings Directive) version 2018/844/EU should be applied. This directive obliges the Member States to describe a national calculation method by following the five EPB (Energy Performance of Buildings) standards (European Parliament, 2018) as presented in Figure 3.

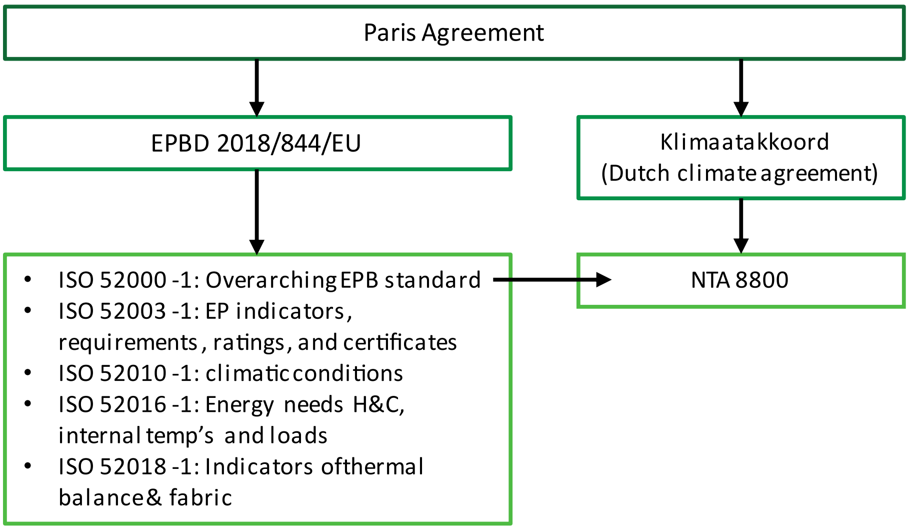

Figure 3 Relation between legislation for energy labelling of buildings.

ISO 52000-1 is one of the EPB standards which should be followed when assessing the energy performance of new and existing buildings (CEN, 2017). This standard mentions the NTA 8800 as the Dutch national method to assess the energy performance of buildings. The NTA 8800 has been mandatory in the Netherlands since 1 January 2021 (Rijksoverheid, 2020). With the NTA 8800, the energy label of a building can be determined (NEN, 2022). This can be done for domestic buildings as well as utility buildings. An energy label represents the primary fossil energy use during the use phase of a building, expressed in kWh/m^{2}y. To determine the primary fossil energy use of a building according to the NTA 8800, the primary energy use in a building for heating, humidification, ventilation, lightening, cooling, dehumidification, and hot tap water are summed. This is added to the total amount of auxiliary energy used. The renewable energy produced by for example PV panels on the terrain of the building will be subtracted from this value (NEN, 2022). With this computed primary fossil energy use, the energy label can be selected from Table 1. This table can be used for domestic as well as utility buildings.

Table 1 Dutch energy labels for buildings and the corresponding primary fossil energy use in kWh/m2.y (Wettenbank, 2022).

Energy label	Primary fossil energy use (kWh/m^2.y)
A++++	< 0.00
A+++	0.01 to 50.00
A++	50.01 to 75.00
A+	75.01 to 105.00
A	105.01 to 160.00
B	160.01 to 190.00
C	190.01 to 250.00
D	250.01 to 290.00
E	290.01 to 335.00
F	335.01 to 380.00
G	>380.00

Besides European legislation, the Paris Agreement is also the basis of the Dutch 'klimaatakkoord' (climate agreement) published in 2019. The Dutch Climate Agreement aims to reduce GHG emissions in the Netherlands in 2030 by 49 per cent compared to 1990 (Rijksoverheid, 2019). This objective impacts the Dutch building sector to diminish its GHG emissions by reducing 1 Mton of CO_2 emissions in the utility sector in 2030 (Rijksoverheid, 2019). Utility buildings are non-residential buildings like offices, schools, stores, hospitals, sports facilities, and hotels. To reduce GHGs for these building types, the Dutch government set up the following steps (RVO, 2022):

1) In January 2023, all utility buildings must have the Dutch energy label C;
2) It is not mandatory, however, striven towards having the Dutch energy label A for all utility buildings in January 2030;
3) In January 2050, all utility buildings must be energy neutral.

An energy neutral building has an (EPC)-value of zero (RVO, 2014). EPC means Energy Prestation Coefficient and indicates the energy efficiency of a building. The lower the value, the more efficient the building (Klimaatexpert, n.d.). The energy neutral concept means that the energy use of fossil energy is compensated by renewable energy. Therefore, an energy neutral building can still use fossil fuels as long as it is compensated (RVO, 2014), making it not the same as a fossil-fuel-free building. Fossil-fuel-free or gas-free is a building without a gas connection and therefore does not directly use gas as an energy source. This type of building relies on other energy sources like electricity or geothermal heat.

2.2.2 Lifecycle emissions

To reach the required Dutch energy label and goal of becoming energy neutral, energy-saving measures should be applied to buildings (Ramesh et al., 2010; UNEP, 2022). These measures play a large role in reducing GHG emissions in the construction sector. Implementing energy-saving measures, lead to a reduction in primary fossil energy use of the building. This reduction in energy usage leads to a reduction in GHG emissions. However, only the use phase of the building is taken into account. As can be seen in Figure 4, this is only part B6 of a building's life cycle. However, energy is required in all lifecycle phases of a building where 80-90 per cent of the lifecycle energy is related to operating energy during the use stage. The other 10-20 per cent results from embodied energy used during the product and construction stages. The end-of-life (EoL) stage has a little or negligible share (Ramesh et al., 2010). In the case of buildings that are highly energy efficient, for instance those with an A++++ energy label or higher, the lifecycle energy may shift more towards embodied energy. To reduce the lifecycle energy, first, the operating energy should be reduced. For existing buildings, this can be achieved by implementing energy-saving measures (Ramesh et al., 2010).

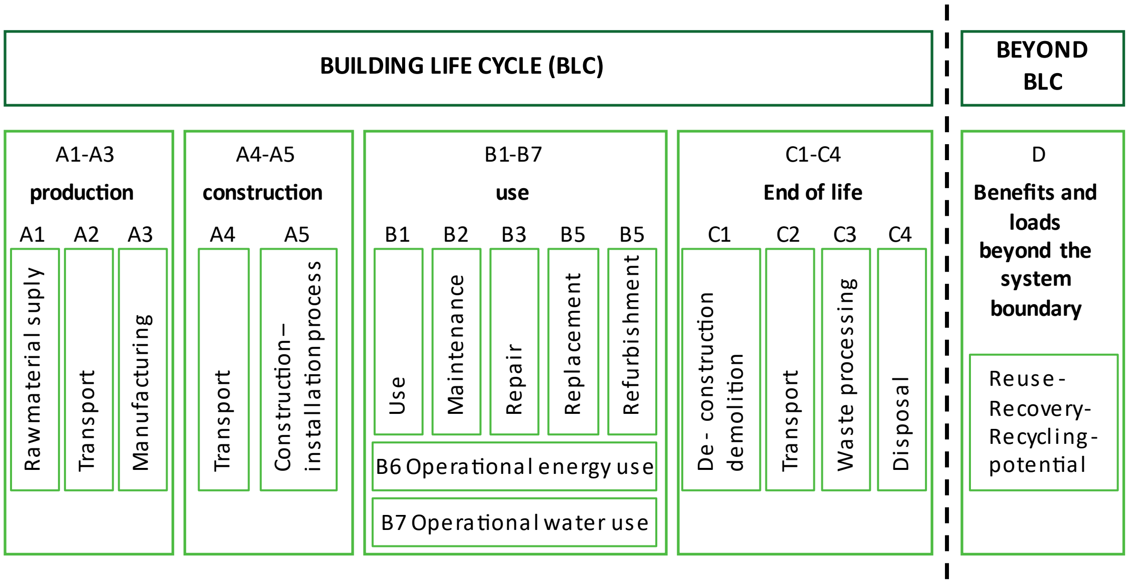

Figure 4 Lifecycle of a building. Adapted from NEN-EN 15978 (CEN, 2011).

In the Netherlands, 22 per cent of all utility buildings have an energy label. A quarter of these buildings do not yet fulfil the requirement of having at least energy label C (Vastgoed Journaal, 2022). Therefore, the percentages of Ramesh et al. (2010) seem representable for the Netherlands. This also declares the focus of the Dutch government on reducing the primary fossil energy use during the use phase of existing buildings. Because the obligation of energy labels will ensure that energy-saving measures are applied. However, these measures require materials, leading to an increase in embodied energy. This brings us to the challenge of the building sector to consider the GHGs emitted over the whole lifecycle instead of only looking at the use phase. The European Union set a goal towards reaching a net zero whole-life carbon emission from the European building stock in 2050 (WGBC, 2022). This makes material choices even more important. Because even though embodied energy has a lower share, "its opportunities for reduction should not be ignored" (Ramesh et al., 2010, p.1594). For example, by choosing low-energy materials with high thermal properties and a long lifetime (Ramesh et al., 2010). To get insight into the emitted GHGs per lifecycle of construction products, an LCA study can be conducted.

2.3 Advising energy-saving measures at Antea Group

The department "Building and Installations" of Antea Group determines energy labels and uses this to advise clients about energy-saving measures. This process is elaborated on in Section 2.3.1. Since the introduction of the NTA 8800 in 2021, a different software version has been used for this process. The differences and effects on the outcomes between the two software versions are provided in Section 2.3.2.

2.3.1 Determining the energy label and energy-saving measures

When a client wants to receive advice about energy-saving measures for a utility building, Antea group follows the process as presented in Figure 5.

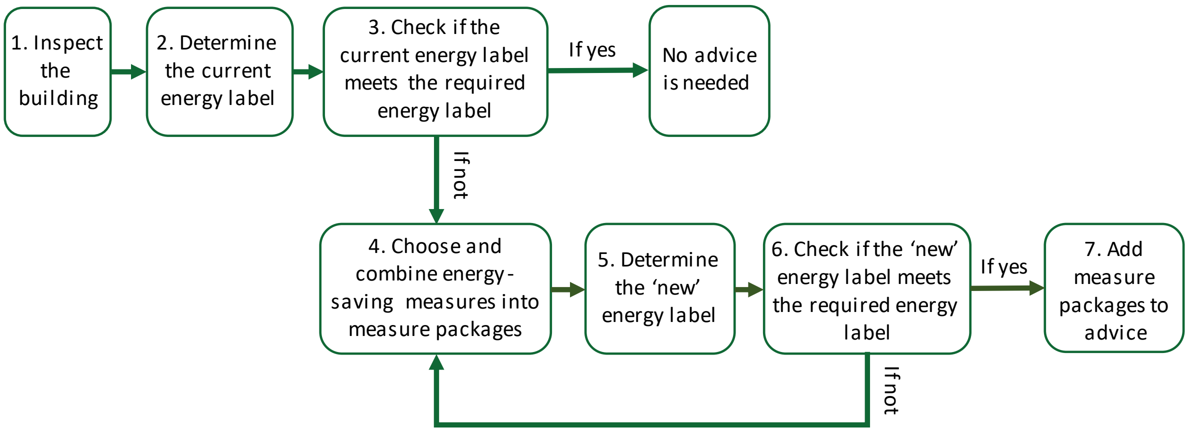

Figure 5 Process of how Antea Group determines the energy-saving measures that are included in the advice.

The first step is to determine the current energy label. Antea Group obtains this by inspecting the building and using this information as input for the Vabi EPA-U software. This software can compute the energy performance according to the NTA 8800 (Vabi, n.d.). When the building does not comply with the required energy label, energy-saving measures can be applied. The possible energy-saving measures are manually combined into measure packages based on the trias energetica principles (Entrop & Brouwers, 2009):

1. Prevent energy use;
2. Use renewable energy efficiently to cover the energy demand as much as possible;
3. In the case of remaining energy demand, make efficient use of fossil fuels.

The 'new' energy label can be determined with the formulated measure packages. This is done by using the current building, including the selected measures, as input of the Vabi EPA-U software. The output of the Vabi EPA-U software is a new primary fossil energy use and corresponding energy label. If this meets the objective energy label, the measure package can be included in the advice.

Energy-saving advices contain two types of measures, considered measures and advised measures. The considered measures will be examined to determine whether they can be applied in a measure package or whether they will be omitted. A considered measure incorporated in a measure package is called an advised measure. These advised measures can be placed in one or multiple measure packages leading to (slightly) differing measure packages. This process is visualised in Figure 6.
A project contains several buildings for which advice has been drawn up. The advice for one building consists of one or multiple measure packages where each package contains multiple advised measures, see Figure 6. In his example, twelve measure are considered. Of these twelve, only five measures are advised. Hence, these are selected in one or multiple measure packages. Measure B has been selected in three packages, measures D, F, and J are selected in two packages, and measure G is selected in one package. Adding up all advised measures in the packages results in ten measures.

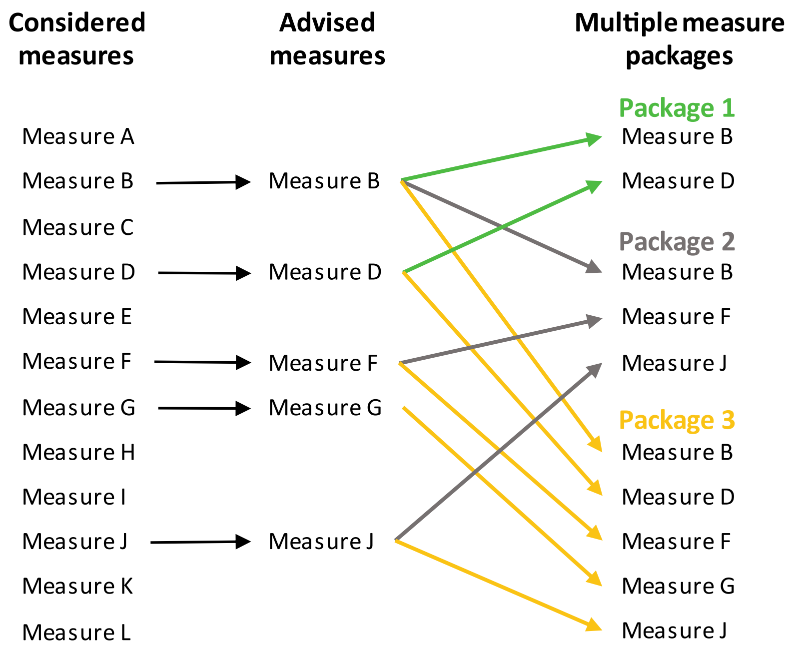

Figure 6 The process from considered measure to multiple measure packages.

One of Antea Group's recent projects is a utility building in a municipality located in Gelderland. The selected measure packages of this project are presented in Table 2. The financial payback period is based on the saved costs as a result of saving energy. The energy saving potential is a multiplication of the gas and electricity price by the amount of gas and electricity saved per year. The CO_2 reduction is calculated by multiplying the gas and electricity saved per year by the emission factors of gas and electricity. Based on this information, Antea Group can advise the client about the to-be-implemented measure package. In this case, measure package 1b is advised due to the short financial payback period. However, the client can also choose measure packages 2, 3, or 4 when it wants to become gas-free (Blokker & Smit, 2022).

Table 2 Measure package formulated by Antea Group for a utility building in a municipality located in Gelderland (Blokker & Smit, 2022).

Measure package	Investment (€)	Payback period (year)	Energy label	Energy saving (€/year)	CO_2 reduction (%/year)
1. HR++, LED, pr. det.	397,488	10.6	A 2+	32,526	12.0
1b. HR++, LED, pr. det., 1500 PV	967,488	7.7	A 4+	113,588	41.7
2. HR++, LED, pr. det., LT HP	1,853,488	11.4	A 3+	138,671	47.2
3. HR++, LED, pr. det., LT HP, 750 PV roof	2,138,488	10.4	A 4+	179,203	62.1
4. HR++, LED, pr. det., LT HP, 1500 PV	2,423,488	9.7	A 5+	219,734	76.9

** HR++: HR++ glazing; LED: LED lighting; pr. det.: presence detection; PV: PV panels; LT WP: Low Temperature Heat Pump*

2.3.2 Vabi software versions

The software used by Antea Group to compute energy labels is called Vabi. This software enables the calculation of a building's energy performance according to the NTA 8800. This allows advisors to determine the energy label of a building and the required energy-saving measures to achieve a higher energy label. Before the NTA 8800 was mandatory in January 2021, this software was based on NEN 7120. The NEN 7120 follows a different method to assess the energy performance of a building than the NTA 8800. For example, in the NEN 7120, it was rather easy to receive a better energy label as long as PV panels were included. However, the NTA 8800 focuses more on the trias energetica. Hence, first reducing energy use by insulating the building's shell. Thereafter, reducing primary fossil energy

use by introducing renewable energy sources. This leads to different outcomes of the primary fossil energy use and energy label when assessing the same building. Therefore, it is not possible to compare energy labels before and after January 2021.
Both software versions focus on the measure's energy-saving potential, leading to a reduction in primary fossil energy use of the building. This reduction in energy use leads to a reduction in CO_2 emissions, which is presented in the last column of Table 2. However, as mentioned in Section 2.2.2, only the use phase of the building is taken into account while energy is required in all lifecycle phases. The lifecycle phases are also addressed in the net zero whole lifecycle carbon aim of the European Union. This aim makes it important to conduct LCA studies. Therefore, the next section will focus on the LCA methodology. Furthermore, low-carbon material choices should be applied to reach the European aim. Currently, Antea Group does not advise specific materials or products for their energy-saving measures. However, an overview of the environmental impact of generally used materials and their environmentally friendly material alternatives can lead to more comprehensive advice. This can create awareness among employees and clients.

2.4 Lifecycle Assessment method

Lifecycle Assessment (LCA) is a method that makes it possible to compute a system's potential environmental impact by considering the environmental aspects of that system's lifecycle (ISO, 2006a). An LCA contains four stages: goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO, 2006a). As visualised in Figure 7, it is an iterative process and changes are likely to be made during this process. The following sections elaborate on the steps of the LCA method.

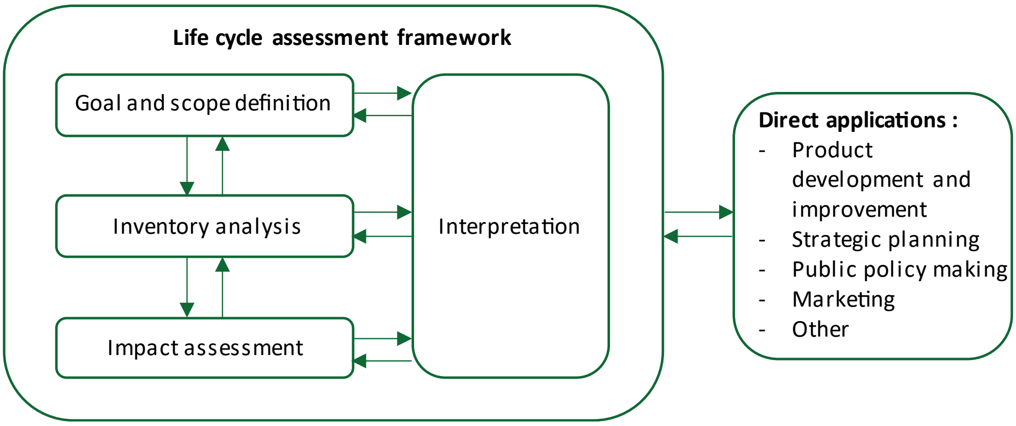

Figure 7 Stages of an LCA (ISO, 2006a).

2.4.1 Goal and scope definition

The first step of an LCA study is to define the goal and scope definition. The goal and scope definition is important since it describes the system and the applied methods that will be used in the next steps of the LCA. Table 3 presents the definitions of the aspects included in the goal and scope definition. The system boundary and allocation procedure are elaborated on in more detail in this section.

Table 3 Terms of the goal and scope definition.

Aspect of goal and scope definition	Definition
Goal definition	In the goal definition, the following aspects should be described: the intended application, the reason for carrying out the study, the intended audience, and whether the study will be a comparative assertion intended for disclosure or not (ISO, 2006a).

Aspect of goal and scope definition	Definition
Function	The function describes the performance characteristics of the system, product, or service under study.
Functional unit (FU)	A FU is a quantified and measurable description of the system's function and serves as a reference basis for the calculations made during the impact assessment (Arzoumanidis et al., 2020). This means that the calculated impact will be expressed per FU, for example, the impact per m^2.
Reference flow	The reference flow is the amount of the system that is required to fulfil the FU (ISO, 2006a).
System boundary	In the system boundary, it is described which lifecycle processes are included in the LCA study (ISO, 2006a).
Elementary flow	Within the system boundary, only elementary flows can be modelled. The inflows represent raw resources as inputs which are directly taken from the environment. The outflows are emitted pollutants and materials as outputs of the system boundary which are directly released into the environment (Edelen et al., 2018).
Cut-off criteria	Since it is not possible to include all flows in an LCA study, cut-off criteria are mandatory. This can be a certain percentage of the mass or volume, economic value, or environmental significance of the system/product that is excluded from the study (ISO, 2006a).
Allocation procedure	When a process has multiple in- and/or output flows, these should be partitioned among the different products required for or resulting from that unit process (ISO, 2006a). This is done with an allocation procedure.
Impact category	With an LCA study, potential emissions into the environment are calculated. Since a lot of emissions exist and each emission has a different unit, it will become cluttered when computing them all separately. Therefore, emissions with similar impacts on the environment are grouped and each group has one unit. These groups are also called impact categories (Hillege, 2019b).

System boundary

In the system boundary, it is decided which lifecycle stages are considered. The lifecycle of a building is visualised in Figure 4. It consists of a production, construction, use, and end-of-life phase, and can be extended with a recycling phase. When conducting an LCA study of a (construction) product, three distinctions for the system boundary, as presented in Figure 8, can be made (Quist, 2019):

- Cradle-to-gate. This first type only takes into account the lifecycle stages from material extraction to the product leaving the factory gates. Looking at Figure 4, this will include building lifecycle stages A1-A3.
- Cradle-to-grave. This type includes all stages of the cradle-to-gate option and adds the construction, use, and EoL stages. For a building, this will include A1-A5, B1-B7, and C1-C4.
- Cradle-to-cradle. This type includes all cradle-to-grave stages, including the recycling process of materials to use in other products. Therefore, all lifecycle stages of a building are included.

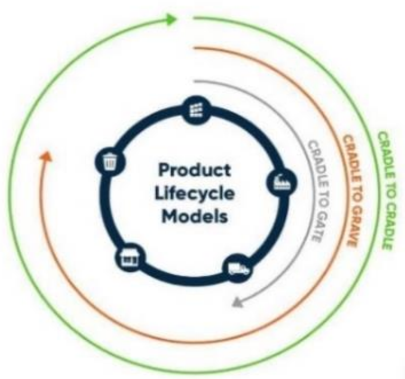

Figure 8 Product lifecycle model (Quist, 2019).

Allocation procedure

The best way to conduct allocation is to avoid it. For example, by dividing the unit process and its in- and outputs into multiple sub-processes. Each sub-process will have its sub-inputs and -outputs. In this case, only data should be collected about the in- and outputs of the required sub-process for the product under study. Another possibility to avoid allocation is by including the additional functions of the co-products in the study's scope (ISO, 2006b).

When the allocation procedure cannot be avoided, the in- and outputs of the process should be partitioned between the different products or functions based on their physical characteristics. When this is also not possible, the allocation should be based on the economic value of the products (ISO, 2006b). In the case that several allocation procedures seem suitable, a sensitivity analysis should indicate the effect of these allocation procedures on the outcomes of the LCA study.

The final step of the goal and scope definition is to define the assumptions, limitations, initial data quality requirements, type of critical review and the type of report that should be defined (ISO, 2006a).

2.4.2 Lifecycle inventory

After the completion of the goal and scope definition, the lifecycle inventory (LCI) can be conducted. This mainly includes collecting required data, presenting it in a flow diagram, and modelling it in LCA software. The flow diagram contains the unit processes, their interrelationships, and the inputs and outputs of the processes during the considered lifecycle (ISO, 2006b). After this data is collected, validated, and related to the functional unit, the LCI is completed.

2.4.3 Lifecycle impact assessment

The lifecycle impact assessment (LCIA) can be executed when all data is collected. The results of the LCIA are the impacts for the selected impact categories per FU of the described system. As this study will consider impacts on climate change and energy use, these two impact categories are briefly outlined.

Global warming potential

To compare the potential impact on climate change of the many existing GHG emissions, these impacts are grouped as the Global Warming Potential (GWP). The GWP is specified for a certain period, usually 100 years. Thereby, the focus is on the GWP of a GHG over 100 years (IPCC, 2007).

Each GHG has a different contribution towards GWP. These different contributions should be taken into account when combining the GHG emissions into one unit. Therefore, characterization factors are applied. For example, CH_4 has a 21 times higher contribution towards global warming (over 100 years) compared to CO_2 (IPCC, 2007). Therefore, the characterization factor of CO_2 will be 1, and for CH_4 this is 21. Hence, these characterization factors are different for other time periods. The emissions determined in the Lifecycle Inventory (LCI) will be multiplied by these characterization factors, making it possible to get one unit. For the GWP, the unit is CO_2 equivalents.

Energy use

Energy use in lifecycle assessment has been systematically explored by Arvidsson and Svanström (2015). Their framework, as visualised in Figure 9, shows the lifecycle of a product or service and its four different possible energy inputs. These energy inputs are categorised based on:

1. Renewable or non-renewable sources;
2. Primary energy (extracted from nature) or secondary energy (energy commodities);
3. The intention to use the energy for energy purposes (fossil fuels or electricity) or material purposes.

When conducting an LCA considering energy use as an impact category, the choices within these three categories will determine the type of impact category to apply. Arvidsson and Svanström (2015) conclude that the most preferable choice is to include both renewable and non-renewable energy (1) for both energy and material purposes (3) and thereby focus on primary energy (2). The impact category Cumulative Energy Demand (CED) is in line with these requirements (Arvidsson and Svanström, 2015).

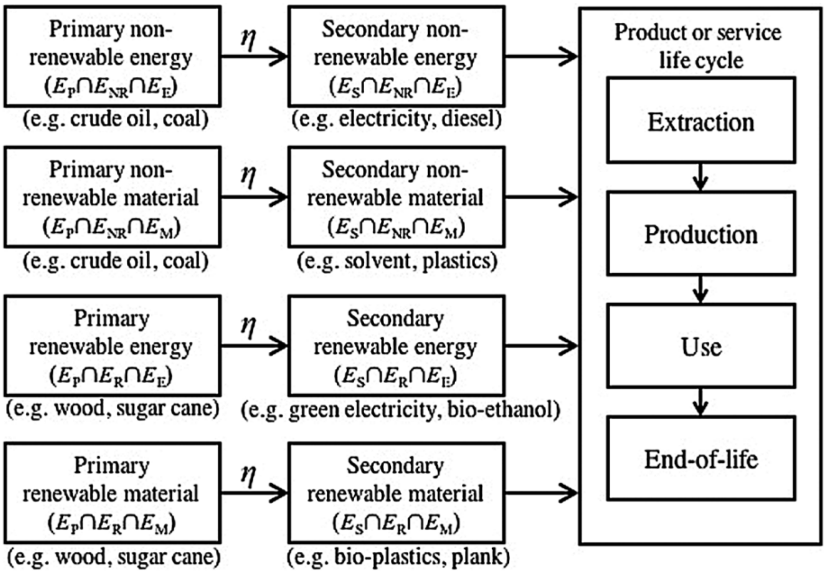

Figure 9 Framework for energy use indicators in LCA (Arvidsson, & Svanström, 2015).
E_P=lifecycle primary energy use, E_S=lifecycle secondary energy use, E_R=lifecycle renewable energy use, E_{NR}=lifecycle non-renewable energy use, E_E=lifecycle energy use intended for energy purposes, E_M=lifecycle energy use intended for material purposes, and η=primary-to-secondary energy conversion factor.

Since impact categories have different units, they cannot be directly compared. To make it possible to interpret the results, it is optional to apply normalization, grouping, and weighting methods. With the normalization method, the values of the impact categories are divided by a selected reference value. This can for example be the total input and output for a given area (ISO, 2006b). Grouping implies that impact categories are combined into one or more classes. These classes can be defined by nominal bases (inputs and outputs, a global region, or spatial scales) or by hierarchy (high, medium, or low priority) (ISO, 2006b). An important note is that the results of the impact categories will not change. This is the case with the weighting method where the results of the impact categories are multiplied by a certain factor. These weighting factors represent the relevance of impact categories. After the multiplication, all outcomes will be aggregated into a single score (ISO, 2006b). However, the relevance of impact categories is interpreted differently by different people and is therefore a non-scientifically based value choice. This makes the application of weighting factors not allow for comparative studies which will be published (ISO, 2006b).

2.4.4 Interpretation

After the LCIA and optional normalization, grouping, and weighting methods, the significant issues of the LCA study can be identified. This is the main goal of the interpretation phase. Laurent et al. (2020) proposed a framework for how to perform the lifecycle interpretation. According to them, first, the completeness of the LCI and LCIA should be evaluated. This completeness check is performed to verify if information from the previous steps in the LCA study is sufficient for drawing conclusions. This is followed by the consistency check. With the consistency check, the following five cross-cutting issues are checked (Laurent et al., 2020):

- Is the study performed according to the LCA standards?
- Are the correct LCA terms and definitions used?
- Are the LCI and LCIA consistent concerning the described system?

- Do the LCI and LCIA steps meet the objectives of the study, conclusions, and recommendations?
- Are the value choices (FU, aggregation methods etc.) made necessary? If so, what is their potential influence on the results?

The third step of the interpretation phase is the sensitivity check. This is applied to determine in what way the conclusions of the LCA study are affected by uncertainties, i.e. to check the robustness of the conclusions. The uncertainties can relate to the LCI data, LCI modelling, LCIA methods, or the calculation of category indicator results (Laurent et al., 2020).
After these three checks, significant issues can be identified. Issues can relate to the validity or reliability of the study. These types of issues can be identified by comparing the results and conclusions with previously conducted research. Significant issues can also be found within the study. For example, if the results can provide an answer to the study's objective (Laurent et al., 2020). When significant issues are identified, conclusions and recommendations can be drawn.

2.5 LCA for energy-saving measures in the construction sector

In the construction sector, LCA studies can be conducted for whole buildings, construction products, or services. Since an LCA study only considers the aspects as defined in the goal and scope, the environmental impacts will be determined for this goal and scope only (ISO, 2006a). This makes the goal and scope definition important. Because when the same product is analysed for a different goal and scope, this can lead to differing outcomes. Examples of these differences are elaborated on in Section 2.5.1. Product Category Rules (PCR) can be used to overcome these differences. The construction PCR and its complementary PCRs (c-PCR) are elaborated on in Sections 2.5.2 and 2.5.3. Another commonly used LCA method in the Dutch building sector called MPG is explained in Section 2.5.4.

2.5.1 Aspects in LCA studies that can lead to different LCA results

Differences in the goal and scope definition of an LCA study can lead to different outcomes. For example, when different allocation procedures are chosen or when different credits for avoided burdens are given (Curran, 2014). Another example is the FU. In a review paper about LCAs of buildings, Nwodo & Anumba (2019) describe that the FU is inadequately chosen for the studies they reviewed. This leads to LCA results that cannot be compared. These differences in FU were also found by Vilches et al. (2017) who conducted a literature review about LCAs of building refurbishment. The non-residential buildings they reviewed have a FU of $1m^2$/year, 1 year of use, variable FU, and non-defined FU. Other papers about LCAs of energy-saving measures for buildings have a FU of $1m^2$ (Angrisano, et al., 2021; Pombo et al., 2016), the total area of the building (González-Prieto et al., 2021), $1m^3$ (Günkaya, Özkan, & Banar, 2021), and the whole building (Beccali et al., 2013; Opher et al., 2021). However, none of these studies focuses on the materials or products of the energy-saving measures only. Therefore, the results of these studies can only be used as an indication of the impacts for similar building types, floor areas, or building volumes. When comparing material types for certain measures, different LCA studies should be conducted per measure type. Likewise, the FU should be selected separately for each type of measure.

2.5.2 Product Category Rules and Environmental Product Declaration

Product Category Rules (PCR) are introduced to overcome the differences in decisions regarding the goal and scope. A PCR contains specific rules on how to conduct an LCA for a specific product or system. This specific study is called an Environmental Product Declaration (EPD). Therefore, EPDs contains quantified environmental information based on LCA studies. Furthermore, information regarding environmental aspects can be added. For instance, "potential impacts on biodiversity, toxicity related to human health, geographical aspects, or preferred waste management options"

(CEN, 2010, p.15). Therefore, an EPD is considered ecolabel 3 which is mainly used for business-to-business communication (CEN, 2010). Since EPDs have similar goals and scopes, similar methods are used, which makes the results better comparable (CEN, 2019b). The EN 15804:2012+A2:2019 is the main PCR for construction products and is applicable for all construction products and services (CEN, 2019b).

When following the EN 15804:2012+A2:2019, the possible EPD types or system boundaries are presented in Figure 10. The types d and e can only be applied when the product or material does not contain biogenic carbon (CEN, 2019b). For LCAs about energy-saving measures, this would indicate that only types a, b, and c are applicable.

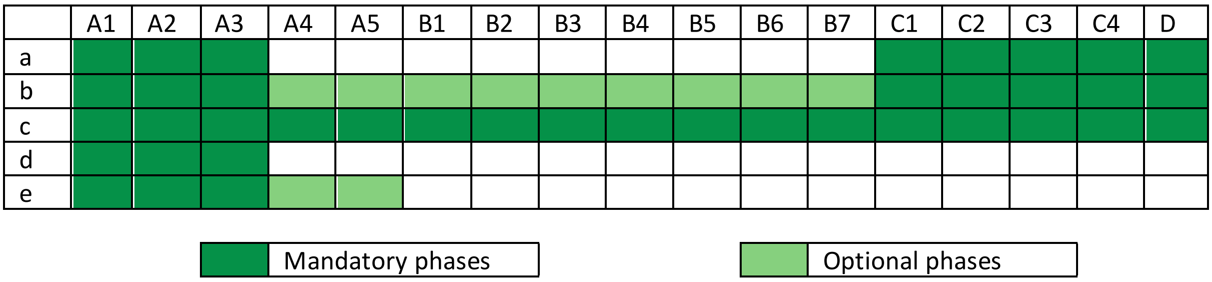

Figure 10 Lifecycle phases per EPD type (CEN, 2019b).

Implementing energy-saving measures is similar to building refurbishment since they both require removing current building elements and replacing them with new materials. Vilches et al. (2017) proposed the system boundaries for building refurbishment as visualised in Figure 11. The lifecycle stages of building refurbishment are at least the new embodied materials at the product stage (A1-A5), operational use (B1-B7), and the EoL stage of the new embodied materials (C1-C4). This can be extended with the EoL stage of the removed materials of the current building before the refurbishment is executed. Another possible extension is the EoL stage of the remaining existing building materials at the EoL stage of the whole building. Furthermore, the accumulated impacts are the impacts of the building itself before and after refurbishment (Vilches et al., 2017). These system boundaries can be used for energy-saving measures, however, it does not match one of the PCR types.

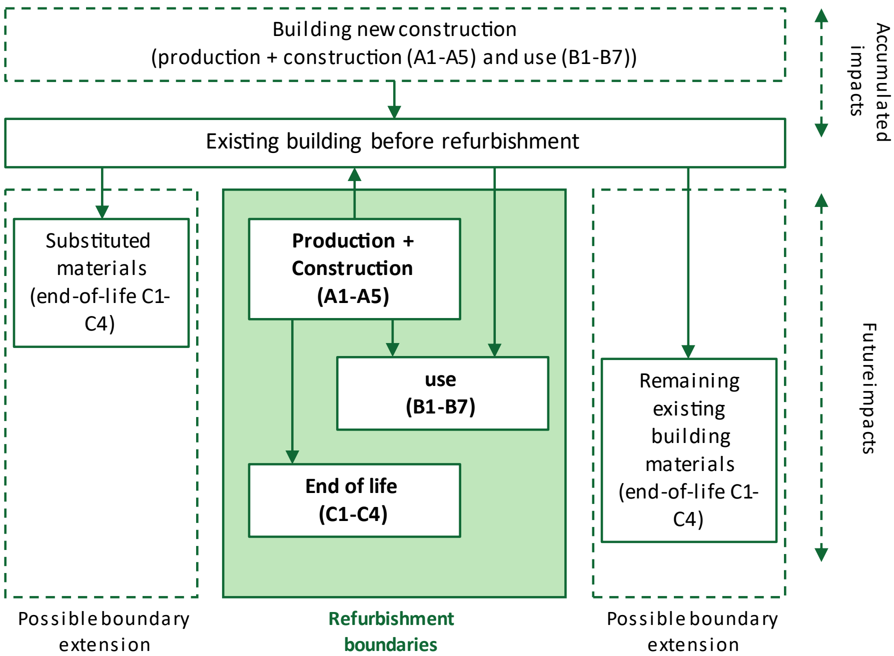

Figure 11 System boundaries of building refurbishment. Adapted from Vilches et al. (2017).

2.5.3 Complementary PCR

The main construction PCR (EN 15804:2012+A2:2019) has 23 complementary PCRs (c-PCR) containing additional rules for specific construction product categories. These c-PCRs should be used when available. Otherwise, the main construction product PCR can be used (CEN, 2019b). The c-PCRs related to energy-saving measures are:

- c-PCR-005: Thermal insulation products
- c-PCR-007: Windows and doors
- c-PCR-009: Flat glass products
- c-PCR-016: Photovoltaic modules and parts thereof
- c-PCR-018: Ventilation components

No c-PCR is available for heat pumps and lighting systems. Therefore, only the rules of the main PCR for construction products are applicable. Table 4 presents which scope has been maintained by the c-PCR and if additional requirements compared to the EN 15804:2012+A2:2019 are required or not.

Table 4 Additional requirements of c-PCRs related to energy-saving measures compared to the main construction products EN 15804:2012+A2:2019.

c-PCR	Scope	Additional requirements compared to EN 15804:2012+A2:2019	Standard
Thermal insulation products	Factory-made and in situ thermal insulation products. Areas of applications are ceiling, roof, floor, wall, and perimeter.	The FU should be 1 m2 for a specific thermal resistance (R-value) in the case of batts, boards, and similar types of thermal insulation. Maintenance and repair actions, and energy and water use are excluded.	NEN-EN 16783:2024 (CEN, 2024)
Windows and doors	Windows or internal and external pedestrian doorsets.	The FU should be 1 m^2. Maintenance only includes cleaning, lubricating, surface treatment, and replacement of worn/degraded parts.	NEN-EN 17213:2020 (CEN, 2020)
Flat glass products	Flat glass products used in buildings and other construction works.	The FU should be 1 m^2, complemented with a performance characteristic such as U-value. Phase B1 may be neglected. Maintenance only includes cleaning. Operational energy and water use are not applicable.	NEN-EN 17074:2019 (CEN, 2019a)
Photovoltaic modules and parts thereof	Photovoltaic modules or parts thereof used in the building and construction industry.	Lifecycle phases A1-A5, C1-C4 and D are required for PV-modules. The FU for a cradle-to-grave scope of a PV-module should be 1 Wp The produced electricity by the PV-module shall not be declared in the LCA or EPD.	NPCR 029 (EPD-Norge, 2022)
Ventilation components	Ventilation components including air duct products and air distribution equipment.	Lifecycle phases A1-A5, C1-C4 and D are required. Default values are presented for transport and EoL scenarios at the product level.	NPCR 030 (EPD-Norge, 2021)

2.5.4 Environmental performance of buildings (MPG)

Another method to compute the environmental impacts in the construction sector is by conducting an LCA study and use weighting factors to calculate a single-score indicator (Hillege, 2019a). In the infrastructure sector, a specific single-score indicator is known as the Environmental Cost Indicator (ECI). In the building sector, this is called the environmental performance of buildings (Milieprestatie van gebouwen or MPG in Dutch). The weighting factors to compute the single-score indicator are monetary values or shadow prices. Shadow prices are market values that would likely arise if a market for environmental impacts existed (Rijkswaterstaat, n.d.). However, this makes shadow prices intangible and gives significant room for bias (Hayes, 2021). This room for bias is the reason ISO14044 does not allow weighting methods when conducting and publishing an LCA study where different products are compared (ISO, 2006b). Since the MPG is used to compare different construction products, it can therefore be questioned if this is a scientifically correct method. Furthermore, a single-score indicator expressed in monetary values does not provide information about the impact categories separately. Therefore, it is not possible to find trade-offs between impact categories or to calculate energy and GHG payback periods.

3. Methodology

This research aims to determine the CO_2 equivalents and energy use over the lifecycle of the energy-saving measures advised by Antea Group. Furthermore, the goal is to find out how this knowledge affects the decisions made by Antea Group and its clients. Therefore, as mentioned in Section 1, the following four research questions will be answered during this research.

1. What are the GWP and CED over the lifecycle of the conventional and alternative products that are currently being applied in practice for the most commonly advised measures by Antea Group?
2. How can the lifecycle GWP and CED of a measure package be implemented in the energy-saving advice?
3. How will the current prioritisation of criteria for selecting energy-saving measures, according to clients and employees of Antea Group, be affected by the introduction of the GWP and CED?

These questions will be answered according to the methodology as visualised in Figure 12.

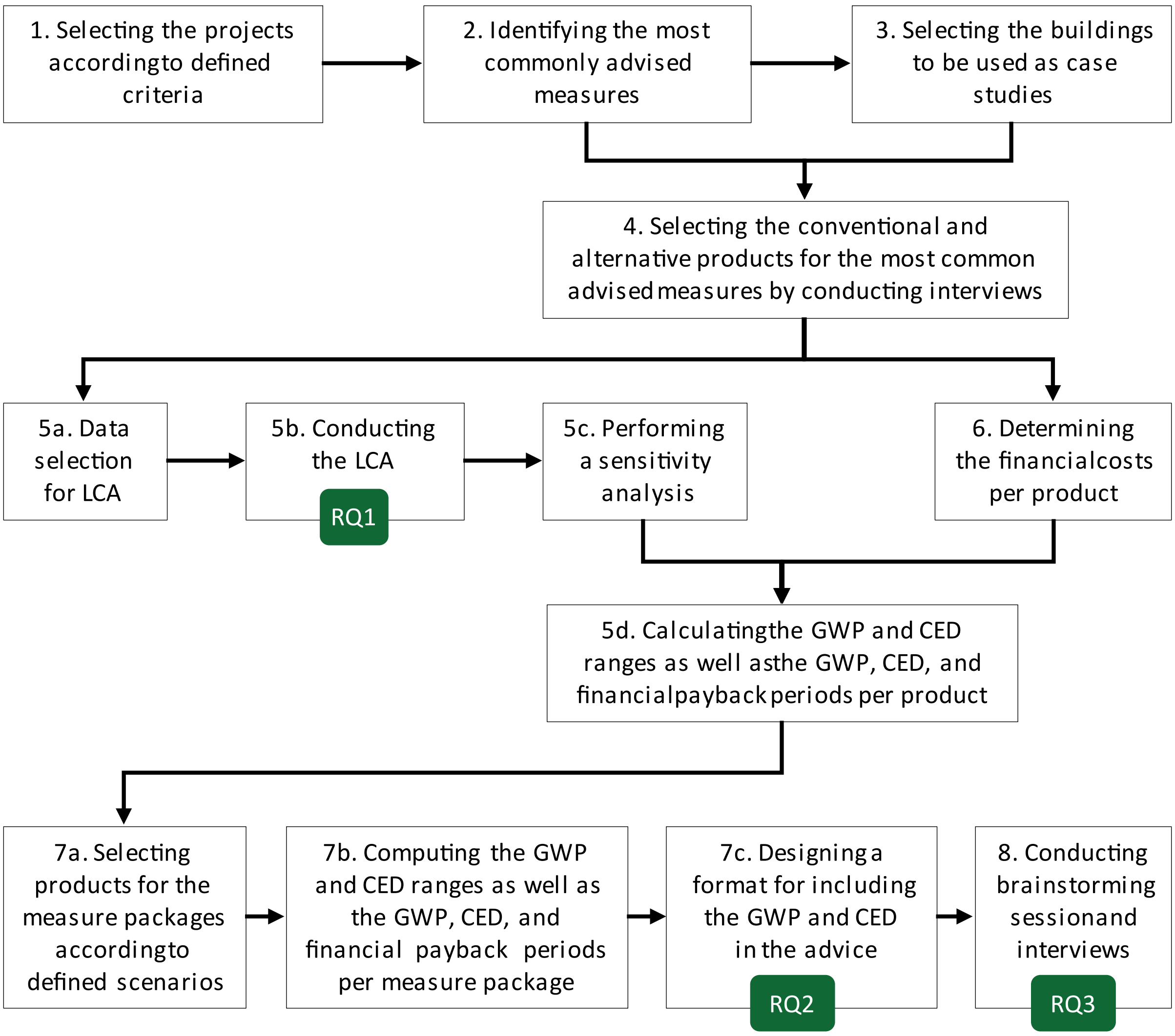

Figure 12 Flow chart research methodology.

First, projects are collected to identify the most commonly advised energy-saving measures. Based on these measures and other criteria, six buildings are selected to serve as a case study in the LCA study.

Other inputs for this LCA study are the products which can be implemented for each energy-saving measure. Since Antea Group does not specify this in their advice, the fourth step is to select conventional and alternative products for the most commonly advised measures. This will be conducted through interviews and a literature study. Subsequently, data will be collected regarding the CO_2 equivalents and energy use over the lifecycle of the selected materials (step 5a), which will serve as the input for the LCA study (step 5b). The LCA results provide an overview of the GWP and CED impacts per product and its significant lifecycle phases. After the sensitivity analysis (step 5c) of these values, a range in GWP and CED will be provided. These ranges can be used in step 5d to calculate the GWP and CED impact and payback periods per product for each building. In addition to the GWP and CED payback periods, the financial payback period is also included in this study. Therefore, the financial costs are determined per product in step 6.
Up to this point, the GWP and CED of the products can only be compared within an energy-saving measure, for example, two different insulation materials. Other measure types have a different FU and can therefore not be compared. Therefore, a second FU is required to compute the GWP and CED of a measure package, hence a combination of products. This second FU is defined as all measures required for a building to achieve a specific energy label. In this study, the labels A and Energy Neutral are considered. To calculate the GWP and CED according to this second FU, one product per measure should be selected (step 7a). This is done based on three scenarios. When the products are selected, the GWP and CED impacts and payback periods can be computed (step 7b). To include the GWP and CED impacts in future energy-saving advice projects, a format has been designed (step 7c). In the final step, a brainstorming session with employees and interviews with clients are organised in which the GWP and CED results are presented. This allows for the gathering of information regarding the opinions of clients and employees on the GWP and CED, as well as the determination of their potential use in future projects. The following sections provide a more detailed explanation of the steps as presented in Figure 12.

3.1 Selecting the projects

Antea Group writes advice reports in which energy-saving measures are proposed to the client. A project usually contains multiple buildings where energy-saving measures are proposed for each building. To use these buildings as a case study, projects should be selected first. This is done in accordance with the following requirements:

- Energy-saving measures are advised for utility buildings located in the Netherlands
- The project should be executed in 2018 or later

In January 2021, the NTA 8800 was introduced and Antea Group started to use a new software versio n to determine energy labels. The advised measures for projects initiated after January 2021 have not yet been implemented. Therefore, product specifications are currently not available. Given the preference for the use of primary data in case study research, I decided to expand the scope and include projects since 2018. Based on the requirements above, four projects of Antea Group could be selected. The clients for these projects are different municipalities that have one or more buildings for which an advice has been provided. The characteristics of the projects are provided per municipality in Table 5.

Table 5 Characteristics of selected projects.

Client	Province	Consulting agency	Year	Number of utility buildings for which advice is provided
Municipality 1	Overijssel	Antea Group	2018	53
Municipality 2	Limburg	Antea Group	2022	10
Municipality 3	Drenthe	Antea Group	2022	8
Municipality 4	Gelderland	Antea Group	2022	1

During the project in 2018, the previous software version of Vabi was applied. This may result in different considered and advised measures in 2022 compared to 2018. Therefore, the project of the municipality located in Overijssel is separated from the other three projects when determining the most commonly advised measures.

3.2 Identifying the most commonly advised measures

The four selected projects were used to identify the most commonly considered and advised measures. The advised measures could be divided into eleven measure categories, of which the six largest are used in the remainder of the study. It emerged that the measure categories are similar for 2018 and 2022. Therefore, I consider the six largest measure categories and the project of the municipality located in Overijssel reliable for this study.

3.3 Selecting the buildings to be used as case studies

Buildings can have different initial energy labels, and therefore require different measures to achieve energy label A or Energy Neutral, e.g. the goals of the Dutch government in 2030 and 2050 respectively. To find out if this effects the GWP and CED, buildings are selected as case study. Since the measures for the projects in 2022 have not yet been implemented and the project in 2018 is considered reliable despite the use of the previous Vabi software version, the 2018 project has been selected to determine the case study buildings. This means that the buildings are only selected from the municipality located in Overijssel.

These buildings are selected based on the following requirements:

- Only the six most commonly advised measure types can be included in the measure packages. If another measure type is also included, the building will not be considered as a case study. Because the GWP and CED will only be calculated for the six commonly advised measure types. In the case of another measure, this would lead to an increase in the energy savings of the building, without taking into account the GWP and CED of the measure. This would lead to unfair payback period results
- At least two measure packages should be included in the advice. These should be the packages that will result in the achievement of labels A and Energy Neutral
- At least one of the measure packages should include four of the six most commonly advised measures. At least one of these four should be thermal insulation, as this is the most frequently advised measure
- The difference between the initial and objective energy labels must be at least two steps. For example, measure packages with labels from C to A are included, while those with labels from B to A are excluded. Additionally, an initial label of A++ or better is excluded since these are already relatively high labels.

This results in 21 buildings. However, it is not feasible to include this number of buildings in this study. Therefore, the most common building type and net usable area are selected. This is a sports/recreation building (SBI code 93) with a net usable area of approximately 400 m^2. Following the second selection process, six buildings remain of which the characteristics are presented in Table 6. The packages and measures of these buildings are presented in Appendix F.

Table 6 Characteristics of the selected case study buildings (EN = Energy Neutral).

Building	Net usable area (m^2)	Initial label	Objective label	Number out of six most commonly advised measure types
Building 1	451	E	C / A / EN	1 / 2 / 6
Building 2	452	E	C / A / EN	1 / 2 / 6

Building	Net usable area (m^2)	Initial label	Objective label	Number out of six most commonly advised measure types
Building 3	438	D	B / A / EN	1 / 2 / 6
Building 4	438	C	A / EN	1 / 5
Building 5	438	C	A / EN	1 / 5
Building 6	438	C	A / EN	1 / 4

3.4 Selecting the conventional and alternative products

To compute the GWP and CED of the selected measures, products should be selected. These products can be divided into conventional and alternative products. Since Antea Group does not provide product advice, interviews are conducted to find out which conventional products are commonly used in practice and which alternative products are increasingly being applied. Ten interviews were conducted between 1 May and 6 June 2023. Eight respondents are employees of Antea Group with expertise in determining energy labels, advising on energy-saving measures, and advising on installations such as lighting, PV panels, heat pumps, and ventilation systems. The other two respondents are an advisory company for LED lighting and a manager of real estate at a municipality. Because of the different expertise of the respondents, they are specialised in one or more of the selected measures. This leads to three or four different opinions per measure. The results of the interviews are compared with the literature to select the alternatives for conventional products which are being applied in practice. Based on this information, the products could be chosen for use in the remainder of the study. The interview questions, an overview of the respondents, and a summary of their answers are provided in Appendix B.

3.5 Conducting the Lifecycle Assessment

An LCA study will be conducted to find the GWP and CED of the measure packages in the case studies. To achieve this, the GWP and CED impacts of the selected conventional and alternative products will be calculated first. The impacts of the products can then be compared in two ways. Firstly, products can be compared within measures. For example, by comparing different insulation materials within the insulation measure category. Secondly, products can be compared between measures. For example, when insulation materials with PV panels. In this study, the products are compared within measures.

To have a fair comparison of products within measures, the same FU is used per product category (see Table 7). As products of different measures are grouped together to form a measure package, a second FU is defined to calculate the GWP and CED of a measure package. This second FU is defined as all measures required for a building to achieve a specific energy label. In this study, the labels A and Energy Neutral are considered because these labels are the goals of the Dutch government in 2030 and 2050 respectively. Since this second FU requires a combination of products, the goal and scope of all products have been kept as similar as possible. Therefore, the same reference service life (RSL) has been applied to all products. This is the remaining lifetime of the building after the implementation of the measures. The case study buildings were constructed approximately 50 years ago, similar to the study by Pombo et al (2016), which considered a remaining lifetime of 50 years. An RSL of 50 years is also adopted by Becalli et al. (2013) and Günkaya et al. (2021), and is therefore also chosen for this study. When products have a shorter lifecycle than 50 years, multiple product lifecycles are required. This is shown as the reference flow (RF) in Table 7. The reference flows for the second FU are the different measures and their quantities required to achieve a certain energy label. These reference flows are presented per building in Appendix H.

Table 7 Functional units, reference flows, and used sources for the considered products.

Product	FU	Service year	RF (y)	Source
Rock wool	1 m2 of insulation material with an Rc-value of 1 m2K/W	50	1.0	(Knauf Insulation, 2023)
Glass wool		50	1.0	(Knauf Insulation, 2021)
PIF		50	1.0	(Pepi Rer, 2022; Assan Alüminyum, 2021))
PIR		50	1.0	GaBi
PUR (foam)		50	1.0	GaBi
EPS (pearls)		50	1.0	(Tenapors, 2022)
Thermofoam		50	1.0	GaBi
Hemp fiber		50	1.0	GaBi
Wood fiber		50	1.0	(Thünen-Institut für Holzforschung, 2023)
Triple glass	1 m2 of a glazing system with a Rc-value of 1 m2K/W	50	1.0	(SSC Group, 2022)
HR++ glass		50	1.0	Assumption based on triple glass (GUBU, n.d.)
Vacuum glass		50	1.0	
Air-air heat pump	1 heat pump with a capacity of 20-70 kW	15	3.3	GaBi
Air-water heat pump		15	3.3	GaBi
Heat pump with refrigerator: Propane		15	3.3	Assumptions based on air-air and air-water heat pumps (Wu et al., 2022)
Heat pump with refrigerator: CO_2		10	5.0	Assumptions based on air-air and air-water heat pumps (Louws, 2019)
Mono crystalline	1 kWp	25	2.0	(Longi, 2023)
Poly crystalline		25	2.0	Assumption based on mono crystalline (Vidal et al., 2021)
Thin film panel (CdTe)		20	2.5	
Thin film panel (CIGS)		20	2.5	
Thin film panel (A-Si)		20	2.5	
LED + fixture	1 lamp	14	3.6	(Trilux, 2023)
LED + daylight detection		15	3.3	Assumption based on LED + fixture (Yavuz et al., 2012)
LED + presence detection		15	3.3	Assumption based on LED + fixture (Kaneko et al., 2013)
Heat recovery general	1 ventilation system with heat recovery and a capacity of 1000 m3/h	25	2.0	(Swegon Group, 2021)
Heat recovery + CO_2 detection		25	2.0	Assumption based on heat recovery general (Esfehani et al., 2019)
Heat recovery + presence detection		25	2.0	Assumption based on heat recovery general (Pang et al., 2020)

In addition to the same RSL, Europe is selected as a geographical scope, and the main PCR for constructions (EN 15804:2012+A2:2019) and its c-PCRs are used to ensure that the goal and scope definitions are as similar as possible for all products. Based on the literature review, it can be concluded that the required PCRs have the same goal and scope definitions. However, the PCR for construction products considers different system boundaries. PCR type A excludes the use phase. PCR type B has optional lifecycle phases and type C includes all phases. Since PCR type C is the most comprehensive, this system boundary has been chosen. However, when selecting this system boundary, the cut-off criteria and allocation procedures must be carefully considered. Therefore, those of the EN 15804:2012+A2:2019 are adopted. This means that a maximum of 5% of the energy consumption and mass may be neglected. The allocation is based on physical properties such as mass or volume. In addition, the principle of avoided burden is adopted. In this principle, the first lifecycle includes processes related to the recovery and recycling of material flows. Secondary materials leaving the system boundary can be used by the second lifecycle to avoid the burden of raw materials. The first lifecycle receives credits for this avoided burden, which creates an incentive for recycling (Laurin, 2019).

Based on these criteria, lifecycle information on GWP and CED can be selected from databases. This secondary data is less specific than primary data. However, the results of this study will be used in the advice reports of Antea Group. These reports are formulated in the initiative phase and therefore do not represent actual values. This allows the outcomes of the LCA study to have some deviation as well. Furthermore, it is expected that the use of secondary data will be less time-consuming. This makes it possible to include more types of energy-saving measures, which creates the potential for a more comprehensive analysis and conclusion.
To comply with the PCR rules, it is preferable to use data from EPDs. For example, the EPD library of the international EPD system (The International EPD System, n.d.). This freely available online dataset complies with the EN 15804:2012+A2:2019. Furthermore, freely available data from Ökobaudat version 2021-II (Ökobaudat, 2021) were used. This dataset is generated based on GaBi background data and also complies with EN 15804:2012+A2:2019. When data was not available in these datasets, data from the GaBi library was used. Table 7 shows the sources used per product. Complementary PCRs are used for some of the products. C-PCR 05 has been utilised for rock wool, glass wool, and EPS (pearls), and c-PCR 016 has been applied to the PV panels. For the other products, only the EN 15804:2012+A2:2019 has been used.

Since not all lifecycle phases are included in these datasets, supplementary processes are added based on assumptions. These assumptions are based on other products within a measure category for which the missing phase is available. Values for phases A1-A3 are available for all products. When focusing on insulation materials, phase A4 is missing for thermofoam, PIR, PUR, EPS, hemp fibre, and wood fibre. For the remaining four insulation materials, where phase A4 is available, the percentage of phase A4 in relation to phases A1-A3 can be calculated. The average of these percentages can then be used to determine the missing value for phase A4 in relation to phases A1-A3. The majority of the assumptions regarding thermal insulation are made for phases A4-A5, C1-C4, and D. The heat pump and ventilation system have missing values for phases A4-A5, B6 (heat pump only) and C1-C2.

After calculating the GWP and CED per product and FU as presented in Table 7, a sensitivity analysis was conducted to assess the robustness of the results. Due to the use of EPD data, LCI models are not available. Therefore, the sensitivity analysis cannot be based on significant processes. Instead, differences between products that affect the GWP and CED are analysed. For insulation and glazing systems, this is the thermal conductivity coefficient. Because this coefficient affects the thickness of the material, resulting in a change in the quantity of material required. This, in turn, affects the GWP and CED. For installations, the lifecycle of products within a measure category varies. An RSL of 50 years is considered in this study. The number of lifecycles required to reach these 50 years will vary if a product has a longer or shorter lifecycle than considered. The outcome of the sensitivity analysis will be a range of the GWP and CED per product.

These GWP and CED ranges are used to calculate the GWP and CED per measure package, hence according to the second FU. However, this requires the selection of a single product per measure. The optional products per measure are presented in Appendix F. The selection of these products is based on three scenarios:

- Scenario 1: the product with the lowest GWP payback period
- Scenario 2: the product with the lowest CED payback period
- Scenario 3: the product with the lowest financial payback period

The payback periods are calculated for all products by using the formulas presented in Table 8. The yearly saved kg of CO_2 eq. and MJ of energy per product are determined by the saved MJ of gas and kWh of electricity of a measure as calculated by the Vabi software. To convert these values into GWP and CED impacts, the dataset of Ecoinvent 3.8 has been used. Consequently, 1MJ of natural gas is equivalent to 0.077kg CO_2 eq. and 1.291MJ of energy where 1m3 of gas is 35.17MJ of gas. Furthermore, 1kWh of electricity is equivalent to 0.399kg CO_2 eq. and 6.123MJ of energy.

Table 8 Equations for payback period calculations Adapted from Beccali et al (2013).

Equation	Variable	Unit
$E_{P,T} = \frac{CED}{E_{s,y}}$ [1]	$E_{P,T}$ = Energy payback time	year
	CED = CED value resulting from the LCA study	MJ
	$E_{s,y}$ = yearly saving of energy due to the implementation of the energy-saving measure	MJ/year
$Em_{P,T,GWP} = \frac{GWP}{GWP_{s,y}}$ [2]	$Em_{P,T,GWP}$ = Emission payback time	year
	GWP = GWP value resulting from the LCA study	Kg CO_2 eq.
	$GWP_{s,y}$ = yearly avoided GWP due to the implementation of the energy-saving measure	Kg CO_2 eq./year
$F_{P,T} = \frac{Costs}{F_{s,y}}$ [3]	$F_{P,T}$ = Financial payback time	year
	Costs = Financial costs to implement the energy-saving measure	€
	$F_{s,y}$ = yearly saving of financial costs due to the implementation of the energy-saving measure	€/year

The financial payback period is calculated by dividing the financial costs of the products (presented in Appendix E) by the annual cost savings resulting from gas and electricity savings. These annual cost savings are calculated by using a gas price of €1.50/m^3, an electricity price of €0.27/kWh, and a yearly inflation of 3%. The gas price has increased by 54% in 2023 in comparison to 2021. Similarly, the price of electricity has risen by 51% over the same period (CBS, 2024). It is expected that this change in prices will not affect the amount of saved gas and electricity resulting from the implementation of energy-saving measures. Consequently, this will probably not affect the saved GWP and CED. However, different prices can affect the financial payback periods, which in turn can affect scenario 3, i.e. the selection of products with the lowest financial payback period. Therefore, a sensitivity analysis has been conducted in Section 4.6. In this sensitivity analysis, the payback periods are calculated for each product by using the initial gas and electricity prices, the minimum prices (initial gas price -54% and initial electricity price -51%), and the maximum prices (initial gas price +54% and initial electricity price +51%).

To incorporate the calculated GWP and CED into future energy-saving advice reports, a format has been designed (see Appendix M). This format is a table in which an overview of the GWP and CED are presented separately. Symbols are used to present the GWP and CED of the products, since this makes it easier to distinguish differences between products than by using numbers. The lowest GWP is represented by five symbols, while the highest is indicated by half a symbol. The intermediate symbols are derived by dividing the difference between the minimum and maximum GWP into ten ranges, with each range corresponding to half an additional symbol. A similar approach is employed for the CED. The objective of this format is to collect as many symbols as possible when aiming to achieve the lowest GWP and CED impacts.

3.6 Conducting interviews and a brainstorming session

Before implementing the GWP and CED into the advice, it would be beneficial to determine the extent to which clients and employees of Antea Group are currently aware of the impacts and if they intend to use the impacts for selecting measures in future projects. Therefore, interviews were conducted with five clients of Antea Group. The interview questions are provided in Appendix K. The clients comprise two municipalities, a governmental organisation, a school community, and a community house. All of them received energy-saving advice from Antea Group. During the interviews, respondents were asked to list and rank the criteria they used to select energy-saving packages, measures, and products. During this first part of the interview, no information was provided regarding the impact of the products throughout their entire lifecycle. This explanation was provided in the second part, supported by the calculated values of the GWP and CED of the products. The respondents were asked to rank the GWP and CED impact in their current ranking. The criterion with the highest ranking receives five points, while the criterion with the lowest ranking receives one point. When a criterion is not mentioned by a respondent, it receives zero points. The average score per criterion is calculated and presented in Section 4.7.

To obtain responses from Antea Group employees on this topic, a brainstorming session was organised following a survey (see Appendix L). The survey asked employees to list and prioritise the criteria they use when developing energy-saving measures. Eight employees completed the survey. During the brainstorming session, the research results and survey responses were discussed with six employees to determine whether sharing the findings might affect their perspectives and methods of advising measures.

4. Results and analysis

The results of this study are presented and analysed in this section. In Section 4.1, the most commonly advised measures are determined, of which the conventional and alternative products are identified for these measures in Section 4.2. The results of the LCA study conducted for these products are presented and analysed in Section 4.3. As part of the LCA study, a sensitivity analysis is conducted of which the results are elaborated in Section 4.4. The ranges of the GWP and CED resulting from the sensitivity analysis, as well as the financial costs per product are used as input for the case studies. With this input, the GWP, CED, and financial costs and payback periods could be calculated per measure package of each building (see Section 4.5). Two options are proposed in Section 4.6. to incorporate these GWP, CED, and financial results into future advice reports. Finally, the results are shared with clients and employees of Antea Group. The outcomes of the interviews and the brainstorming session are elaborated in Section 4.7.

4.1 Most commonly advised measures

As outlined in Section 2.3 of the Background, an energy-saving advice contains two types of measures: considered and advised measures. Where a considered measure incorporated in a measure package is called an advised measure. A total of 116 measures were considered in the four projects presented in the Methodology in Table 5. From these considered measures, 96 measures are advised over 162 measure packages. This results in a total number of 550 advised measures divided over 72 buildings. The 96 different advised measures are divided into 11 categories of which an overview is provided in Appendix A. For example, the category insulation contains insulation of facades, cavities, roofs, and floors. Figure 13 visualises the eleven categories for both 2018 and 2022. The six largest categories are presented separately, while the remaining seven categories are grouped under "Other". The latter category represents only 4.6% of all categories in 2018 and 1.1% in 2022. This indicates that almost all measure categories are included in the top six. In both years, insulation is the most commonly advised measure and mechanical ventilation ends in sixth place. The categories in between have similar percentages. Therefore, the 2018 project of the municipality located in Overijssel is reliable for this study. Even though, an older software version with different determination rules underlies this advice. For each of the six most commonly advised measure categories, an analysis is conducted to identify the conventional and alternative products. This will be addressed in the next section.

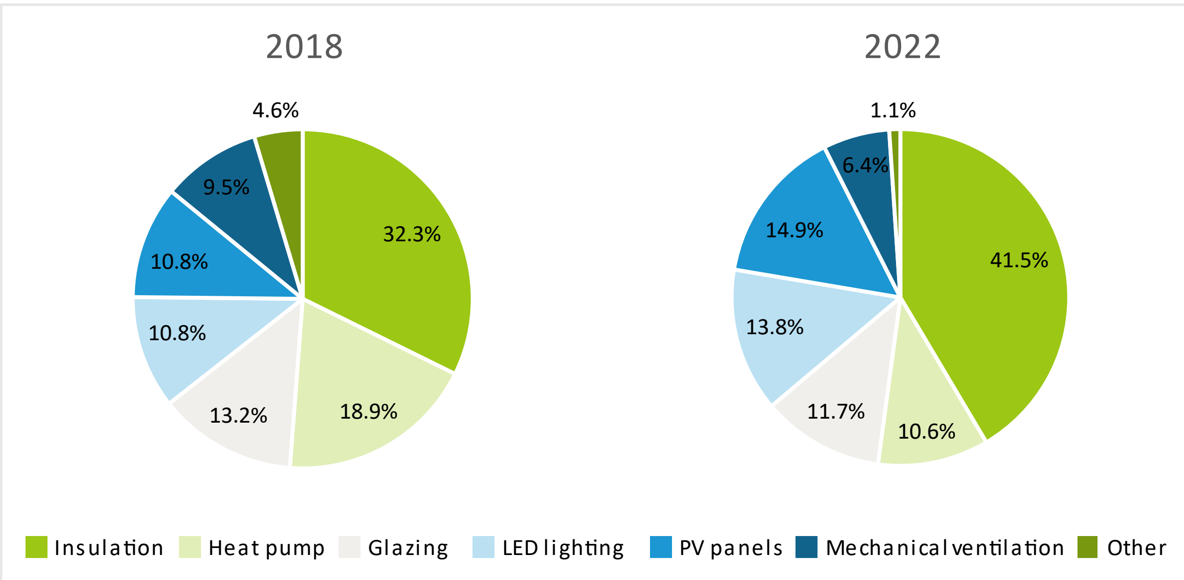

Figure 13 Division of measure categories. Project of the municipality located in Overijssel (2018) and the projects of the municipalities located in Limburg, Drenthe, and Gelderland (2022).

4.2 Conventional and alternative products

As elaborated in Section 3.4 of the Methodology, ten interviews were conducted to identify the conventional products which are commonly applied in practice and their alternatives which are increasingly being applied. In this section, the answers provided by the respondents are analysed per measure category. It concludes with an overview of the conventional and alternative products considered in the remainder of the study.

4.2.1 Thermal insulation

Thermal insulation can be divided into the following three categories (Füchsl et al., 2022; Dovjak et al., 2017; Schulte et al., 2021):

- Inorganic materials. Examples are stone wool, glass wool, and foamed glass
- Organic non-renewable materials. Examples are EPS, XPS, PUR, and PIR
- Organic renewable materials. Examples are cork, hemp, cellulose, wood fibre boards, straw bales, flax, and miscanthus

In practice, different insulation materials are applied to facades, roofs and floors. Therefore, a distinction is made in these categories when asking the respondents about the conventional insulation materials. Three out of four respondents mentioned glass wool and rock wool as conventional insulation materials for the façade. For the roof insulation, three respondents named PUR and two mentioned PIR. Additionally, two respondents indicated EPS pearls and PUR foam as common insulation materials for floors. Füchsl et al. (2022) and Dovjak et al. (2017) also considered these material types in their comparative LCA studies. Therefore, these six types are selected as conventional insulation materials.
Regarding the alternative insulation materials, it was more challenging for the respondents to identify specific types per building element. Therefore, the products are generally described. The results of the studies by Füchsl et al. (2022), and Schulte et al. (2021) indicate that cellulose, hemp fibre, wood fibre and miscanthus can be considered as environmentally friendly insulation materials. In the interviews, all four respondents named hemp fibre, followed by wood fibre, which was mentioned by two of the respondents. Cellulose was named once, and miscanthus was not mentioned by any respondents. Therefore, only hemp fibre and wood fibre are selected. Thermofoam is included in this list since it is PUR on water-basis (ThermoFoam, n.d.), used as insulation for the façade in the project of the municipality located in Overijssel.

4.2.2 Heat pumps

Heat pumps can transfer heat from one source to another via a refrigerant. First, the refrigerant evaporates, making it possible to absorb heat from a source. This source is generally located outside the building. For example, air, groundwater, or surface water. When the refrigerant condenses in the heat pump, the absorbed heat is released to the heat sink. This sink is a source within the building. When the heat pump is used for space heating, this source can be the air within the building or water for underfloor heating. The source of the heat sink is also water when the heat pump is used for the heating of tap water (Wu, 2009).

Three respondents mentioned that air-air, air-water, water-water, and VRF systems are commonly applied to utility buildings. A VRF system is capable of heating a single space while simultaneously cooling another. This is not possible for the other types. In that case, a space can only be heated or cooled. In the advice of the 2018 project, the air-air heat pump is applied for space heating, and the air-water heat pump for hot tap water. Therefore, these two types are considered conventional products. As an alternative, the respondents mention different refrigerants such as propane or CO_2, or the downsizing of the heat pump. Since this downsizing is situation-dependent and therefore different to consider in an LCA study, it is decided to only consider the different refrigerants as alternatives. When using propane or CO_2 as a refrigerant, this leads to a reduction in carbon footprint (Wu et al., 2022; Louws, 2019). Drawbacks are, however, the high-pressure CO_2 required and the risk of explosion when working with propane (Louws, 2019). This requires complex installations which can be less energy efficient and are more difficult to install and maintain.

4.2.3 Glazing

Three respondents were asked about conventional and alternative glazing systems. As a conventional glazing system, HR++ glass and triple glass are listed twice. However, the respondents found it challenging to identify alternatives to glass. One respondent mentioned a different gas infill. Currently, Argon is commonly used as a gas infill, although Krypton and Xenon can also be used. However, an Argon infill already has the lowest environmental impact and embodied energy (Asif, 2019). Therefore, different gas infills are not considered alternatives to glazing systems.
Another alternative mentioned is the use of vacuum glass and recycled glass. Since this research only considers raw materials, recycled glass cannot be included in this study. Therefore, the vacuum glass is selected as an alternative glazing system.

4.2.4 PV panels

PV panels can be divided into four generations. The first generation includes single and multi-crystalline silicon cells, which have relatively thick layers and thereby relatively high efficiencies. The second generation has a thin layer of active material, which results in lower investment costs. The third generation strives towards a balance between high efficiency and low investment costs by using more recent chemical compounds. The fourth generation aims to use organic-based nanomaterials (Pastuszak and Węgierek, 2022).

The four respondents mention that mono- and polycrystalline panels are the conventional types. Two of the respondents indicate thin film panels as an alternative option for PV panels. Examples of thin-film panels are Copper Indium Gallium Selenide (CIGS), Cadmium Telluride (CdTe), and Amorphous Silicon (a-Si) solar panels (Pastuszak, & Węgierek). Both respondents mention that these types have a lower efficiency. Therefore, they expect to need more panels to generate the same amount of energy as conventional PV panels. However, they also mention that the impact per thin film panel would be lower than that of a conventional PV panel. This corresponds with the results of Reshedi and Khanam (2020), who compared mono-crystalline silicon (mono-Si), multi-crystalline silicon (multi-Si), a-Si and CdTe. Thin film panels will be considered as alternatives to PV panels.

4.2.5 Lighting system

Light-emitting diode (LED) lighting is the only type of lighting recommended by Antea Group. Furthermore, all four respondents mention LED lighting as the basis for conventional and alternative products of lighting systems. According to Bertin et al. (2019) and Souza et al. (2019), LED lights have the lowest environmental impacts compared to CFLs when the LED has a lifecycle longer than 15,000h. Therefore, no alternative for LED will be selected. Even though respondents do not see an alternative for LED, they all mention some adjustments to the conventional LED light. Namely, by adding demand-driven light control, which can be in the form of presence detection and daylight sensors.

4.2.6 Mechanical ventilation

Three respondents were interviewed regarding mechanical ventilation systems. All three respondents mentioned mechanical ventilation with heat recovery as the conventional product. Heat recovery can be achieved by different installation systems. Namely, a heat wheel, cross-flow exchanger, or a twin coil system. The latter option is only used when the inflow and outflow of air are not regulated within the same ventilation area. This does not often occur in utility buildings. Therefore, the focus is on the cross-flow exchanger and heat wheel, both of which are frequently applied.

The alternative for a mechanical ventilation system is only mentioned in a form where larger channels are used. However, this is situation-dependent since not all buildings have space for this. The other option is demand-driven control, which was identified by all three respondents. Esfehani et al. (2019) found that CO_2-based demand-control ventilation could reduce the annual energy consumption of a sports centre by 40%. Furthermore, presence detection can reduce the energy used by an office building's ventilation system between 19% and 44% (Pang et al., 2020). Therefore, CO_2 control and presence detection are included as alternatives for mechanical ventilation.

An overview of the conventional and alternative products for the selected measure types is provided in Table 9.

Table 9 Overview of selected products per measure category.

Measures	Conventional	Alternative
Thermal insulation	Glass wool Rock wool PUR (foam) PIR EPS (pearls)	Hemp fibre Wood fibre Thermofoam
Heat pumps	Air-air Air-water	Refrigerator propane Refrigerator CO_2
Glazing	HR++ glass Triple glass	Vacuum glass
PV panels	Monocrystalline Polycrystalline	CIGS CdTe a-Si
Lighting system	LED	Presence detection Daylight detection
Mechanical ventilation	Heat recovery	Presence detection CO_2 level sensors

4.3 Lifecycle-based GWP and CED of products

For each product in Table 9, the lifecycle-based GWP and CED are determined based on EPDs attached to EN 15804:2012+A2:2019 and its c-PCRs. This results in the GWP and CED per product, according to their FU and an RSL of 50 years. Further details of this process can be found in Section 3.5 of the Methodology. The raw results, in total and per lifecycle phase, are presented in Appendix C. These results are visualised in Figure 14 for the construction measures (insulation and glass) and in Figure 15 for the installations (heat pump PV panel, lighting system, and ventilation system). In these figures, the graphs on the left present the GWP, while the graphs on the right present the CED.

The results of the CED indicate that the production phase A is the most significant for construction measures, whereas the use phase B is the most significant for installations. This can be explained by the frequent use of electricity during the use phase of installations, in contrast to construction products which require almost no energy during the use phase. Instead, the energy consumption of the construction products is concentrated in the production phase.
Since energy consumption leads to GHG emissions, it is expected that a significant CED for a specific phase will also result in a significant GWP in the same phase. This is the case for construction products where the production phase is the most significant for both the GWP and CED impacts (see Figure 14). However, this is not reflected in the results of the installations, except for LED lighting, as can be seen in Figure 15. Because where the use phase B has the most significant CED, the most significant phase for the GWP is divided between the production phase A and use phase B.

Besides the significant phases, it can be noticed in Figure 14 and Figure 15 that the graphs for the GWP are similar to those of the CED. This indicates a relation between the two impacts, with the GWP representing a percentage of the CED. The minimum, maximum, and average percentages of the GWP as part of the CED are presented in Table 10. The maximum value of 89% is observed in the case of PIF insulation, while the second-largest percentage is 16%. Excluding the 89% value results in an average of 7% for construction products and 4% for all products.

Table 10 Percentages of GWP as part of the CED for construction and installation products.

Type of product	Min	Max	Average
Construction products	-1%	89%	14%
Installation products	0%	4%	2%
All products	-1%	89%	7%

The similarity between the GWP and CED impacts does not account for wood fibre insulation where the EoL phase C has a significantly negative CED. This is because 99.7% of the EoL phase is dominated by phase C3, waste processing (Thünen-Institut für Holzforschung, 2023). During this process, wood fibre insulation is incinerated to produce energy. This leads to credits for CED in the next lifecycle which is reflected by a negative CED. However, this process is accompanied by the emission of GHGs. As a result, the GWP of wood fibre insulation is high in the EoL phase C. Furthermore, the production phase A has a notable negative GWP impact. Because the production of wood fibre insulation requires the cultivation of trees. Trees store CO_2 during their growth process which leads to a negative GHG emission.
Another finding is the proportion of phase D for the GWP and CED, which is notable for wood fibre insulation, PIF insulation, the three types of glazing, heat pumps, and ventilation systems. These products contain materials with high recycling efficiencies. For instance, the aluminium foil of PIF, glass of the glazing systems, and metals in the heat pumps and ventilation systems. The recycling of materials can help avoid the use of raw materials and the associated impact in the next lifecycle. Since the production phase A of the mentioned products is the most significant, the credits in phase D for avoiding this impact will also be relatively high.

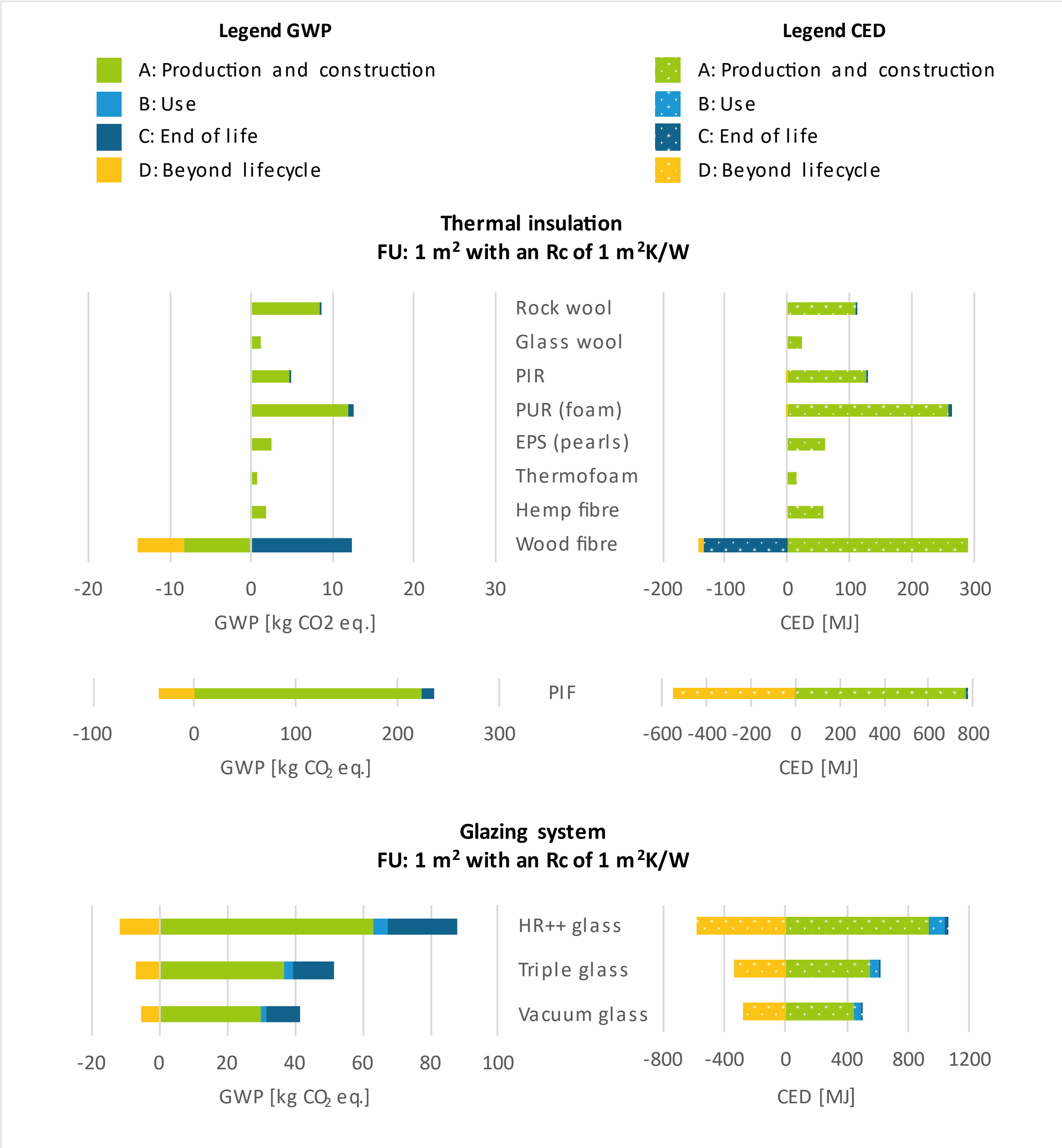

Figure 14 Distribution of GWP and CED per FU over the lifecycle of the construction products.

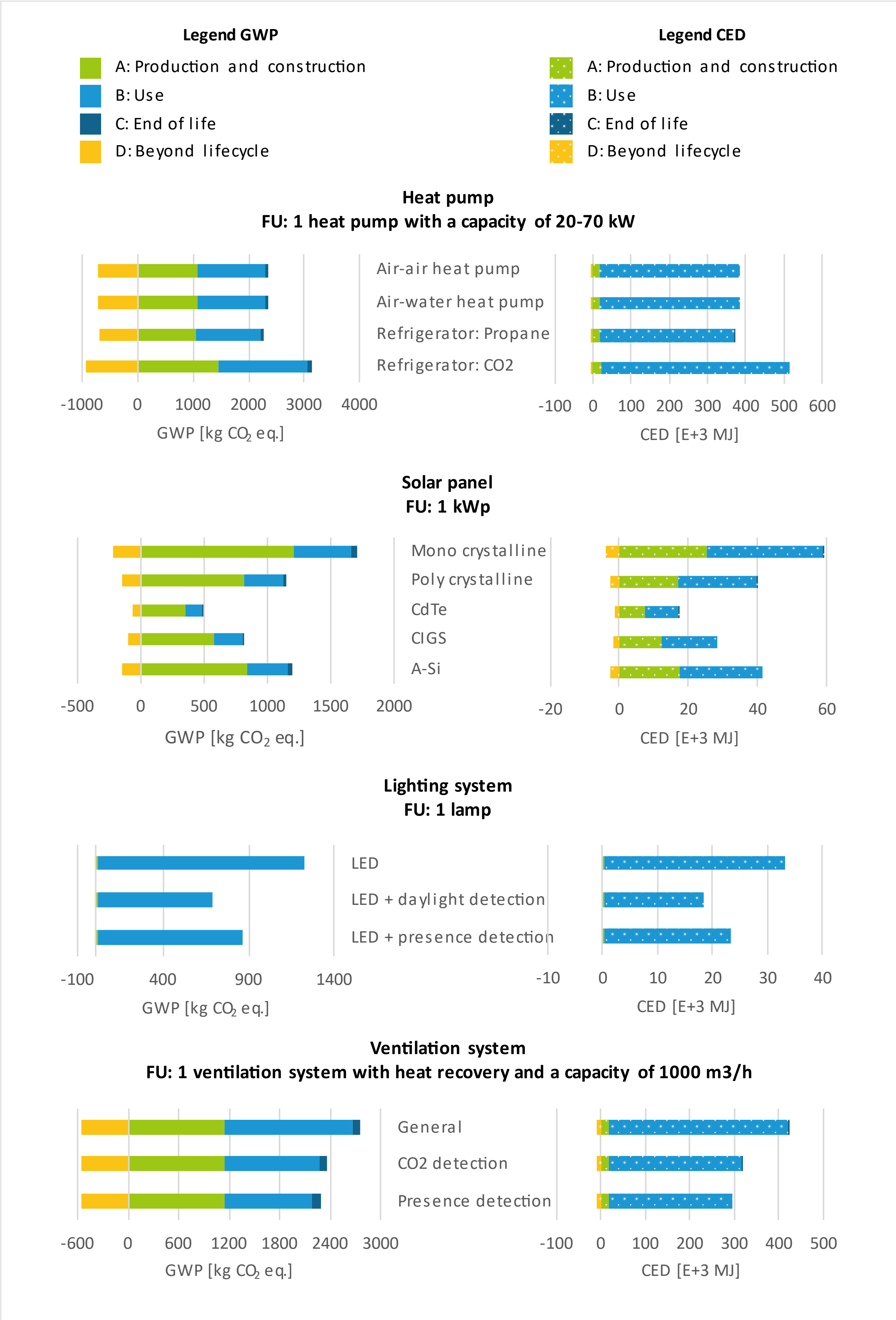

Figure 15 Distribution of GWP and CED per FU over the lifecycle of the installations.

4.4 Sensitivity analysis of lifecycle-based CED and GWP

Two types of sensitivity analyses have been conducted on the results as presented in the previous section. One was conducted for construction-related products and another for installations. The results of the sensitivity analysis are ranges of the CED and GWP per product which are used in the remainder of the study.

The insulating capacity of a material depends on the thermal conductivity coefficient or so-called λ-value. The lower this coefficient, the less heat a material can transfer which leads to a better insulating capacity. When the thickness of the material is considered, the thermal resistance coefficient or Rc-value can be calculated. The thicker the material, the higher the Rc-value. This makes it possible to reach a high Rc-value even though the material has a high thermal conductivity coefficient. In the LCA calculations, the FU for insulation and glass contain an Rc-value of 1 m^2K/W. Since the thermal conductivity coefficient of materials varies, the thickness of the material to reach an Rc-value of 1 m^2K/W can vary as well. Therefore, the GWP and CED impacts can change when different thermal conductivity coefficients for the same materials are applied. To find out the impact of the variation in thermal conductivity coefficients, a sensitivity analysis has been conducted. Similar to the thermal conductivity coefficient, the U-value represent the rate of heat transfer through glass. The higher this value, the lower the insulating capacity. Therefore, a sensitivity analysis was carried out on glazing to determine the effect of varying U-values. The minimum and maximum thermal conductivity coefficients of insulation materials and the minimum and maximum U-values for glazing are presented in Appendix D.

The lifecycle of a product is a significant factor affecting the resulting GWP and CED. In this study, an RSL of 50 years is considered. If the product's lifecycle is shorter than initially assumed, more lifecycles are required to fulfil the RSL of 50 years, resulting in a higher impact than initially calculated. Conversely, if the product's lifecycle is longer than initially considered, fewer lifecycles are needed to meet the RSL of 50 years. Then, the impact would be lower than the initially determined. Since the construction products have a lifecycle of 50 years, it is assumed that a slightly longer or shorter lifecycle would not significantly affect the resulting GWP and CED. The impact of different thermal conductivity coefficients and U-values, as discussed above, is expected to be higher. Therefore, a sensitivity analysis that focuses on the product's lifecycle and its effect on the resulting GWP and CED is conducted solely for the installations. The minimum and maximum lifecycles of the installations are presented in Appendix D.

The input for the sensitivity analysis is used to compute the minimum and maximum GWP and CED impacts. These extreme values are compared with the initial GWP and CED as previously calculated and presented in Appendix C. The difference between the minimum and initial impact has been calculated as well as the difference between the maximum and initial impact. Both values are presented in Figure 16 as percentages of the initial value. These percentages are the same for the GWP and CED for all products except for PIF insulation. This is because PIF contains an insulation layer and a thin layer of aluminium. Different thermal conductivity coefficients are analysed for the insulation layer, however, the coefficient for the aluminium layer remained the same. As a result, the initial GWP and CED of both layers of PIF may not be affected by the same factor, as is the case for the other products. Therefore, the CED and GWP of PIF are presented separately in Figure 16.
The initial impact is more reliable when the minimum and maximum percentages are close together. For example, in the case of hemp fibre. This indicates that the GWP and CED are the least reliable for wood fibre, heat pumps with a CO_2 refrigerator, and LED lighting. To present the results as transparent as possible, the minimum, initial, and maximum values of the CED and GWP of the products (see Appendix D) will be used when the impact per building is calculated.

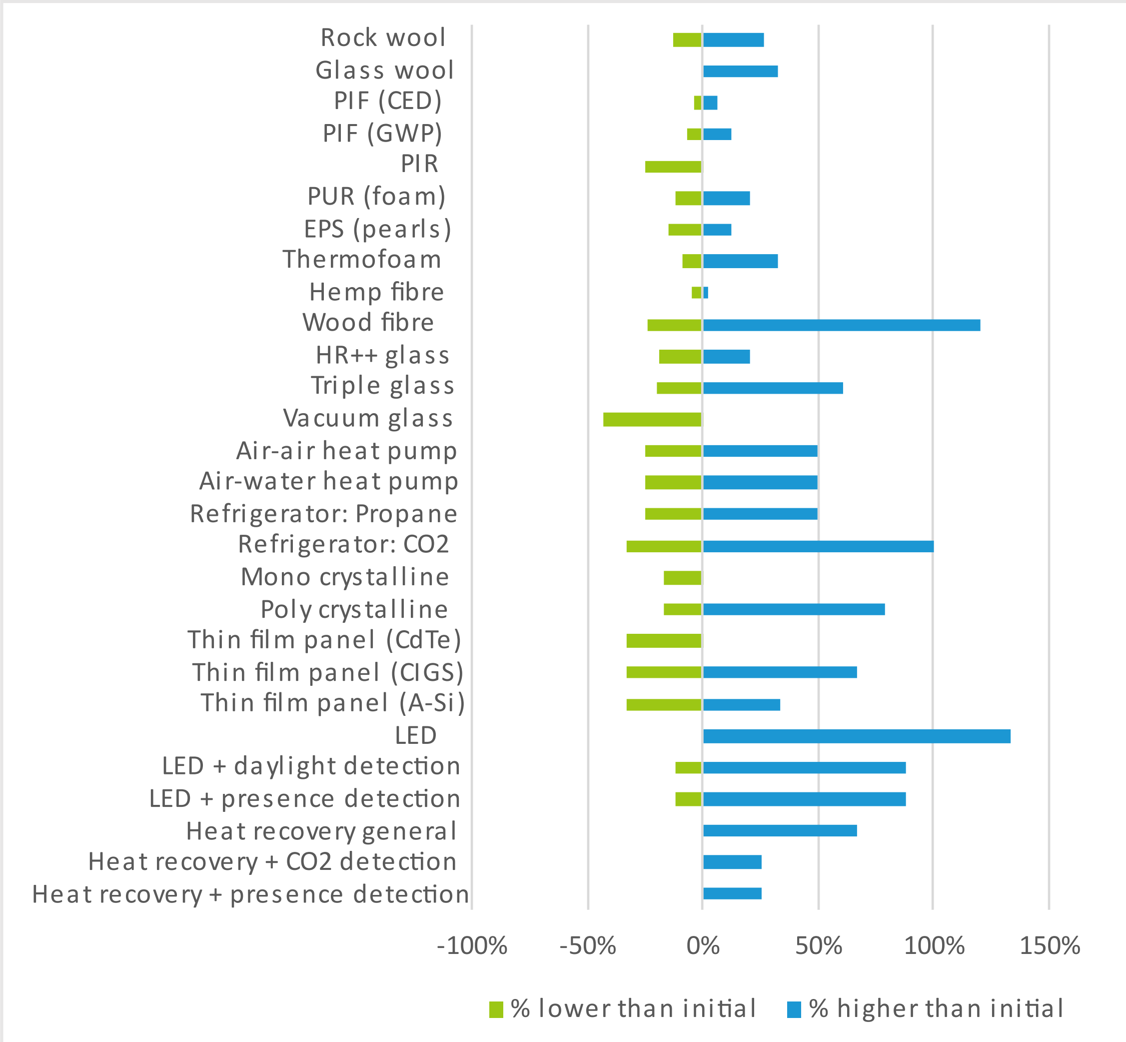

Figure 16 Ranges of GWP and CED per product compared to initial GWP and CED.

4.5 Lifecycle-based GWP and CED, financial costs, and payback periods of measure packages

The GWP and CED ranges of the previous section are used as input for the LCA studies for each building. In addition, the financial costs as determined per product (see Appendix E) are used to compute the financial costs per building. As mentioned in Section 3.5 of the Methodology, the GWP, CED, and financial costs and payback periods are first determined for all possible products of each measure. These results are elaborated in Section 4.5.1. This is again input for the GWP, CED, and financial costs and payback periods of the measure packages, hence according to the second FU as mentioned in Section 3.5 of the Methodology. The results of the costs per measure packages will be presented and analysed in Section 4.5.2, while this is done for the payback periods in Section 4.5.3.

4.5.1 GWP, CED, and financial costs and payback periods per product

The results of the GWP, CED, and financial costs are presented in Appendix G. These results are used to calculate the payback periods (see Appendix G) by using the formulas as presented in Section 3.5 of the Methodology. The average GWP and CED payback periods per product are presented in Table 11 where the shortest payback period is indicated by the darkest colour. From this table, it can be observed that the payback periods of LED lighting and PIF insulation are longer than the building's remaining lifetime of 50 years, while the other measures have payback periods within these 50 years. Furthermore, for most measures accounts that the lower the CED payback period, the lower the GWP payback period. Except for wood fibre insulation where a relatively high CED payback period has a negative GWP payback period, and PIF insulation where the CED payback period is relatively low compared to the GWP payback period.

Table 11 Average GWP and CED payback periods for the products per measure.

Measure	Product	Average GWP payback time (y)	Average CED payback time (y)
Insulation cavity	Thermofoam	0.3	0.3
	EPS pearls	0.9	1.3
	PUR foam	4.8	5.9
Insulation facade	Wood fibre	-4.0	21.3
	Thermofoam	1.3	1.6
	Glass wool	2.5	2.7
	Hemp fibre	3.4	6.2
	Rock wool	16.4	12.8
	PUR foam	23.7	29.5
Insulation floor	EPS pearls	2.6	3.7
	PUR foam	13.2	16.4
	PIF	209.5	14.0
Insulation roof	Wood fibre	-1.6	9.7
	EPS	1.9	3.1
	PIR	3.3	5.9
Glazing	Vacuum glass	13.0	4.6
	HR++ glass	15.2	5.4
	Triple glass	17.3	6.1

Measure	Product	Average GWP payback time (y)	Average CED payback time (y)
Heat pump	air-air heat pump	0.3	4.2
	air-water heat pump	0.3	4.2
	Refrigerant: Propane	0.3	4.0
	Refrigerant: CO2	0.5	6.3
Ventilation system	Heat recovery + presence detection	0.2	1.2
	Heat recovery + CO2 detection	0.2	1.3
	Heat recovery general	0.2	1.9
Solar panels	Thin film panel (CdTe)	1.3	2.7
	Thin film panel (CIGS)	1.9	5.6
	Thin film panel (A-Si)	3.3	7.3
	Poly crystalline	3.9	8.5
	Mono crystalline	4.0	9.8
Lighting	LED + daylight detection	109.2	196.8
	LED + presence detection	137.4	248.6
	LED	225.2	408.7

As mentioned in Section 3.5 of the Methodology, the price of gas and electricity increased by 54% and 51% respectively in 2023 compared to 2021. To find out how this affects the financial payback periods for each product, a sensitivity analysis was conducted. Figure 17 illustrates the range between the minimum and maximum payback periods, including the initial payback period of the products. The data used for this figure are presented in Appendix D.

It can be observed from Figure 17 that the discrepancy between the initial and maximum payback periods is greater than that between the initial and minimum payback periods. This discrepancy can be attributed to the formula used to calculate the payback period, namely, the division of the costs by the savings per year. In this sensitivity analysis, the costs remain constant. A reduction in the yearly cost savings by 54% and 51% for gas and electricity respectively, will result in a reduction of the saved costs by more than a half. This will in turn lead to a payback period that is more than doubled. Hence, this is the maximum payback period in Figure 17. Conversely, an increase in the yearly costs savings by 54% and 51% for gas and electricity respectively, will result in a payback period that is almost halved. Hence, this is the minimum payback period in Figure 17.

Furthermore, it can be observed that the product with the shortest initial payback period within a measure type, for instance triple glass, also exhibits the shortest minimum and maximum payback periods compared to the other products within the same measure type, e.g. HR++ glass and vacuum glass. Besides the glazing system, this can also be observed for the other measure types. Therefore, the sensitivity analysis indicates that the varying prices of gas and electricity do not influence the selection of the products for the third scenario, as will be elaborated in the following section.

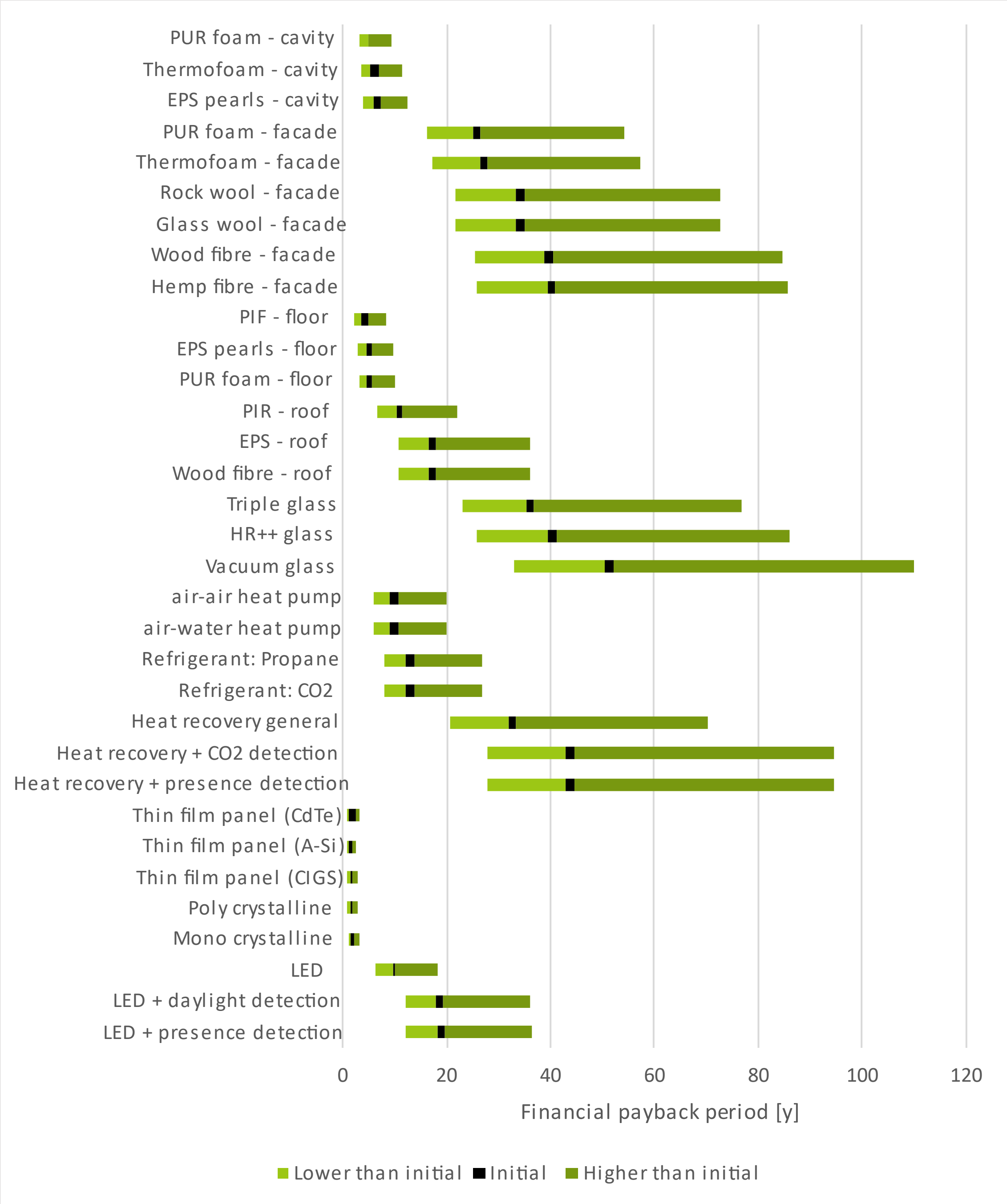

Figure 17 Ranges of financial payback period resulting from the sensitivity analysis.

4.5.2 GWP, CED, and financial costs per measure package

To compute the impacts and payback periods per measure package, one product should be selected per measure. This is done based on the three scenarios as defined in Section 3.5 of the Methodology:

- Scenario 1: the product of a measure with the lowest GWP payback period
- Scenario 2: the product of a measure with the lowest CED payback period
- Scenario 3: the product of a measure with the lowest financial payback period

The selected products for each project are presented in Appendix I. The analysis of these results reveals that for each project, the same products are selected per scenario and measure type. These products are listed in Table 12. This table shows that for PV panels, the CdTe thin-film panel has the lowest GWP, CED, and financial payback period in all six projects. Hence, only in the packages of the projects where PV panels are included. Regarding the facade and roof insulation, it can be observed that each scenario has a different optimal product. Furthermore, the general types of heat pumps, lighting, and ventilation systems have the lowest financial payback period. In contrast, more advanced installations including sensors or a different refrigerant, have the lowest GWP and CED payback period.

Table 12 Corresponding products selected for measure packages across six projects divided per scenario.

Measure	Scenario 1: Min. GWP payback period	Scenario 2: Min. CED payback period	Scenario 3: Min. financial payback period
Insulation cavity	Thermofoam	Thermofoam	PUR foam
Insulation facade	Wood fibre	Thermofoam	PUR foam
Insulation floor	EPS pearls	EPS pearls	PIF
Insulation roof	Wood fibre	EPS	PIR
Glazing	HR++ glass	HR++ glass	Triple glass
Heat pump	Refrigerant: Propane	Refrigerant: Propane	air-air heat pump
PV panels	Thin film panel (CdTe)	Thin film panel (CdTe)	Thin film panel (CdTe)
Lighting	LED + daylight detection	LED + daylight detection	LED
Ventilation system	Heat recovery + presence detection	Heat recovery + presence detection	Heat recovery general

For each scenario, the products as presented in Table 12 are selected to calculate the GWP, CED, and financial costs per measure package (see Appendix J). Figure 18 presents the GWP and CED impacts in ranges for each initial energy label to reach label A. The three scenarios are divided accordingly. Additionally, the financial costs for achieving label A are provided for each building. The same information is presented in Figure 19, though this is for achieving the label Energy Neutral.

From these figures, it can be observed that the highest GWP, CED, and financial costs are associated with transitioning from label E to label A or Energy Neutral. This is because a larger label step requires more energy-saving measures and therefore more materials. Consequently, initial label C, with a smaller label step, has the lowest GWP, CED, and financial costs when achieving label A or Energy Neutral, as can be observed in Figure 18 and Figure 19.
Moreover, it is remarkable that the GWP and CED of scenario 3 (products with the lowest financial payback period) are higher than those of the other two scenarios in almost all label steps presented in Figure 18 and Figure 19. Thereby, the difference between scenario 3 and the other two scenarios is larger for the GWP than for the CED. This is because PIF is the type of floor insulation that has been applied to buildings 1, 2, and 3 for reaching label A and in all buildings for achieving the Energy Neutral

label. PIF insulation has the shortest financial payback period. However, it has a significantly higher GWP compared to other floor insulation materials (see Figure 14).
Figure 18 illustrates that the GWP of scenario 3 is less significant in the transition from label C to label A than in the transition from labels E and D to label A. This is because the initial label C only requires roof insulation to reach label A. PIR is the cheapest material for this measure, with a significantly lower GWP than PIF.

Looking at the financial costs in Figure 18 and Figure 19, it can be seen that the buildings with the same initial label have nearly the same financial costs in each scenario. The three buildings transitioning from label C to A in Figure 18 'Financial costs', have identical costs as only the roof insulation needs to be implemented, and the roof areas for these buildings are identical. The financial costs for achieving label A may vary slightly for the other buildings due to differences in the quantities of each measure. To achieve the label Energy Neutral (Figure 19 'Financial costs'), the financial costs also depend on different measures for buildings with the same initial label. For example, building 4 and 5 with label C include glazing, which results in higher costs for these buildings compared to building 6 with label C. However, building 4 only requires one ventilation system whereas the other two buildings require two systems to achieve the Energy Neutral label. Therefore, the financial costs of buildings 4 and 6 are similar, whereas the costs of building 5 are higher.

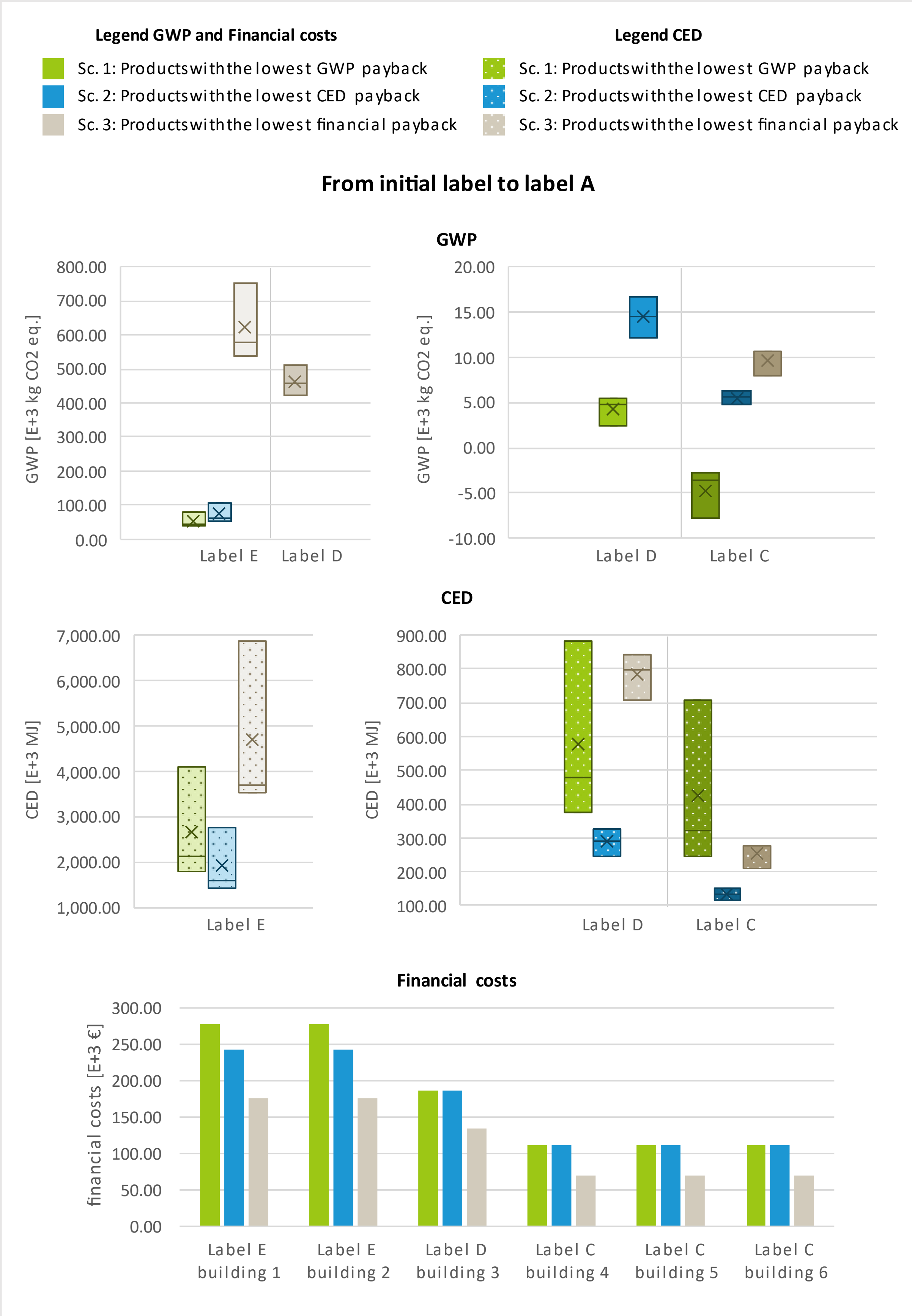

Figure 18 GWP, CED, and financial costs to go from the initial label (E, D, or C) to label A.

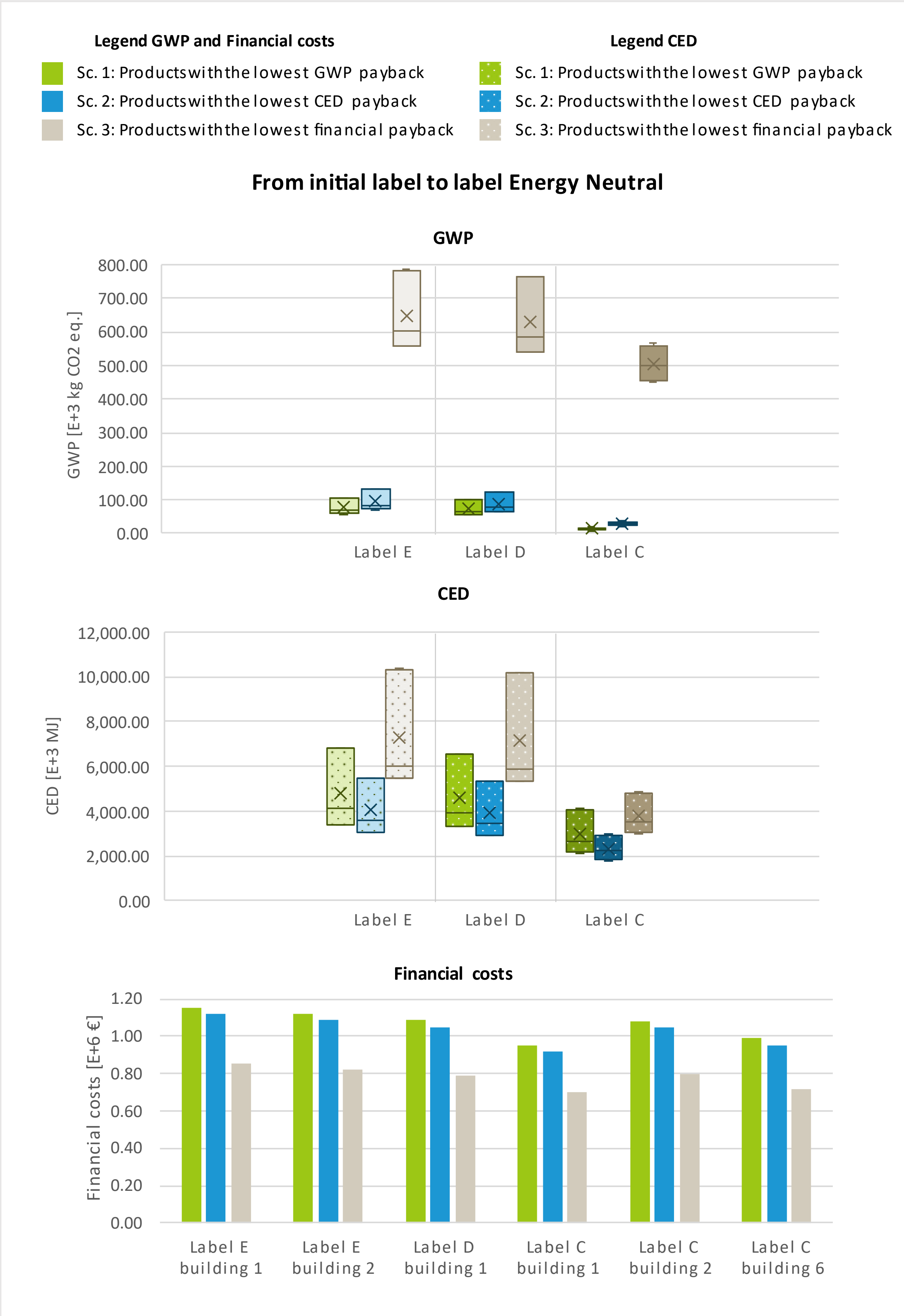

Figure 19 GWP, CED, and financial costs to go from the initial label (E, D, or C) to label Energy Neutral.

4.5.3 GWP, CED, and financial payback periods per measure package

The results presented in Figure 18 and Figure 19 are used to calculate the payback periods of the measure packages for each building. The GWP and CED payback periods are presented in Figure 20, and the financial payback periods in Figure 21. The raw results are provided in Appendix J, along with the data used to generate Figure 18 and Figure 19.

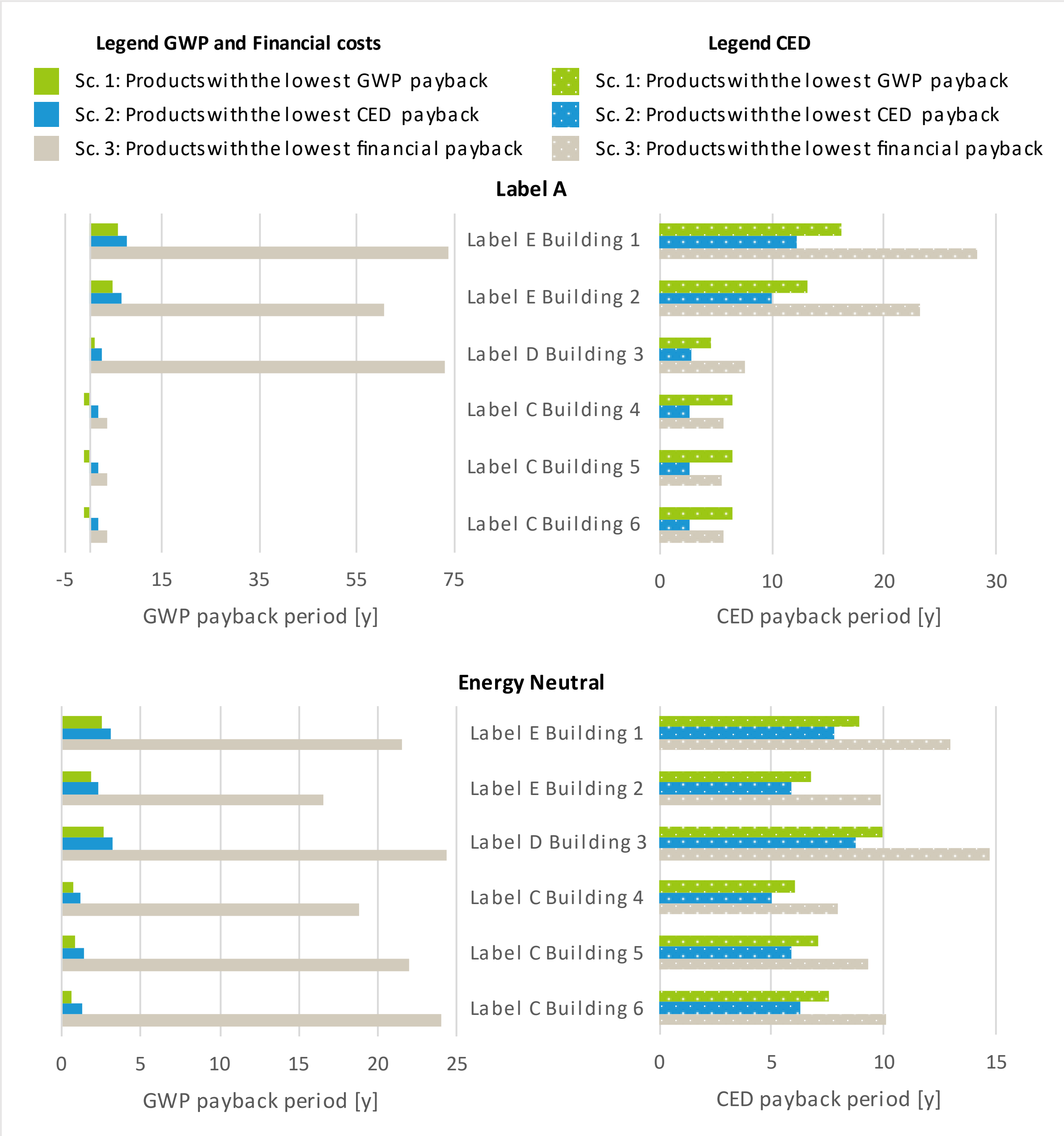

Figure 20 GWP and CED payback periods of measure packages (label A and Energy Neutral) per building.

In Figure 20, it is visible that selecting the products with the lowest financial payback period (scenario 3) leads to the highest GWP and CED payback periods in all label steps. Thereby the GWP payback periods of scenario 3 are significantly higher than those of the other scenarios. This can be declared by the high GWP impact of PIF floor insulation applied to achieve label A (buildings 1, 2, and 3) and Energy Neutral (all buildings), as elaborated in Section 4.5.2.

With regard to the CED payback periods, scenario 3 has a longer payback period for buildings 1 and 2 than for the other buildings. This is because buildings 1 and 2 require LED lighting to achieve label A. As presented in Table 11, the LED lighting including sensors has lower GWP and CED payback periods than conventional LED lighting. However, conventional LED lighting has a lower financial payback period and is therefore selected for scenario 3, leading to a longer CED payback period than scenarios 1 and 2. LED lighting is also required for buildings 1, 2, and 3 to reach the Energy Neutral label. However, LED lighting is not as significant for the CED payback periods as PIF is for the GWP payback periods. Therefore, LED lighting is not the main product leading to the higher payback periods of scenario 3. Another finding from Figure 20 is that the GWP and CED payback periods for all scenarios fall within the 50-year remaining lifetime of the building. With the exception of the GWP payback periods associated with scenario 3.

Figure 21 presents the financial payback periods per scenario for each building (the raw results are provided in Appendix J). From this figure, it can be observed that selecting the products with the lowest GWP payback period results in the highest financial payback period for reaching label A as well as the label Energy Neutral. Furthermore, it can be observed that the financial payback periods for the label Energy Neutral are longer than those for label A for the buildings 3, 5, and 6. In contrast, the financial payback periods for label A are higher than for the label Energy Neutral for the other three buildings.
According to the formulas as presented in Section 3.5 of the Methodology, the financial payback period will increase as the ratio between investment and saved costs increases. As elaborated in Section 4.5.2, the investment costs associated with achieving label Energy Neutral are higher than those of achieving label A for all six buildings. Therefore, the observed differences between the financial payback periods of the buildings in Figure 21 might be caused by the investment costs. Nevertheless, it is difficult to identify the exact cause of these differences due to the diverse combinations of measures and quantities of required products across the six buildings.

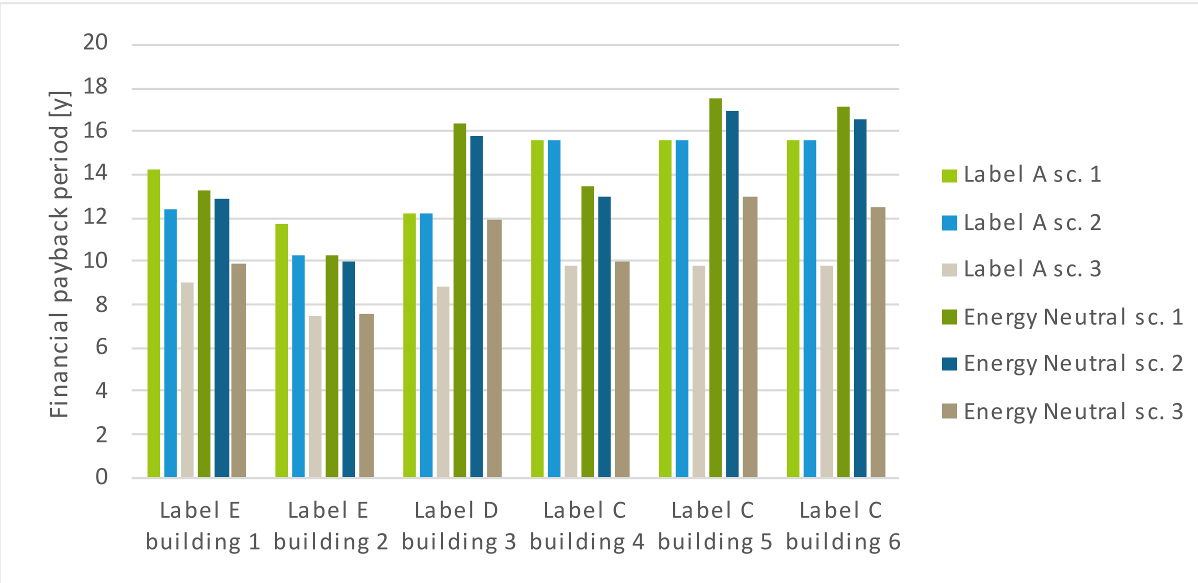

Figure 21 Financial payback periods measure packages (Label A and Energy Neutral) for six buildings.

4.6 Including the GWP and CED into the energy-saving advice

In the previous section, the GWP and CED, along with their payback periods, have been determined per product and per measure package. During the interviews with five clients, as elaborated in the following section, it was asked how the GWP and CED could be implemented in an understandable way. This resulted in two different options.

The first option is to incorporate it into the decision table of the energy-saving advice. An example of a decision table is provided in Table 2 in Section 2.3.1 of the Background. This table already includes the financial payback period, which is used by four out of five interviewed clients. Consequently, the GWP and CED payback periods of the measure packages can be incorporated into the energy-saving advice in this manner.

The second option is to include the GWP and CED of the products in an appendix to the energy-saving advice. Two respondents opted for the use of symbols instead of numbers, as this would facilitate the identification of differences between products. Table 13 provides an example of the GWP and CED of insulation materials per FU, expressed in symbols. As elaborated in Section 3.5 of the Methodology, each half a symbol encompasses a range of the impacts, which is presented in Appendix M. The lowest impact is represented by five symbols, while half a symbol represents the highest impact. In the last column of Table 13, the symbols are used to indicate financial costs. Here, the lowest financial costs are represented by half a symbol, while five symbols indicate the highest financial costs. Therefore, the more "leaf" symbols a client collects, the lower the GWP and CED impacts will be. Conversely, the fewer "coin" symbols, the lower the financial costs of the product.

Table 13 Visualisation of the GWP, CED, and financial costs of insulation materials using symbols.

Measure	Product	GWP*	CED*	Financial costs**
Insulation cavity	PUR foam	🍃🍃	½	🪙🪙🪙
	Thermofoam	🍃🍃🍃🍃🍃	🍂🍂🍂🍂🍂	🪙🪙🪙½
	EPS pearls	🍃🍃🍃🍃½	🍂🍂🍂🍂½	🪙🪙🪙½
Insulation facade	Rock wool	🍃🍃🍃	🍂🍂🍂½	🪙🪙🪙🪙½
	Glass wool	🍃🍃🍃🍃½	🍂🍂🍂🍂🍂	🪙🪙🪙🪙½
	PUR foam	🍃🍃	½	🪙🪙🪙
	Thermofoam	🍃🍃🍃🍃🍃	🍂🍂🍂🍂🍂	🪙🪙🪙½
	Hemp fibre	🍃🍃🍃🍃½	🍂🍂🍂🍂½	🪙🪙🪙🪙🪙
	Wood fibre	🍃🍃🍃🍃🍃	🍂🍂½	🪙🪙🪙🪙🪙
Insulation floor	PIF	½	🍂	½
	PUR foam	🍃🍃	½	½
	EPS pearls	🍃🍃🍃🍃½	🍂🍂🍂🍂½	½
Insulation roof	PIR	🍃🍃🍃🍃	🍂🍂🍂	🪙🪙🪙
	EPS	🍃🍃🍃🍃½	🍂🍂🍂🍂½	🪙🪙🪙🪙🪙
	Wood fibre	🍃🍃🍃🍃🍃	🍂🍂½	🪙🪙🪙🪙🪙

**The more leaf symbols, the lower the GWP and CED impact.*
***The more the coin symbols, the higher the financial costs.*

In the case a client wishes to select floor insulation, it can be observed from Table 13 that the three products have similar financial costs. Consequently, the client may opt for EPS pearls when seeking to achieve lower GWP and CED impacts in comparison to PIF and PUR foam. The selection of products for the other measures can be conducted in a similar manner by using the tables for the other measure types which are presented in Appendix M. It is important to note that comparisons between products can only be made within the same measure type, given that different measure types have different FUs.

4.7 The effect of lifecycle-based GWP and CED on advised and chosen measures

The GWP, CED, and financial costs and payback periods as analysed in Sections 4.3 and 4.5 are presented to clients and employees of Antea Group. To find out how this will influence their decision-making in future projects. This is achieved through interviews and a brainstorming session, of which the results are presented in the respective subsections.

4.7.1 Interviews with clients

The interviews were conducted with five clients of Antea Group. A more detailed description of these clients and the interview questions is provided in Section 3.6 of the Methodology. The respondents were asked to list and rank criteria for selecting energy-saving packages, measures, and products for their buildings. The criterion with the highest rank receives five points and the one with the lowest rank one point. Figure 22 presents the average scores for the criteria named by the five respondents. The individual responses of the clients are provided in Appendix K.

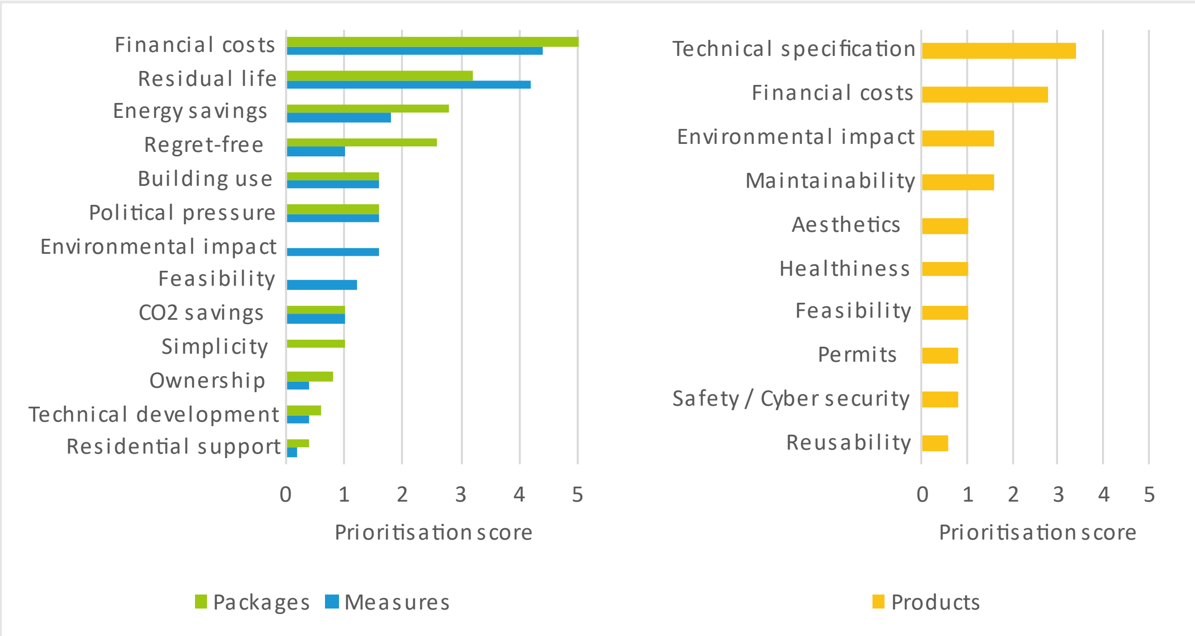

Figure 22 Prioritisation of criteria by interviewed clients (n=5).

Figure 22 shows that the top three prioritised criteria by the respondents are the same for packages and measures. Thereby, financial costs are identified as the most important, followed by the residual life of current products or buildings. Four respondents associated this second criterion with financial costs. Because, if a product is replaced at the scheduled time, money is already available. However, replacing it earlier would mean incurring additional costs. For instance, it may be more cost-effective to apply new roof insulation during the replacement of the roof covering. This approach avoids the need to remove and replace the roof covering twice, once for the new insulation and again for the replacement of the roof covering. Furthermore, three respondents indirectly linked 'residual life' to the delay in material use. They noted that the current product is still functioning, and therefore replacement is not yet necessary. In third place is the criterion 'energy-saving potential'. This is remarkable as the clients want to reduce energy in the first place. However, it appears that this is not the primary criterion for selecting packages and measures.

Only one respondent mentioned CO_2 reduction, despite this being part of the advice. After asking the other respondents if CO_2 reduction is considered or not, they replied that CO_2 reduction is linked to energy reduction. Therefore, this is not considered a separate criterion. Another remarkable criterion is the environmental impact. Although it is not mentioned in the package selection, two respondents mentioned it in the measure selection. They described this criterion as trying to avoid toxic substances in materials, and to avoid the use of raw materials due to material scarcity.

As visible in Figure 22, the criteria for selecting products differ significantly from those for selecting packages and measures. The respondents still consider financial costs to be important, however, they prioritise the technical specifications of materials. This indicates that respondents prefer energy-efficient materials. Furthermore, the criteria 'reusability' and 'maintainability' can reduce the need for raw materials. Therefore, it can be connected to environmental impact. Together with the third place of the criterion 'environmental impact' in Figure 22, the respondents appear to consider environmental impact more important for product selection than for selecting packages and measures.

In addition to the ranking of criteria, respondents were asked whether they followed all recommended measures or not. Two respondents implemented all measures as advised by Antea Group, while the others first considered some criteria before deciding to include the measures.

During the first part of the interview, no information was provided regarding the impact of the products throughout their entire lifecycle. This explanation was provided in the second part, supported by the calculated values of the GWP and CED of the products. Feedback on this explanation was that it is hard to comprehend without in-person clarification.

After the explanation, all respondents expressed confidence in using the GWP and CED results in future projects to select products with a lower environmental impact. Thereby, two respondents instinctively interpreted a low CED as more important than a low GWP when selecting a product. One respondent found them equally important, and one respondent stated that there are more impacts besides these two. However, four out of five respondents mentioned that they would only choose the products with a lower GWP and CED as it fits the budget.

A different type of answer was given by the respondent from the governmental organisation. They are already focusing on operational emissions as a criterion. Additionally, they are exploring methods to include embodied emissions and other environmental impacts as criteria, in addition to GWP and CED. The financial costs are of lesser importance to the governmental organisation as they aim to set a good example in terms of environmental impact for the rest of the country.

Besides financial costs, three respondents mentioned the practical applicability. This is explained by the example that thicker insulation packages are not always technically feasible. In those cases, less sustainable products are chosen.

At the end of the interview, four respondents mentioned that they have become more aware that the sustainability of buildings encompasses more than just reducing a building's operational energy. It was noted that the selected products have an impact on the environment during their entire lifecycle. Therefore, the respondents mentioned that they will use the GWP and CED to make more informed choices, although financial costs remain a more important factor.

4.7.2 Brainstorming session with employees

To obtain responses from Antea Group employees on this topic, a brainstorming session was organised following a survey. A more detailed explanation of this survey and the brainstorming session is explained in Section 3.6 of the Methodology. The survey answers are provided in Appendix L.

Before the brainstorming session, the criteria with the highest priority according to the employees are energy savings, financial costs, sustainable energy generation, and customer demand. Sustainable energy generation can be linked to energy savings, as it has a positive impact on the energy label (NEN, 2022). The current advice to clients includes energy savings and financial costs, which declares the prioritisation of the criteria above. However, similar to the prioritisation of the clients, the CO_2 savings

are part of the advice, yet only one employee mentioned this as an important criterion. During the brainstorming session, it was concluded that employees tend to focus on meeting the client's demands, which are primarily related to financial costs and energy savings. As a result, employees perceive CO_2 savings as an additional factor on top of the challenge of saving energy within the given budget. Therefore, CO_2 savings are given a lower priority.
To change this, the attendees concluded that the advisor should initiate discussions on sustainability and CO_2 savings, even if the client did not mention them initially. To accommodate this, it was suggested that a database containing this information should be available to facilitate the calculation of the environmental impact or CO_2 savings. Otherwise, it may become too time-consuming, which could lead to increased costs for the client. As clients place high importance on financial costs, one employee recommended including the financial costs of each measure in the advice, in addition to the environmental impacts.

The employees provided feedback after the brainstorming session. They emphasised the importance of considering the impact over the entire lifecycle and expressed concern that the client's demands were given too much priority. They also acknowledged that this is a difficult theme but stressed the importance of including it in the advice.

5. Discussion

In this section, the methodology will be discussed by zooming in on the use of EPD databases and the methodology used for conducting the interviews and the brainstorming session. Additionally, the results of this study will be discussed by comparing the LCA results with other studies. Thereby, the focus is on the significant lifecycle phases, the GWP and CED ranges resulting from the sensitivity analysis, and a general discussion on the reproducibility of LCA studies. Furthermore, the results of the interviews and the brainstorming session are discussed.

5.1 Discussion of the methodology

5.1.1 EPD databases

The data used as input for the LCA study are from EPD databases and the GaBi background data. Primary data from the selected projects would have resulted in more specific GWP and CED outcomes. However, not all advised measures are already applied in the buildings due to the maintenance budget and planning, which results in low primary data availability. Additionally, the study's objective is to identify the effect of adding the GWP and CED to energy-saving advice. Therefore, an LCA study was conducted for 6 measure types and their 26 optional products. This would not have been feasible by using primary data within the given time. Fewer products could have been selected, however, this would have made it difficult to compare different products within a measure category. Additionally, fewer measures could have been selected. However, this would have made it impossible to provide the GWP and CED impacts and payback periods of the measure packages, while this is the main concept of the advice. Since energy-saving advice is formulated in the initiative phase, less specific values are required. This allows the outcomes of the GWP and CED to have some deviation as well. Therefore, the method of using EPD datasets was feasible for this research. The deviation of the GWP and CED impact is covered in the sensitivity analysis to provide transparency. When using the results of this study in future research, this provided deviation should be considered.

5.1.2 Uncertainties

The utilisation of EPD databases is a viable option for this study, although certain limitations must be acknowledged. First, not all lifecycle phases were included in the EPDs. Nevertheless, the GWP and CED results for phases A1-A3 were available in all EPDs. Therefore, assumptions of missing phases were based on these values. Since the production phase is the most significant for insulation and glazing (see Figure 14), it is unlikely that the results of these products will change significantly. For the installations, assumptions have only been made for heat pumps and ventilation systems. Since the use phase was found to be the most significant for these products (see Figure 15), the uncertainties related to this phase could influence the results for the heat pumps and ventilation systems more than for the other products. The calculated GWP and CED payback periods of heat pumps and ventilation systems are relatively low (see Table 11). When the GWP and CED impacts appear to be higher, the payback periods of the products will increase. As a result, the GWP and CED impacts and payback periods of the measures will also increase. Nevertheless, this increase will be reflected in all three scenarios depicted in Figure 18, Figure 19, and Figure 20. It is therefore expected that the difference between the scenarios in these figures will remain relatively constant.

Second, data was not accessible for all products considered in this study. For instance, only data about triple glass was available. The GWP and CED of the other glass types are assumed based on product properties. Third, a European scope was not available for PV panels and LED lights. These products were produced globally and the remaining lifecycle took place in Europe. Furthermore, data about the insulation materials PIR, PUR, and thermofoam only have a geographical scope in the United States. The energy and electricity mixes of different countries can vary considerably (Pargana et al., 2014), which affects the GWP and CED. According to the Ecoinvent 3.8 dataset, the GWP and CED for 1 MJ of gas and the CED of 1 kWh of electricity are similar for Europe, the US, and a global scope. However, the GWP impact of 1 kWh of electricity doubles in the US compared to Europe. For a global scope, the GWP impact of 1 kWh of electricity is 82% higher than in Europe. Consequently, if a client wants to implement one of the five mentioned products, and they are produced in Europe rather than in the US or on a global scope, the GWP impact and payback periods as presented in the results would likely be lower. Similarly to the situation where the GWP and CED impacts might be higher for heat pumps and ventilation systems, a lower GWP impact and payback period would be reflected in all three scenarios depicted in Figure 18, Figure 19, and Figure 20. Therefore, the differences between the scenarios in these figures are expected to remain relatively constant.

Fourth, the databases did not include the modelled flow diagrams of the LCI processes. Therefore, an analysis of the most significant processes could not be conducted in the sensitivity analysis. This made it not possible to identify which production processes could be improved to reduce the GWP and CED impacts. Nevertheless, this shortcoming does not affect the results of this study. The sensitivity analysis in this study was conducted by considering the conductivity coefficients for insulation and glazing, as well as the lifecycles for the installations. This resulted in GWP and CED ranges which were used in the remainder of the study to provide transparency.

5.1.3 Interviews and brainstorming session

In this study, two different interviews and a brainstorming session were conducted. In the first interview, ten respondents were asked about conventional and alternative products. This ensured that at least three different respondents could provide an answer for each of the six measures considered in this study. Since similar responses were provided, this method was appropriate for this study.

The second interview was conducted to find clients' criteria for selecting packages, measures, and products before and after sharing information about environmental impacts and the study results. This information was not shared at the start of the interview to prevent respondents from providing socially acceptable answers. Therefore, it could be found out if criteria, such as CO2 savings, sustainability, and environmental impact, currently play a role for clients in the selection of packages, measures, and products. It also made it also possible to find out if the priority of these criteria would change after sharing the information. This method is applicable since one of the objectives this is to find out how the knowledge of the GWP and CED affects the decisions made by clients.
Five different types of clients were selected for the interview. This includes two municipalities, a governmental organisation, a school community, and a community house. While this is a relatively small number of respondents, they are from different organisations, which allows for insights into the prioritisation of criteria for different organisations.

A similar set of questions was posed to employees of Antea Group during a brainstorming session. To ensure that the dominant respondents could not influence the answers of the less dominant respondents, a survey was distributed to the respondents prior to the brainstorming session. Furthermore, a second survey was conducted with five respondents after the brainstorming session. The results might be socially accepted answers due to the conclusions drawn during the session. This should be considered when drawing conclusions.

5.2 Discussion of the results

5.2.1 Significant phases

The results of the GWP and CED per product are presented in Appendix G and visualised per phase in Figure 14 and Figure 15. It is found that insulation materials have a significant GWP and CED during the production phase. This is in line with the findings of Dovjak et al. (2017), Schulte et al. (2021), and Füchsl et al. (2022). They found that the melting process during production and the use of additives were significant for rock wool and glass wool. For PIR, PUR, and EPS this is the extraction of raw materials (Dovjak et al., 2017; Füchsl et al., 2022). For hemp fibre and wood fibre, the significant processes in the production phase are caused by binders and additives, the drying process, and the impact of fertiliser production and application (Dovjak et al., 2017; Schulte et al., 2021; Füchsl et al., 2022). The carbon taken up during the growing process leads to positive impacts on the GWP during the production phase. However, this carbon will also be released during the incineration process in the EoL phase, leading to negative and significant processes again (Schulte et al., 2021; Füchsl et al., 2022). This is also visualised in the results of wood fibre (Figure 14) where the production phase has a GWP below zero, and the EoL phase has a GWP above zero.

Looking at the impact of glazing, Figure 14 shows that the production phase is the most significant. This is in line with the study of Souviron et al. (2019) who found that the melting of raw materials for the production of glass is the most significant process. The use phase has little impact on the execution of maintenance (Souviron et al., 2019). However, replacement can have significant impacts on GWP and CED (Asdrubali et al., 2021). Replacement is not considered in this study since a lifecycle of 50 years is taken into account for the glazing systems, which is the same as the considered RSL of 50 years. This declares that the impact of the use phase for GWP and CED in Figure 14 is not significant.

Going to the installations, Figure 15 shows that the use phase has the most significant GWP and CED for most products. For heat pumps and ventilation systems, the significant CED is caused by the energy demand during the use phase. This leads to a significant GWP, however, this depends on the electricity mix of the country. When this is mainly non-renewable energy, the impact of the use phase will be higher than when renewable sources would have been used (Marinelli et al., 2020; Saoud et al., 2021). According to the results in Figure 15, the impact of the production phase for GWP is also quite significant, while this does not account for the CED. This is corresponding to the findings of Marinelli et al. (2020). For the production phase, copper and steel need to be extracted. In the EoL phase, these materials can be recycled which reduces the impact of the production phase in the next lifecycle (Marinelli et al., 2020; Saoud et al., 2021). This declares that phase D of the GWP is quite significant in Figure 15.

For PV panels, both the production phase and use phase are significant. Zhang et al. (2017) compared the embodied energy over the lifecycle of five different PV panels. Thereby, a use phase of one year and a landfill disposal were considered. It was concluded that over 95% of the embodied energy is concentrated in the production phase. This is also reflected in the CED of the PV panels in Figure 15 where the production phase has a relatively significant CED compared to the other installations. Assuming one year of use and excluding phase D, the production phase of the monocrystalline PV panel in Figure 15 accounts for 97% of the CED, corresponding with the findings of Zhang et al. (2017). The D-phase is neglected in this example because Zhang et al. (2017) used landfill disposal, while the monocrystalline PV panel received credits for recycling. Since the production phase of PV panels has a significant CED, the resulting GHG emissions lead to a higher GWP for the production phase than the use phase.

Figure 15 presents that the GWP and CED of LED lighting are dominated by the use phase. This is also mentioned by Ferreira et al. (2021) who found that this is caused by the electricity consumption during the use phase. Reducing the electricity consumption by implementing sensors for daylight and presence detection can thereby significantly reduce the GWP and CED impact, which is reflected in Figure 15. However, the reduction of GWP largely depends on the electricity mix of the country (Ferreira et al., 2021).

5.2.2 GWP and CED results of products

After computing the GWP and CED results per product, it is found that the GWP is between -1% and 16% of the CED. This is in line with previous studies. In previous studies, for insulation this percentage is found between 1% and 11% (Füchsl et al, 2022; Pargana et al., 2014; Schiavoni et al., 2016). For glazing this is between 3% and 8% (Saadatian et al., 2021; Asdrubali et al., 2021; Tushar et al., 2022). PV panels have a percentage between 5% and 9% (Soares et al., 2018; Vidal et al., 2021). For heat pumps and ventilation systems, this is between 0.02% and 7% (Marinelli et al., 2020; Saoud et al., 2021). For LED lights this is between 3% and 4% (Ferreira et al., 2021; Souza et al., 2019).

The sensitivity analysis has resulted in a range of GWP and CED impacts for each of the products. When comparing these results with previous studies, some impacts appear to be within or close to the calculated GWP and CED ranges: Insulation (Pargana et al., 2014; Kunič, 2017; Schiavoni et al., 2016); glazing (Souviron et al., 2019; Saadatian et al., 2021; Asdrubali et al., 2021; Tushar et al., 2022); PV panels GWP (Vidal et al. (2021), and CED (Soares et al. (2018); lighting (Ferreira et al., 2021; Souza et al., 2019). However, other impacts from previous studies are different: Insulation (Dovjak et al., 2017; Füchsl et al., 2022; Pargana et al., 2014; Schiavoni et al.); glazing (Saadatian et al., 2021; Asdrubali et al., 2021); PV panels (Lunardi et al., 2021; Soares et al., 2018). It also appears that some values of the same research are within the ranges, while other values of that research are outside the ranges.

The differences between the GWP and CED ranges in this study and previous GWP and CED impacts can be attributed to several aspects. First, this study includes a cradle-to-cradle scope by including all lifecycle phases, whereas the other researchers mainly include a cradle-to-gate or cradle-to-grave scope and thereby exclude some lifecycle phases. Second, this study has a European scope. Previous studies have also used European data, however, mainly for a specific country rather than for Europe in general. Data from Canada, the USA, and Australia were also used. Countries can have different production technologies and energy and electricity mixes (Pargana et al., 2014), which affect the GWP and CED. In particular, the GWP and CED of the use phase of installations, since this is the most significant phase due to energy consumption. Third, this study uses data from 2021-2023. However, previous studies have used datasets or LCA studies from 2007 to 2022. Older LCA studies use older assessment methods and databases than newer studies, which can lead to different LCA results (Füchsl et al., 2022). Fourth, the use of different allocation procedures, transport distances, datasets, or end-of-life treatments can lead to different LCA results (Warrier et al., 2024). However, not all previously conducted studies mention these aspects. This makes it difficult to determine the exact cause of the differences between the GWP and CED results of this study and those of previous studies. Finally, the LCA studies are conducted by different researchers. Andersen et al. (2023) found that assumptions made by different LCA practitioners affect the LCA results. This makes it difficult to reproduce LCA studies and thereby declares the results of this study being different than previous LCA studies.

The GWP and CED impacts are used to calculate the payback periods for each product as presented in Table 11. The results show that the payback periods for PIF insulation and LED lighting are relatively high. This indicates that the impact of these products is significant compared to the yearly savings resulting from their implementation. Some products have a payback period of less than one year. However, it cannot be assumed that their impact is negligible in comparison to the savings. Because the GWP and CED savings depend on the quantity of gas and electricity saved by the building. The magnitude of these savings again depends on the current levels of gas and electricity consumption. This may vary for different buildings and therefore the payback periods are situation-dependent.

5.2.3 GWP and CED results of packages

The GWP and CED results of the products are used as input for the GWP and CED results of the packages. Therefore, three scenarios have been devised. These involve the selecting of the products with the lowest GWP, CED, and financial payback period for scenario 1, 2, and 3 respectively. The impact of each scenario is presented in Figure 18 for achieving label A and in Figure 19 for achieving label Energy Neutral. The results show that scenario 3 exhibits the highest GWP and CED impacts for all label steps except for the step from label C to label A. A similar pattern is visible in the GWP and CED payback periods in Figure 20. These considerably higher GWP impacts and payback periods of scenario 3 can be attributed to the selection of PIF insulation, with 75% to 91%. When PIF insulation would not have been considered in this study, EPS pearls would become the floor insulation type with the lowest financial payback period. This product is currently also selected for scenario 1 and 2. When EPS pearls would be selected in scenario 3 instead of PIF, the GWP and CED impacts and payback periods would change with the percentages as presented in Table 14. For the changes of label A, only buildings 1, 2, and 3 have been considered, since the other three buildings do not require floor insulation to achieve label A.

Table 14 Change of the GWP and CED impacts and payback periods of scenario 3 of measure packages (label A and Energy Neutral) when EPS pearls are considered as floor insulation type instead of PIF.

	Label A	Energy Neutral
GWP payback period	-74%	-78%
GWP impact	-79%	-87%
CED payback period	-8%	-10%
CED impact	-8%	-28%

From Table 14, it can be observed that the GWP impacts and payback periods will reduce significantly in comparison to the ones presented in Figure 18, Figure 19, and Figure 20. Similarly, the CED impacts and payback periods will reduce as well, although to a lesser extent. Nevertheless, the impacts and payback periods of scenario 3 are still higher than those of scenarios 1 and 2. Especially for the label steps towards Energy Neutral and from label E to label A. Therefore, for these label steps, it is possible to achieve lower GWP and CED impacts and payback periods when considering scenarios 1 and 2 during the decision-making process.

However, the EU ETS2 will be implemented in 2027. This regulation will result in the implementation of carbon pricing for GHG emissions throughout the lifecycle of buildings (European Commission, 2023). This may influence the product selection for scenario 3. Carbon pricing means that the polluter needs to pay for the GHGs it emits. Therefore, the financial costs will increase for products with higher GHG emissions, and therefore a higher GWP. This will result in an increase in the financial payback period for those products, whereas products with a lower GWP are more likely to exhibit a shorter financial payback period. Consequently, products with lower GWPs will be selected for scenario 3, thereby reducing the GWP payback periods for scenario 3. However, it depends on the level of the carbon price whether the products selected for scenario 3 will also have the lowest GWP payback period. In that case, scenarios 1 and 3 become equal and the GWP impact and payback period would become indirect factors in the decision-making process.

5.2.4 Interviews and brainstorming session

In the first interview, the respondents independently gave identical answers for the conventional products. This suggests that the products considered in this study are indeed the most conventional and commonly used products in practice. However, there was more variation in the responses for alternative products. For insulation, this can be caused by the large number of materials that can be used as insulation. Füchsl et al. (2022) already identified 29 different insulation materials in their review study. However, it seems that the number of potential products was not the case for the variation in answers of the other measures. Because respondents were more likely to mention modifications to the conventional product rather than new materials or products. More interviews could have been conducted for these alternative products. However, it is unlikely that this would have yielded in different answers as the majority of the respondents found it difficult to answer this question. Therefore, a literature review has been conducted to select the final products from the respondents' answers. This aligns the product selection with practice and previous studies.

The criteria mentioned by the five clients during the second interview differed considerably. It is therefore not possible to state with absolute certainty that the resulting criteria are representative of all clients, e.g. owners of utility buildings who need to select energy-saving packages. However, it was observed that a high prioritisation of financial costs and the energy-saving potential, and a low prioritisation of environmental-related criteria, were similar for the five clients. These findings align with the results of a study that examined the Dutch peoples' attitudes, behaviours, and willingness to change their habits when it comes to climate. It is found that "financial considerations have more influence on behaviour than sustainability considerations or social norms" (Versantvoort et al., 2024, p.10). Therefore, the findings of the interviews can be considered valid.
The survey conducted prior to the brainstorming session was completed by eight employees. The results show similar answers as the clients and are thereby also in line with the findings of Versantvoort et al. (2024).

6. Conclusion

The objective of this study is to calculate the lifecycle GWP and CED of the six most commonly advised energy-saving measures of Antea Group. Additionally, the aim is to find out if clients and employees of Antea Group intend to use the calculated GWP and CED in future projects and how this potentially affects the decision-making process. To achieve these objectives, the following research questions have been answered:

1. What are the GWP and CED over the lifecycle of the conventional and alternative products that are currently being applied in practice for the most commonly advised measures by Antea Group?
2. How can the lifecycle GWP and CED of a measure package be implemented in the energy-saving advice?
3. How will the current prioritisation of criteria for selecting energy-saving measures, according to clients and employees of Antea Group, be affected by the introduction of the GWP and CED?

To answer these questions, an LCA study was conducted for six buildings from the municipality located in Overijssel. In this LCA study, the products of the six most commonly advised measures were selected via interviews and literature research. Lastly, the LCA results were discussed with clients and employees of Antea Group through interviews and a brainstorming session.

The results of this study show that the six most commonly advised measures of Antea Group are insulation, glazing, heat pumps, PV panels, LED lighting, and mechanical ventilation. Insulation is the most commonly advised measure (32% to 42% of all advised measures) and mechanical ventilation comes in sixth place (6% to 10%). The other measures are advised in similar proportions (between 11% and 20% each). The ten interviews about conventional and alternative products of these six measures lead to 26 different products. An overview of the selected products is provided in Table 9. For all these products, the lifecycle based GWP and CED (Appendix C) are determined to answer the first research question. The GWP is found to be between -1% and 16% (average of 7%) of the CED. This means that a high lifecycle energy consumption (CED) leads to a high lifecycle GHG emission (GWP). An exception to this conclusion is PIF insulation where the GWP is 89% of the CED due to a high GWP in the production phase and high CED credits from recycling aluminium foil. Looking at the GWP and CED per lifecycle phase, it can be concluded that the production phase is the most significant for the construction measures (insulation and glazing), while the use phase is the most significant for the installations. Only for PV panels, both the production and use phases are significant. As discussed in the preceding section, this is in line with previous studies.

A sensitivity analysis was conducted, resulting in ranges of the GWP and CED. It was discussed that previous research results for GWP and CED are within these ranges. However, some values may be outside these ranges. This mainly depends on the different goal and scope definitions of the used EPDs. The ranges of this sensitivity analysis are used to transparently compute the GWP and CED for the six buildings. It is found that transitioning from label E to label A or Energy Neutral results in the highest GWP, CED, and financial costs. The lower outcomes of other label steps depend on the selected measures, products, and quantities of the products. Antea Group provides energy-saving advice for existing buildings with fixed dimensions. Furthermore, the energy labels determined by the government are likely to require this study's six examined measures. Consequently, the selected measures and quantities of products for these measures will not differ significantly. It can therefore be concluded that the selection of products becomes important when reducing the GWP and CED in future projects.

To incorporate these GWP and CED impacts into the advice, formats have been provided in Appendix M. In these formats, the GWP and CED impacts are presented as symbols. According to two interviewed clients, this is a more understandable way of presenting the impacts than by using numbers. Furthermore, the current advice includes financial payback periods for each measure package. These are used by four out of five interviewed clients to select the package to be implemented. Therefore, the GWP and CED can be implemented understandably by presenting the payback periods per measure package. With these two options, an answer is provided to the second research question.

To compute these payback periods, the products were selected for each measure. This is done based on three scenarios: the lowest GWP payback period, the lowest CED payback period, and the lowest financial payback period. It appeared that the same products were selected for each scenario in all six buildings (see Table 12).
The results show that only selecting the products with the lowest financial payback periods (scenario 3), leads to the highest GWP and CED impacts and payback periods of all label steps considered in this study. However, this mainly depends in the PIF floor insulation with significantly high GWP and CED impacts, and GWP payback period. Nevertheless, when EPS pearls would have been selected instead of PIF, the GWP and CED impacts and payback periods of all label steps are still the highest for scenario 3. Except for the CED when transitioning from label C to label A. This might be caused by the need for roof insulation only, whereas other label steps require multiple measures. This is a cause for concern, as the five interviewed clients consider financial costs to be the most important criterion for selecting energy-saving measures. Furthermore, during the brainstorming session with the employees of Antea Group, it was concluded that employees tend to focus on the client's demand. This means, a focus on financial costs and energy savings, and thereby a low prioritisation of environmental impacts (ninth out of thirteen for clients, and eighth out of nine for employees).
During the interviews and brainstorming session, the GWP and CED results were presented to find an answer to the third research question. The clients and employees found it challenging to comprehend this information without in-person clarification. However, after clarification, four out of five clients became more aware of the impacts and therefore expressed a willingness to include the GWP and CED as criteria in future projects. However, the financial cost will remain the most important criterion. The employees became aware of their focus on client demand. Consequently, they concluded that they want to initiate discussions on this subject, even if the client does not mention it initially.

This research has shown that adding the GWP and CED payback periods of energy-saving measure packages to the advice would not change the composition of selected measures. Therefore, the energy-saving potential during the use phase of the building does not change compared to the current advice. However, when the GWP and CED impacts and payback periods are available, it is found that clients and employees of Antea Group become more aware of the lifecycle impact of products and thereby the measure packages they select. Clients express confidence in choosing products with lower GWP and CED impacts, and employees want to provide environmental information instead of only focusing on the client's demand, i.e. the lowest financial costs. This indicates that the will to change is present on both sides. However, the financial costs remain important for clients because it should remain within their budget. This can be jeopardising, since selecting only products with the lowest financial costs, results in the highest GWP and CED impacts and payback periods. Therefore, Antea Group needs to keep informing clients about the environmental impact of the products they select. Because awareness is the first step of lifecycle thinking.

7. Recommendation

This study shows that the consideration of lifecycle GWP and CED of products can lead to lower GWP and CED impacts and payback periods of measure packages. Especially for a relatively large label step, such as from label E to label A, or when transitioning to Energy Neutral. Furthermore, it was found that providing information about lifecycle GWP and CED can make clients more aware of lifecycle impacts. This enables them to select alternative products. To put this into practice, recommendations are provided for raising awareness among clients and employees, calculating GWP and CED impacts, and communicating these results to clients.

Currently, many clients do not consider incorporating environmental impacts when selecting measures and products. This is due to unawareness and a primary focus on saving the most energy with the least amount of financial costs. Furthermore, it has been observed that Antea Group advisors tend to prioritise client demand. Consequently, if clients do not initially consider environmental impacts, advisors are unlikely to include it either. To address this issue, **advisors should raise awareness** by explaining lifecycle impacts, LCA calculations, and how a different product selection can reduce the lifecycle impact. It is important to do this **even if the client does not initially request it**. Because, as shown in this study, clients are more likely to choose products with lower GWP and CED impacts after receiving in-person clarification. Even if they were previously unaware of these impacts or did not initially consider them. This can be combined with the innovation project 'kansenkaart' which is a part of the multi-year plan "Blauwdruk".
To raise awareness among clients, **employees need to be educated** first. Therefore, a session can be organised with general information about LCA calculations, how to interpret and use the results, and how to communicate this to clients. This can be organised internally since some employees are already conducting LCA studies. This approach can reduce investment costs and make it more accessible to ask questions than when an external organisation will be employed. Additionally, a concise document containing this information and answers to previously asked questions can be provided to employees as a reference tool. To ensure that all employees are using the same background information when providing explanations to clients, it is recommended that new employees also receive this document.

Once clients have been informed and have agreed to the inclusion of GWP and CED impacts in the advice, Antea Group employees have to perform calculations. However, since LCA calculations can be time-consuming, it may become impractical and costly to perform them for every project. To avoid this, a **database with LCA results** can be created, starting with the LCA results for the most common products of the six most commonly advised measures as calculated in this research. This enables the advisors to perform LCA calculations in a relatively short time, resulting in little extra costs to the client for the energy-saving advice. It is important to note that the values in this research are relatively general. For more specific values, it is necessary to perform LCA calculations from scratch, rather than relying solely on EPD data. However, this may be time-consuming and cost-intensive. Furthermore, only virgin materials are used as input for the LCA study, whereas nowadays materials are more often recycled and reused. The effect of using secondary materials instead of virgin materials on the GWP and CED results can be investigated in future research.
In addition to the 26 products considered in this study, there are other products available and more will be developed in the future. To offer clients a complete overview, it is recommended to **expand the database** with LCA results for those products. In the short term, it is advised to focus on insulation as this is the most commonly advised measure and there are many different insulation materials available on the market. This may also make it easier to find data about these materials. In the long term, newly developed glazing systems or installations can be added to the database. Furthermore, it is important to **keep the database updated** as the data can become outdated.
When employees are familiar with the database, **additional impacts can be added** because there are more impacts than only the GWP and CED. For instance, the 18 midpoint indicators of ReCiPe

(Huijbregts et al., 2017), or information regarding the impact on biodiversity or the contributions to a circular economy. It is important to acknowledge that clients may be unaware of the environmental impacts when selecting products. Therefore, it can be overwhelming when all these impacts are presented simultaneously. Since the energy-saving advice primarily focuses on reducing energy consumption and GHG emissions, clients may find it easier to comprehend the concepts of GWP and CED. This can therefore be seen as the first step in raising awareness and changing the product selection of clients.

When the GWP and CED results have been computed, they can be presented in the advice to the client. To ensure clarity and simplicity, three scenarios have been proposed for the product selection in this study. In these scenarios, only products with the lowest GWP payback period, the lowest CED payback period, or the lowest financial payback period were considered. It is advisable to **use these three scenarios as a basis**. This will reduce time and costs involved in providing the advice. Nevertheless, in practice, clients may request a combination of products. Therefore, it is recommended that, in the short term, an **overview of the GWP and CED results per FU will be included** in the appendix of the advice. This will provide clients with insights into the products they can choose. Visualising these results by using symbols will facilitate their interpretation. The more symbols a product receives for GWP and CED, the less impact it has on the environment, and thus, the more environmentally beneficial the product is to choose. A format of this visualisation is presented in Appendix M. However, it should be noted that **products from different measures cannot be compared** because of the different FU for each measure.
This short-term solution, however, requires the cognitive abilities of clients, along with explanation by employees. In the meantime, a more comprehensive solution can be developed for the long term. This may be presented in the form of a **dashboard**, where clients can modify the products and thereby observe the resulting GWP, CED, and financial costs for the measure packages in real-time. Therefore, only a basic comprehension of lifecycle impacts will be necessary. The visualisations allow clients to identify directly that GWP and CED impacts will increase when selecting the products with the lowest financial costs. Through a process of trial and error, clients will be able to select the product with the least GWP and CED impacts that still fits their budget.

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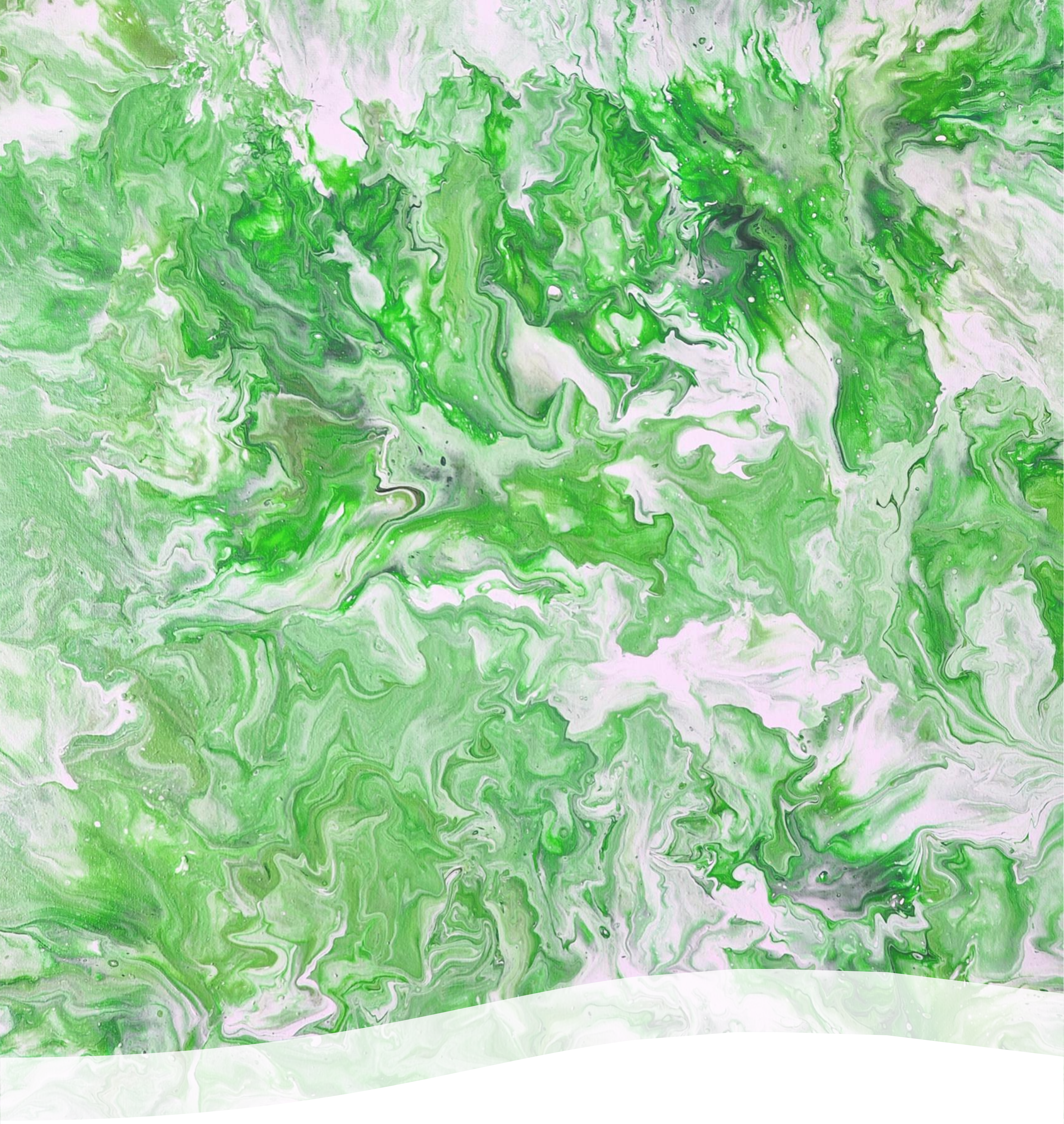

Appendix

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A. Overview of measure categories

The measures of all projects are analysed and divided into eleven categories. The measures that belong to the six most commonly advised measures are presented in Table 1. The measures belonging to the other five categories are presented in Table 2.

Table 1 Corresponding measures of the top six advised measure categories.

Category	Measure	2018	2022
Insulation	Extra insulation roof (flat)	x	x
	Extra insulation roof (non-insulated flat)		x
	Extra insulation roof (slope)	x	x
	Extra insulation floor	x	x
	New floor with extra insulation	x	
	Extra insulation floor (non-insulated)		x
	Extra insulation facade	x	x
	Extra insulation facade (inside)	x	
	Wall insulation	x	
	Insulated pre-walls in front of the facade	x	
	Panel insulation	x	x
	Panel insulation (non-insulated)	x	
	Extra insulation infill panels	x	
	Check insulation cavity wall	x	
	Insulation cavity wall	x	x
	Insulation sheet piling	x	
	Insulation balcony	x	
Glazing	Place HR++ glass	x	
	Single glass to HR++	x	x
	Double glass to HR++ glass	x	x
	Place triple glass	x	
	Single glass to triple glass	x	
	Double glass to triple glass	x	
	HR to HR++ glass	x	x
	HR to triple glass	x	
	HR++ to triple glass	x	
	Triple glass with shading	x	
Heat pump	Place heat pump	x	x
	Heat pump air-air	x	x
	Heat pump tap water	x	x
	Heat pump air-water	x	x
	VRF system	x	x
PV panel	Place PV panels	x	x
Lighting	Replace lighting with LED	x	x
	Replace lighting to LED with presence detection	x	x
Ventilation	Balanced ventilation with heat exchanger	x	x
	Replace mechanical ventilation	x	

Category	Measure	2018	2022
	Balanced ventilation	x	x

Table 2 Corresponding measures of the category 'other measures'.

Category	Measure	2018	2022
Space heating	Low H2O convectors		x
	Central heating installations		x
	Extra floor heating	x	
	Infrared panels	x	
	Pallet kettle	x	
	Split unit air conditioner expires	x	
	District heating	x	
	Remove electric heaters	x	
Tap water heating	Electrical boiler	x	
	Solar boiler	x	
	Close-in boiler	x	
	Replace geyser	x	
	Douche WTW	x	
Special glazing and doors	Closing skylight	x	
	Place monument glass	x	
	Extra insulation up-and-over door	x	
Construction	Place overhang	x	
Swimming pool	New swimming pool pump	x	

B. Conventional and alternative products - interview questions and responses

This appendix presents the interview questions used to collect information about the conventional and alternative products for the six most commonly advised measures. Furthermore, an overview of the respondents (Table 3) and a summary of their answers are provided in

Table 4 to Table 10.

1. What are the most commonly used conventional products used in practice for the following types of energy-saving measures?
    a. Thermal insulation
    b. Glazing
    c. Heat pumps
    d. PV panels
    e. Lighting system
    f. Mechanical ventilation

2. What are (sustainable) alternative products for the following types of energy-saving measures?
    a. Thermal insulation
    b. Glazing
    c. Heat pumps
    d. PV panels
    e. Lighting system
    f. Mechanical ventilation

3. Are these alternatives currently being applied in practice or do you expect this to happen shortly?

Table 3 Overview of respondents for the interview about conventional and alternative products.

Respondent	Intern/extern	Expertise
1	Intern (building and installation)	Determining energy labels and advising energy-saving measures. Expertise in construction and installations.
2	Intern (building and installation)	Expertise in solutions for building constructions.
3	Intern (building and installation)	Manager of sustainability, inspection of buildings, and expertise in solutions for building construction.
4	Intern (building and installation)	Advising clients about building installation. Background in mechanical engineering.
5	Intern (building and installation)	Determining energy labels and advice on energy-saving measures. Expertise in advising installation-related solutions.
6	Intern (city and climate)	Advising energy transition and therefore the implementation of PV panels.
7	Intern (civil engineering)	Background in electrical engineering. Therefore, experience in advising clients about LED lights.
8	Intern (inspections of installations)	Team leader of the inspection group and examiner of PV panel inspections.
9	Extern (lighting company)	Advising Antea Group about LED lighting for utility buildings.
10	Extern (municipality)	Managing, maintaining, and building real estate owned by the municipality.

Table 4 Conventional insulation materials resulting from the interviews.

Type of insulation	Respondent 1	Respondent 2	Respondent 3	Respondent 10
Facade	- Glass wool - Rock wool	- Glass wool - Rock wool	- Glass wool - Rock wool	- PUR foam
Roof	- PUR	- PUR PIR	- PUR	- PIR
Floor	- EPS pearls - PUR foam	- EPS - XPS		- PUR foam

Table 5 Alternative insulation materials resulting from the interviews.

	Respondent 1	Respondent 2	Respondent 3	Respondent 10
Alternative insulation types	- Wood - Hemp	- Denim fibre - Hemp fibre - Flax fibre	- Hemp fibre - Wood fibre / wood wool - Cellulose - Biofoam	- Thermofoam - Hemp fibre

Table 6 Conventional heat pumps and their alternatives resulting from the interviews.

Respondent	Conventional	Alternative
Respondent 1	- Situation cooling and heating at the same time: VRF system or water-water heat pump - Only heating: air-air or air-water	Other refrigerant: Propane or CO2
Respondent 4	- Big installations: water-water - Smaller installations: air-water - Small offices: VRF system	Hybrid heat pump. Therefore, a smaller heat pump can be used as a basis. This can be water-water or air-water. During peak loads, additional heating is provided with a different type of heating system. For example, wood-fired heating
Respondent 5	- Air-water	Other refrigerant: Propane or CO2

Table 7 Conventional glazing systems and their alternatives resulting from the interviews.

Respondent	Conventional	Alternative
Respondent 1	- HR++ (high efficiency) or triple glass - Argon gas between glass layers	- Vacuum glass - Different types of gas
Respondent 2	- If possible, choose triple glass	
Respondent 3	- HR++ (high efficiency)	- Difficult, different types of HR++ exist - Recycled glass is also an option

Table 8 Conventional PV panels and their alternatives resulting from the interviews.

Respondent	Conventional	Alternative
Respondent 1	- Monocrystalline - Polycrystalline	- Preferably not at all because more energy is needed for production than can be generated. Storing energy is important - Different ways of energy generation can be solar collectors
Respondent 6	- Monocrystalline	- Solar cell foil - Solar cell roof tiles
Respondent 8	- Polycrystalline	- Thin film panels
Respondent 10	- Monocrystalline - Polycrystalline	

Table 9 Conventional lighting systems and their alternatives resulting from the interviews.

Respondent	Conventional	Alternative
Respondent 1	LED	- LED + presence detection and daylight sensors
Respondent 4	Armature with LED	- Way of designing: first accent lighting, then mood lighting, latest basic lighting. Because then, fewer armatures are required which saves energy use - Demand-driven light control with sensors
Respondent 7	LED	- No major changes in the development of LED are expected - Therefore, only put lights on when people are present
Respondent 9	LED	- Energy can be saved with dimmers. However, most will be saved by controlling daylight and presence detection - There is no alternative to LED - Old armatures are mostly too old to be reused

Table 10 Conventional mechanical ventilation systems and their alternatives resulting from the interviews.

Respondent	Conventional	Alternative
Respondent 1	- Always mechanical ventilation with heat recovery - Heat wheel, cross-flow exchanger, or twin coil system	- Ventilation controlled by the CO2 level in the room
Respondent 4	- Twin coil only when in and outflow of air are far apart - Cross flow exchanger only when a 100% separated airflow is required - Heat wheel exchanger has the highest efficiency	- Design larger channels. This results in lower air resistance and thereby a lower capacity of the ventilation system. However, more material is required for the channels - Demand-driven control
Respondent 5	- Include heat recovery. Heat wheel has higher efficiency. But cross-flow exchanger is commonly used.	- The profit is in the heat recovery unit and its efficiency. The combination with CO2 control makes it optimal

C. GWP and CED of products - raw results

This appendix presents, the GWP and CED are presented per FU for each product considered in this study with an RSL of 50 years. Table 11 shows the total GWP and CED per product. Furthermore, Table 12 shows the GWP per phase and Table 13 shows the CED per phase. Table 12 and Table 13 are used as input for Figures 14 and 15 in Section 4.3.

Table 11 GWP and CED per FU of all considered products for RSL of 50 years.

Measure	FU	Product	GWP (kg CO2 eq.)	CED (MJ)
Thermal insulation	1 m2 with Rc of 1 m2K/W	Rock wool	8.49	110.43
		Glass wool	1.20	21.86
		Power Insulation Foil (PIF)	199.82	225.33
		PIR	4.81	126.71
		PUR (foam)	12.47	259.82
		EPS (pearls)	2.54	61.01
		Thermofoam	0.64	13.67
		Hemp fibre	1.87	56.49
		Wood fibre	-1.62	145.87
Glazing	1 m2 with Rc of 1 m2K/W	HR++ glass	76.04	484.09
		Triple glass	44.40	282.66
		Vacuum glass	35.72	227.43
Heat pump	1 heat pump with a capacity of 20-70 kW	Air-air heat pump	1,635.97	380,477.37
		Air-water heat pump	1,635.97	380,477.37
		Refrigerator: Propane	1,577.90	366,970.42
		Refrigerator: CO2	2,192.61	509,934.80
PV panel	1 kWp	Monocrystalline	1,482.34	55,421.18
		Polycrystalline	1,001.62	37,448.13
		Thin film panel (CdTe)	432.70	16,177.80
		Thin film panel (CIGS)	712.00	26,620.07
		Thin film panel (A-Si)	1,035.33	38,708.40
Lighting system	1 lamp	LED	1,227.26	33,074.19
		LED + daylight detection	685.99	18,363.38
		LED + presence detection	863.78	23,202.58
Mechanical ventilation	1 ventilation system with heat recovery and a capacity of 1000 m3/h	Heat recovery general	2,204.86	416,690.76
		Heat recovery + CO2 detection	1,812.88	311,295.51
		Heat recovery + presence detection	1,729.96	289,000.36

Table 12 GWP per FU of all considered products for RSL of 50 years presented per lifecycle phase.

GWP - total [kg CO2 eq.]					
Product	**A**	**B**	**C**	**D**	**Total**
Rock wool	8.42	0.00	0.09	-0.02	8.49
Glass wool	1.08	0.00	0.14	-0.02	1.20
Power Insulation Foil (PIF)	222.87	0.00	11.68	-34.72	199.82
PIR	4.57	0.00	0.27	-0.03	4.81
PUR (foam)	11.87	0.00	0.67	-0.07	12.47
EPS (pearls)	2.46	0.00	0.09	0.00	2.54
Thermofoam	0.61	0.00	0.04	0.00	0.64
Hemp fibre	1.78	0.00	0.11	-0.01	1.87
Wood fibre	-8.34	0.00	12.39	-5.67	-1.62
HR++ glass	63.12	4.05	20.65	-11.79	76.04
Triple glass	36.85	2.37	12.06	-6.88	44.40
Vacuum glass	29.65	1.90	9.70	-5.54	35.72
Air-air heat pump	1,084.33	1,205.04	53.82	-707.22	1,635.97
Air-water heat pump	1,084.33	1,205.04	53.82	-707.22	1,635.97
Refrigerator: Propane	1,045.84	1,162.26	51.91	-682.12	1,577.90
Refrigerator: CO2	1,453.28	1,615.05	72.14	-947.86	2,192.61
Monocrystalline	1,203.00	460.00	39.34	-220.00	1,482.34
Polycrystalline	812.87	310.82	26.58	-148.65	1,001.62
Thin film panel (CdTe)	351.16	134.28	11.48	-64.22	432.70
Thin film panel (CIGS)	577.83	220.95	18.90	-105.67	712.00
Thin film panel (A-Si)	840.22	321.28	27.48	-153.66	1,035.33
LED	19.87	1,207.14	1.04	-0.79	1,227.26
LED + daylight detection	18.55	667.21	0.97	-0.74	685.99
LED + presence detection	18.55	845.00	0.97	-0.74	863.78
Heat recovery general	1,149.19	1,507.61	100.79	-552.74	2,204.86
Heat recovery + CO2 detection	1,149.19	1,115.63	100.79	-552.74	1,812.88
Heat recovery + presence detection	1,149.19	1,032.71	100.79	-552.74	1,729.96

Table 13 CED per FU of all considered products for RSL of 50 years presented per lifecycle phase.

Energy use (PERT+PENRT) [MJ]					
Product	**A**	**B**	**C**	**D**	**Total**
Rock wool	109.59	0.00	1.45	-0.61	110.43
Glass wool	22.86	0.00	0.22	-1.22	21.86
Power Insulation Foil (PIF)	768.05	0.00	6.64	-549.36	225.33
PIR	126.19	0.00	2.35	-1.83	126.71
PUR (foam)	258.80	0.00	4.62	-3.60	259.82
EPS (pearls)	60.98	0.00	0.13	-0.10	61.01
Thermofoam	13.62	0.00	0.24	-0.19	13.67
Hemp fibre	56.25	0.00	1.05	-0.82	56.49
Wood fibre	287.80	0.00	-132.98	-8.95	145.87
HR++ glass	938.81	102.81	25.06	-582.59	484.09
Triple glass	548.17	60.03	14.63	-340.17	282.66
Vacuum glass	441.05	48.30	11.77	-273.70	227.43
Air-air heat pump	16,857.69	368,081.18	52.40	-4,513.90	380,477.37
Air-water heat pump	16,857.69	368,081.18	52.40	-4,513.90	380,477.37
Refrigerator: Propane	16,259.24	355,014.30	50.54	-4,353.65	366,970.42
Refrigerator: CO2	22,593.52	493,320.80	70.23	-6,049.75	509,934.80
Monocrystalline	25,140.40	34,000.00	20.78	-3,740.00	55,421.18
Polycrystalline	16,987.39	22,973.83	14.04	-2,527.12	37,448.13
Thin film panel (CdTe)	7,338.64	9,924.82	6.06	-1,091.73	16,177.80
Thin film panel (CIGS)	12,075.51	16,330.98	9.98	-1,796.41	26,620.07
Thin film panel (A-Si)	17,559.08	23,746.98	14.51	-2,612.17	38,708.40
LED	305.61	32,857.14	7.58	-96.14	33,074.19
LED + daylight detection	285.24	18,160.80	7.08	-89.73	18,363.38
LED + presence detection	285.24	23,000.00	7.08	-89.73	23,202.58
Heat recovery general	17,737.95	405,366.36	1,260.69	-7,674.23	416,690.76
Heat recovery + CO2 detection	17,737.95	299,971.10	1,260.69	-7,674.23	311,295.51
Heat recovery + presence detection	17,737.95	277,675.95	1,260.69	-7,674.23	289,000.36

D. Sensitivity analysis - applied values and raw results

A sensitivity analysis has been conducted to find the impact of thermal conductivity coefficients of insulation materials, U-values of glass, and the lifecycles of installations on the GWP and CED. Table 14 presents the minimum and maximum thermal conductivity coefficients of insulation materials. The values of thermofoam are assumed based on the ranges of the other thermal conductivities. In Table 15, the U-values of different glazing systems are provided. The minimum and maximum lifecycles of the installations are presented in Table 16.

Table 14 Thermal conductivity coefficients (λ-values) of insulation materials.

Insulation material	Min. λ-value (W/mK)	Max. λ-value (W/mK)	Initially used λ-value (W/mK)	Source
Rock wool	0.048	0.033	0.038	(Kunič, 2017)
Glass wool	0.045	0.034	0.034	(Kunič, 2017)
PIF	0.045	0.037	0.058	(Soloveva et al., 2022)
PIR	0.028	0.021	0.028	(Gravit et al., 2017)
PUR	0.030	0.022	0.025	(Kunič, 2017)
EPS	0.045	0.034	0.040	(Kunič, 2017)
Thermofoam	0.045	0.031	0.035	Assumption
Hemp fibre	0.041	0.038	0.040	(Lekavicius et al., 2015)
Wood fibre	0.110	0.038	0.050	(Kunič, 2017)

Table 15 U-values of glazing systems (Aguilar-Sanana et al., 2020).

Glazing system	Min. U-value (W/m2K)	Max. U-value (W/m2K)	Initially used U-value (W/m2K)
HR++ glass	1.80	1.20	1.49
Triple glass	1.40	0.70	0.87
Vacuum glass	0.70	0.40	0.70

Table 16 Minimum and maximum lifecycles of installations.

Installation type	Min. lifecycle (y)	Max. lifecycle (y)	Currently used lifecycle (y)	Source
Air-air heat pump	10	20	15	(Saoud et al., 2021)
Air-water heat pump	10	20	15	(Saoud et al., 2021)
Refrigerator: Propane	10	20	15	Assumption based on Saoud et al. (2021)
Refrigerator: CO2	5	15	10	Assumption based on Saoud et al. (2021)
Monocrystalline	25	30	25	(Pastuszak & wegierek 2022; Lunardi et al., 2021)
Polycrystalline	14	30	25	(Pastuszak & wegierek 2022; Lunardi et al., 2021)

Installation type	Min. lifecycle (y)	Max. lifecycle (y)	Currently used lifecycle (y)	Source
Thin film panel (CdTe)	20	30	20	(Pastuszak & wegierek 2022; Lunardi et al., 2021)
Thin film panel (CIGS)	12	30	20	(Pastuszak & wegierek 2022; Lunardi et al., 2021)
Thin film panel (A-Si)	15	30	20	(Pastuszak & wegierek 2022; Lunardi et al., 2021)
LED	6	14	14	(Padmasali & kini, 2020)
LED + daylight detection	8	17	15	(Padmasali & kini, 2020)
LED + presence detection	8	17	15	(Padmasali & kini, 2020)
Heat recovery general	15	25	25	(Violante et al., 2022)
Heat recovery + CO2 detection	20	25	25	Assumption based on Violante et al. (2022)
Heat recovery + presence detection	20	25	25	Assumption based on Violante et al. (2022)

The tables above are used in the sensitivity analysis. The results of this analysis are presented in Table 17 for the GWP and in Table 18 for the CED. Both tables include the initial, minimum, and maximum values, as well as the differences between them. These values are visualised as percentages in Figure 16 in Section 4.4.

Table 17 Minimum and maximum GWP results sensitivity analysis.

Product	Initial GWP (kg CO2 eq.)	Min GWP (kg CO2 eq.)	Max GWP (kg CO2 eq.)	Difference max-min (kg CO2 eq.)	Difference min-initial (kg CO2 eq.)	Difference max-initial (kg CO2 eq.)
Rock wool	8.49	7.37	10.72	3.35	-1.12	2.23
Glass wool	1.20	1.20	1.59	0.39	0.00	0.39
PIF	199.82	185.35	223.95	38.60	-14.48	24.13
PIR	4.81	3.61	4.81	1.20	-1.20	0.00
PUR (foam)	12.47	10.97	14.96	3.99	-1.50	2.49
EPS (pearls)	2.54	2.16	2.86	0.70	-0.38	0.32
Thermofoam	0.64	0.58	0.84	0.26	-0.06	0.20
Hemp fibre	1.87	1.78	1.92	0.14	-0.09	0.05
Wood fibre	-1.62	-1.23	-3.57	-2.34	0.39	-1.95
HR++ glass	76.04	61.24	91.86	30.62	-14.80	15.82
Triple glass	44.40	35.72	71.44	35.72	-8.68	27.05
Vacuum glass	35.72	20.41	35.72	15.31	-15.31	0.00
Air-air heat pump	1,635.97	1,226.98	2,453.96	1,226.98	-408.99	817.99
Air-water heat pump	1,635.97	1,226.98	2,453.96	1,226.98	-408.99	817.99
Refrigerator: Propane	1,577.90	1,183.42	2,366.85	1,183.42	-394.47	788.95
Refrigerator: CO2	2,192.61	1,461.74	4,385.23	2,923.49	-730.87	2,192.61
Monocrystalline	1,482.34	1,235.28	1,482.34	247.06	-247.06	0.00
Polycrystalline	1,133.77	944.80	2,024.58	1,079.78	-188.96	890.82
Thin film panel (CdTe)	502.11	334.74	502.11	167.37	-167.37	0.00

Product	Initial GWP (kg CO2 eq.)	Min GWP (kg CO2 eq.)	Max GWP (kg CO2 eq.)	Difference max-min (kg CO2 eq.)	Difference min-initial (kg CO2 eq.)	Difference max-initial (kg CO2 eq.)
Thin film panel (CIGS)	584.27	389.51	973.78	584.27	-194.76	389.51
Thin film panel (A-Si)	1,144.66	763.10	1,526.21	763.10	-381.55	381.55
LED	1,227.26	1,227.26	2,863.61	1,636.35	0.00	1,636.35
LED + daylight detection	685.99	605.28	1,286.23	680.95	-80.70	600.24
LED + presence detection	863.78	762.16	1,619.58	857.43	-101.62	755.81
Heat recovery general	2,204.86	2,204.86	3,674.77	1,469.91	0.00	1,469.91
Heat recovery + CO2 detection	1,812.88	1,812.88	2,266.10	453.22	0.00	453.22
Heat recovery + presence detection	1,729.96	1,729.96	2,162.45	432.49	0.00	432.49

Table 18 Minimum and maximum CED results sensitivity analysis.

Product	Initial CED (MJ)	Min CED (MJ)	Max CED (MJ)	Difference max-min (MJ)	Difference min-initial (MJ)	Difference max-initial (MJ)
Rock wool	110.43	95.90	139.49	43.59	-14.53	29.06
Glass wool	21.86	21.86	28.93	7.07	0.00	7.07
PIF (CED)	225.33	216.88	239.43	22.55	-8.46	14.09
PIR	126.71	95.03	126.71	31.68	-31.68	0.00
PUR (foam)	259.82	228.64	311.78	83.14	-31.18	51.96
EPS (pearls)	61.01	51.86	68.63	16.78	-9.15	7.63
Thermofoam	13.67	12.43	18.04	5.61	-1.24	4.37
Hemp fibre	56.49	53.66	57.90	4.24	-2.82	1.41
Wood fibre	145.87	110.86	320.92	210.06	-35.01	175.05
HR++ glass	484.09	389.87	584.81	194.94	-94.22	100.72
Triple glass	282.66	227.43	454.85	227.43	-55.23	172.19
Vacuum glass	227.43	129.96	227.43	97.47	-97.47	0.00
Air-air heat pump	380,477.37	285,358.03	570,716.06	285,358.03	-95119.34	190,238.69
Air-water heat pump	380,477.37	285,358.03	570,716.06	285,358.03	-95119.34	190,238.69
Refrigerator: Propane	366,970.42	275,227.82	550,455.64	275,227.82	-91742.61	183,485.21
Refrigerator: CO2	509,934.80	339,956.53	1,019,869.59	679,913.06	-169978.27	509,934.80
Monocrystalline	55,421.18	46,184.31	55,421.18	9,236.86	-9236.86	0.00
Polycrystalline	37,448.13	31,206.78	66,871.66	35,664.89	-6241.36	29,423.53
Thin film panel (CdTe)	16,177.80	10,785.20	16,177.80	5,392.60	-5392.60	0.00

Product	Initial CED (MJ)	Min CED (MJ)	Max CED (MJ)	Difference max-min (MJ)	Difference min-initial (MJ)	Difference max-initial (MJ)
Thin film panel (CIGS)	26,620.07	17,746.71	44,366.78	26,620.07	-8873.36	17,746.71
Thin film panel (A-Si)	38,708.40	25,805.60	51,611.21	25,805.60	-12902.80	12,902.80
LED	33,074.19	33,074.19	77,173.12	44,098.93	0.00	44,098.93
LED + daylight detection	18,363.38	16,202.98	34,431.34	18,228.36	-2160.40	16,067.96
LED + presence detection	23,202.58	20,472.87	43,504.84	23,031.97	-2729.72	20,302.26
Heat recovery general	416,690.76	416,690.76	694,484.60	277,793.84	0.00	277,793.84
Heat recovery + CO2 detection	311,295.51	311,295.51	389,119.39	77,823.88	0.00	77,823.88
Heat recovery + presence detection	289,000.36	289,000.36	361,250.45	72,250.09	0.00	72,250.09

A second sensitivity analysis has been conducted for the financial payback periods. The gas and electricity prices for calculating the saved costs per product are presented in Table 19. These prices are based on the increased gas and electricity prices (e.g. 54% and 51% respectively) of (CBS, 2024).

Table 19 Gas and electricity prices used for the sensitivity analysis.

	Initial costs (€)	Minimum costs (€)	Maximum costs (€)
Gas price	1.50	0.69	2.31
Electricity price	0.27	0.13	0.41

The results of the sensitivity analysis are the initial, minimum, and maximum financial payback periods as presented in Table 20. These values are visualised Figure 17 in Section 4.5.1.

Table 20 Results of sensitivity analysis including the initial, minimum, and maximum financial payback periods.

Measure	Product	Min. financial payback time (y)	Initial financial payback time (y)	Max. financial payback time (y)
Insulation cavity	PUR foam	3.2	5.0	10.8
	Thermofoam	3.4	5.3	11.5
	EPS pearls	3.7	5.7	12.5
Insulation facade	PUR foam	16.2	25.0	54.3
	Thermofoam	17.1	26.4	57.3
	Rock wool	21.7	33.5	72.7
	Glass wool	21.7	33.5	72.7
	Wood fibre	25.3	38.9	84.6
	Hemp fibre	25.6	39.5	85.8
Insulation floor	PIF	2.3	3.5	7.6
	EPS pearls	2.9	4.5	9.8
	PUR foam	3.0	4.6	10.0

Measure	Product	Min. financial payback time (y)	Initial financial payback time (y)	Max. financial payback time (y)
Insulation roof	PIR	6.7	10.4	22.6
	EPS	10.7	16.5	35.9
	Wood fibre	10.7	16.5	35.9
Glazing	Triple glass	22.9	35.2	76.6
	HR++ glass	25.7	39.6	86.0
	Vacuum glass	32.8	50.5	109.9
Heat pump	air-air heat pump	5.9	9.2	20.1
	air-water heat pump	5.9	9.2	20.1
	Refrigerant: Propane	7.9	12.2	26.7
	Refrigerant: CO2	7.9	12.2	26.7
Ventilation system	Heat recovery general	20.6	31.9	70.2
	Heat recovery + CO2 detection	27.8	43.0	94.7
	Heat recovery + presence detection	27.8	43.0	94.7
Solar panels	Thin film panel (CdTe)	0.7	1.1	2.2
	Thin film panel (A-Si)	0.8	1.2	2.5
	Thin film panel (CIGS)	0.9	1.4	2.8
	Poly crystalline	0.9	1.4	2.8
	Mono crystalline	1.0	1.6	3.2
Lighting	LED	6.3	9.5	19.1
	LED + daylight detection	11.9	17.9	36.0
	LED + presence detection	12.1	18.1	36.4

E. Financial costs per product

To determine the financial investment costs of the measures and packages, the prices per product as presented in Table 21 are applied.

Table 21 Financial costs per product.

Measure	Product	Costs (€)	Unit	Source
Insulation cavity	PUR foam	€ 163.31	m2	(RVO, n.d.)
	Thermofoam	€ 172.46	m2	(RVO, n.d.)
	EPS pearls	€ 187.74	m2	(RVO, n.d.)
Insulation facade	Rock wool	€ 218.87	m2	(RVO, n.d.)
	Glass wool	€ 218.87	m2	(RVO, n.d.)
	PUR foam	€ 163.31	m2	(RVO, n.d.)
	Thermofoam	€ 172.46	m2	(RVO, n.d.)
	Hemp fibre	€ 258.27	m2	(RVO, n.d.)
	Wood fibre	€ 254.62	m2	(RVO, n.d.)
Insulation floor	PIF	€ 41.30	m2	(TONZON, n.d.)
	PUR foam	€ 54.03	m2	(RVO, n.d.)
	EPS pearls	€ 53.07	m2	(RVO, n.d.)
Insulation roof	PIR	€ 160.22	m2	(RVO, n.d.)
	EPS	€ 254.74	m2	(RVO, n.d.)
	Wood fibre	€ 254.62	m2	(RVO, n.d.)
Glazing	HR++ glass	€ 771.22	m2	(RVO, n.d.)
	Triple glass	€ 684.52	m2	(RVO, n.d.)
	Vacuum glass	€ 983.76	m2	(RVO, n.d.)
Heat pump	air-air heat pump	€ 126,495.95	piece	(RVO, n.d.)
	air-water heat pump	€ 126,495.95	piece	(RVO, n.d.)
	Refrigerant: Propane	€ 168,239.61	piece	(RVO, n.d.)
	Refrigerant: CO2	€ 168,239.61	piece	(RVO, n.d.)
Ventilation system	Heat recovery general	€ 87,263.44	piece	(RVO, n.d.)
	Heat recovery + CO2 detection	€ 117,635.97	piece	(RVO, n.d.)
	Heat recovery + presence detection	€ 117,635.97	piece	Assumption based on heat recovery + CO2 detection
PV panels	Monocrystalline	€ 1,612.75	kWp	(RVO, n.d.)
	Polycrystalline	€ 1,419.22	kWp	Assumption based on Monocrystalline
	Thin film panel (CdTe)	€ 1,128.48	kWp	Assumption based on Monocrystalline
	Thin film panel (CIGS)	€ 1,410.60	kWp	(RVO, n.d.)
	Thin film panel (A-Si)	€ 1,269.54	kWp	Assumption based on CIGS and CdTe
Lighting	LED	€ 236.25	lamp	(RVO, n.d.)
	LED + daylight detection	€ 444.69	lamp	(RVO, n.d.)
	LED + presence detection	€ 449.72	lamp	(RVO, n.d.)

F. Packages, measures, and optional products per building

The six buildings have multiple measure packages represented by different energy labels. The measures included in each package are shown in Table 22. For each measure, different products can be selected. An overview of these products is provided in Table 23.

Table 22 Measures included in the packages per building. C=label C, B=label B, A=label A, EN=Energy Neutral.

	Building 1			Building 2			Building 3			Building 4		Building 5		Building 6	
	C	**A**	**EN**	**C**	**A**	**EN**	**B**	**A**	**EN**	**A**	**EN**	**A**	**EN**	**A**	**EN**
Insulation cavity	x			x											
Insulation facade		x	x		x	x			x		x		x		x
Insulation floor	x	x	x	x	x	x		x	x		x		x		x
Insulation roof		x	x		x	x	x	x	x	x	x	x	x	x	x
Glazing			x			x		x	x		x		x		
Heat pump			x			x			x		x		x		x
Solar panels			x			x			x		x		x		x
Lighting		x	x	x	x	x			x						
Ventilation system			x			x			x		x		x		x

Table 23 Optional products per measure.

Measure	Product
Insulation cavity	PUR foam
	Thermofoam
	EPS pearls
Insulation facade	Rock wool
	Glass wool
	PUR foam
	Thermofoam
	Hemp fibre
	Wood fibre
Insulation floor	PIF
	PUR foam
	EPS pearls
Insulation roof	PIR
	EPS
	Wood fibre
Glazing	HR++ glass
	Triple glass
	Vacuum glass
Heat pump	air-air heat pump
	air-water heat pump
	Refrigerant: Propane
	Refrigerant: CO2

Measure	Product
Ventilation system	Heat recovery general
	Heat recovery + CO2 detection
	Heat recovery + presence detection
PV panels	Monocrystalline
	Polycrystalline
	Thin film panel (CdTe)
	Thin film panel (CIGS)
	Thin film panel (A-Si)
Lighting	LED
	LED + daylight detection
	LED + presence detection

G. Case study results - example of building 3 to achieve label A

The GWP, CED, and financial costs are calculated per building by multiplying the quantity of the product by the impact or financial costs of the product per FU. These LCA results are presented in Table 24, which only includes building 3 (initial label D) to achieve label A. The measures of the other buildings and packages can be calculated as explained with the GWP and CED impact ranges as presented in Appendix D and the financial costs as provided in Appendix E. The product quantities and measures per package of each building are provided in Appendices H and F respectively.

Table 24 GWP, CED, and financial costs of the measures in Label A at building 3 (initial label D).

Package	Measure	Product	Quantity	Unit	Total GWP [kg CO2 eq.]			Total CED [MJ]			Financial costs [€]
					Min	Initial	Max	Min	Initial	Max	
Label A	Insulation floor	PIF	442.5	m²	410,079.25	442,105.74	495,483.23	479,842.51	498,549.83	529,728.69	€ 18,275.25
		PUR foam	442.5	m²	24,273.75	27,583.81	33,100.57	505,866.20	574,847.96	689,817.55	€ 23,909.84
		EPS pearls	442.5	m²	4,778.01	5,621.19	6,323.84	114,730.33	134,976.86	151,848.96	€ 23,482.30
	Insulation roof	PIR	439.6	m²	7,934.46	10,579.28	10,579.28	208,885.46	278,513.94	278,513.94	€ 70,430.93
		EPS	439.6	m²	4,746.70	5,584.35	6,282.40	113,978.42	134,092.26	150,853.80	€ 111,985.00
		Wood fibre	439.6	m²	-2,709.06	-3,564.56	-7,842.03	243,676.23	320,626.61	705,378.55	€ 111,929.65
	Glazing (initial single)	HR++ glass	34.9	m²	1,431.92	1,777.96	2,147.88	9,116.38	11,319.50	13,674.56	€ 26,915.40
		Triple glass	34.9	m²	1,433.70	1,781.88	2,867.40	9,127.71	11,344.45	18,255.43	€ 23,889.75
		Vacuum glass	34.9	m²	1,018.73	1,782.77	1,782.77	6,485.78	11,350.11	11,350.11	€ 34,333.22
	Glazing (initial double)	HR++ glass	19.5	m²	800.07	993.42	1,200.10	5,093.68	6,324.65	7,640.52	€ 15,038.69
		Triple glass	19.5	m²	801.06	995.61	1,602.13	5,100.01	6,338.59	10,200.03	€ 13,348.14
		Vacuum glass	19.5	m²	569.20	996.11	996.11	3,623.86	6,341.75	6,341.75	€ 19,183.32
	Glazing (entrance)	HR++ glass	11.1	m²	455.42	565.48	683.14	2,899.48	3,600.18	4,349.22	€ 8,560.49
		Triple glass	11.1	m²	455.99	566.73	911.98	2,903.08	3,608.12	5,806.17	€ 7,598.17
		Vacuum glass	11.1	m²	324.01	567.01	567.01	2,062.81	3,609.92	3,609.92	€ 10,919.74

Table 25 presents the payback periods of building 3 (initial label D) to achieve label A. The GWP, CED, and financial savings are calculated based on the Vabi results. The formulas for calculating the payback periods are provided in Section 3.5 of the Methodology.

Table 25 GWP, CED, and financial savings and payback periods of the measures in Label A at building 3 (initial label D).

Package	Measure	Product	Savings			Payback period [y]								
			GWP [kg CO2 eq./y]	CED [MJ/y]	Costs [€/y]	Min GWP	Initial GWP	Max GWP	Min CED	Initial CED	Max CED	Min fin*	Initial fin*	Max fin*
Label A	Insulation floor	PIF	2,098.77	35,188.68	5,091.75	195.39	210.65	236.08	13.64	14.17	15.05	3.6	7.8	2.3
		PUR foam	2,098.77	35,188.68	5,091.75	11.57	13.14	15.77	14.38	16.34	19.60	4.7	10.2	3.0
		EPS pearls	2,098.77	35,188.68	5,091.75	2.28	2.68	3.01	3.26	3.84	4.32	4.6	10.0	3.0
	Insulation roof	PIR	2,981.61	49,990.63	7,233.57	2.66	3.55	3.55	4.18	5.57	5.57	9.7	21.2	6.3
		EPS	2,981.61	49,990.63	7,233.57	1.59	1.87	2.11	2.28	2.68	3.02	15.5	33.7	10.1
		Wood fibre	2,981.61	49,990.63	7,233.57	-0.91	-1.20	-2.63	4.87	6.41	14.11	15.5	33.6	10.0
	Glazing (initial single)	HR++ glass	912.63	15,301.40	2,214.09	1.57	1.95	2.35	0.60	0.74	0.89	12.2	26.4	7.9
		Triple glass	912.63	15,301.40	2,214.09	1.57	1.95	3.14	0.60	0.74	1.19	10.8	23.5	7.0
		Vacuum glass	912.63	15,301.40	2,214.09	1.12	1.95	1.95	0.42	0.74	0.74	15.5	33.7	10.1
	Glazing (initial double)	HR++ glass	159.78	2,678.88	387.63	5.01	6.22	7.51	1.90	2.36	2.85	38.8	84.3	25.2
		Triple glass	159.78	2,678.88	387.63	5.01	6.23	10.03	1.90	2.37	3.81	34.4	74.9	22.4
		Vacuum glass	159.78	2,678.88	387.63	3.56	6.23	6.23	1.35	2.37	2.37	49.5	107.6	32.1
	Glazing (entrance)	HR++ glass	102.91	1,725.38	249.66	4.43	5.50	6.64	1.68	2.09	2.52	34.3	74.5	22.3
		Triple glass	102.91	1,725.38	249.66	4.43	5.51	8.86	1.68	2.09	3.37	30.4	66.2	19.8
		Vacuum glass	102.91	1,725.38	249.66	3.15	5.51	5.51	1.20	2.09	2.09	43.7	95.1	28.4

**fin = financial*

H. Second functional unit - reference flows per building

The second FU in this study is the measures required for a building to reach energy label A or Energy Neutral. The reference flows for this FU are presented for each building in Table 26 for energy label A and in Table 27 for Energy Neutral.

Table 26 Reference flows for buildings to reach energy label A.

Building	Initial label	Reference flow		
		Measure	Quantity	Unit
Building 1	E	Insulation facade	423.1	m^2
		Insulation floor	455.0	m^2
		Insulation roof	452.6	m^2
		Lighting (changing room and entrance)	20.0	pieces
		Lighting (sport function)	49.0	pieces
Building 2	E	Insulation facade	423.0	m^2
		Insulation floor	455.0	m^2
		Insulation roof	452.6	m^2
		Lighting (changing room and entrance)	20.0	pieces
		Lighting (sport function)	49.0	pieces
Building 3	D	Insulation floor	442.5	m^2
		Insulation roof	439.6	m^2
		Glazing (initial single)	34.9	m^2
		Glazing (initial double)	19.5	m^2
		Glazing (entrance)	11.1	m^2
Building 4	C	Insulation roof	439.6	m^2
Building 5	C	Insulation roof	439.6	m^2
Building 6	C	Insulation roof	439.6	m^2

Table 27 Reference flows for buildings to reach energy label Energy Neutral

Building	Initial label	Reference flow		
		Measure	Quantity	Unit
Building 1	E	Insulation facade	423.1	m^2
		Insulation floor	455.0	m^2
		Insulation roof	452.6	m^2
		Glazing (sport function)	48.5	m^2
		Glazing (entrance)	3.6	m^2
		Glazing (changing room)	97.0	m^2
		Heat pump (changing room)	1.0	pieces
		Heat pump (sport function)	1.0	pieces
		Heat pump (tap water)	1.0	pieces
		Ventilation system (changing room)	1.0	pieces
		Ventilation system (sport function)	1.0	pieces
		Solar panels	16.7	kWp
		Lighting (changing room and entrance)	20.0	pieces
		Lighting (sport function)	49.0	pieces

Building	Initial label	Reference flow		
		Measure	Quantity	Unit
Building 2	E	Insulation facade	423.0	m²
		Insulation floor	455.0	m²
		Insulation roof	452.6	m²
		Glazing (initial double)	109.0	m²
		Heat pump (changing room)	1.0	pieces
		Heat pump (sport function)	1.0	pieces
		Heat pump (tap water)	50.0	kW
		Ventilation system (changing room)	1.0	pieces
		Ventilation system (sport function)	1.0	pieces
		Solar panels	15.7	kWp
		Lighting (changing room and entrance)	20.0	pieces
		Lighting (sport function)	49.0	pieces
Building 3	D	Insulation facade	450.1	m²
		Insulation floor	442.5	m²
		Insulation roof	439.6	m²
		Glazing (initial single)	20.0	m²
		Glazing (initial double)	35.0	m²
		Glazing (entrance)	11.0	m²
		Heat pump (sport function)	1.0	pieces
		Heat pump (changing room)	1.0	pieces
		Heat pump (tap water)	1.0	pieces
		Ventilation system (sport function)	1.0	pieces
		Ventilation system (changing room)	1.0	pieces
		Solar panels	10.8	kWp
		Lighting (changing room and entrance)	20.0	pieces
		Lighting (sport function)	49.0	pieces
Building 4	C	Insulation facade	400.0	m²
		Insulation floor	442.5	m²
		Insulation roof	439.6	m²
		Glazing (initial double)	98.0	m²
		Glazing (entrance)	2.9	m²
		Glazing (entrance)	1.0	pieces
		Heat pump (changing room)	1.0	pieces
		Heat pump (tap water)	1.0	pieces
		Ventilation system	1.0	pieces
		Solar panels	11.4	kWp
Building 5	C	Insulation facade	400.0	m²
		Insulation floor	442.5	m²
		Insulation roof	439.6	m²
		Glazing (sport function)	98.1	m²
		Glazing (changing room)	2.9	m²
		Glazing (entrance)	11.1	m²
		Heat pump (sport function)	1.0	pieces
		Heat pump (changing room)	1.0	pieces

Building	Initial label	Reference flow		
		Measure	**Quantity**	**Unit**
		Heat pump (tap water)	1.0	pieces
		Ventilation system (sport function)	1.0	pieces
		Ventilation system (changing room)	1.0	pieces
		Solar panels	11.4	kWp
Building 6	C	Insulation facade	400.0	m²
		Insulation floor	442.5	m²
		Insulation roof	439.6	m²
		Heat pump (sport function)	30.5	kW
		Heat pump (changing room)	30.5	kW
		Heat pump (tap water)	50.0	kW
		Ventilation system (sport function)	1,600.0	m3
		Ventilation system (changing room)	480.0	m3
		Solar panels	9.3	kWp

I. Selected products per scenario

Products should be selected to compute the GWP and CED impact per measure package. These products are selected based on three scenarios:

- Scenario 1: the product of a measure with the lowest GWP payback period
- Scenario 2: the product of a measure with the lowest CED payback period
- Scenario 3: the product of a measure with the lowest financial payback period

In this appendix, the selected products per scenario are provided in Table 30 to Table 29 for the six different buildings.

Table 28 Selected products for each measure of building 1.

Building 1	Measure	Min. GWP payback period	Min. CED payback period	Min. financial payback period
Label C	Insulation cavity	Thermofoam	Thermofoam	PUR foam
	Insulation floor	EPS pearls	PIF	PIF
Label A	Insulation façade	Wood fibre	Thermofoam	PUR foam
	Insulation floor	EPS pearls	EPS pearls	PIF
	Insulation roof	Wood fibre	EPS	PIR
	Lighting (changing room and entrance)	LED + daylight detection	LED + daylight detection	LED
	Lighting (sport function)	LED + daylight detection	LED + daylight detection	LED
Energy Neutral	Insulation façade	Wood fibre	Thermofoam	PUR foam
	Insulation floor	EPS pearls	EPS pearls	PIF
	Insulation roof	Wood fibre	EPS	PIR
	Glazing (sport function)	HR++ glass	HR++ glass	Triple glass
	Glazing (entrance)	HR++ glass	HR++ glass	Triple glass
	Glazing (changing room)	HR++ glass	HR++ glass	Triple glass
	Heat pump (changing room)	Refrigerant: Propane	Refrigerant: Propane	air-air heat pump
	Heat pump (sport function)	Refrigerant: Propane	Refrigerant: Propane	air-air heat pump
	Heat pump (tap water)	Refrigerant: Propane	Refrigerant: Propane	air-air heat pump
	Ventilation system (changing room)	Heat recovery + presence detection	Heat recovery + presence detection	Heat recovery general
	Ventilation system (sport function)	Heat recovery + presence detection	Heat recovery + presence detection	Heat recovery general
	PV panels	Thin film panel (CdTe)	Thin film panel (CdTe)	Thin film panel (CdTe)

Building 1	Measure	Min. GWP payback period	Min. CED payback period	Min. financial payback period
	Lighting (changing room and entrance)	LED + daylight detection	LED + daylight detection	LED
	Lighting (sport function)	LED + daylight detection	LED + daylight detection	LED

Table 29 Selected products for each measure of building 2.

Building 2	Measure	Min. GWP payback period	Min. CED payback period	Min. financial payback period
Label B	Insulation cavity	Thermofoam	Thermofoam	PUR foam
	Insulation floor	EPS pearls	EPS pearls	PIF
	Lighting (changing room and entrance)	LED + daylight detection	LED + daylight detection	LED
	Lighting (sport function)	LED + daylight detection	LED + daylight detection	LED
Label A	Insulation façade	Wood fibre	Thermofoam	PUR foam
	Insulation floor	EPS pearls	EPS pearls	PIF
	Insulation roof	Wood fibre	EPS	PIR
	Lighting (changing room and entrance)	LED + daylight detection	LED + daylight detection	LED
	Lighting (sport function)	LED + daylight detection	LED + daylight detection	LED
Energy Neutral	Insulation façade	Wood fibre	Thermofoam	PUR foam
	Insulation floor	EPS pearls	EPS pearls	PIF
	Insulation roof	Wood fibre	EPS	PIR
	Glazing	HR++ glass	HR++ glass	Triple glass
	Heat pump (changing room)	Refrigerant: Propane	Refrigerant: Propane	air-air heat pump
	Heat pump (sport function)	Refrigerant: Propane	Refrigerant: Propane	air-air heat pump
	Heat pump (tap water)	Refrigerant: Propane	Refrigerant: Propane	air-air heat pump
	Ventilation system (changing room)	Heat recovery + presence detection	Heat recovery + presence detection	Heat recovery general
	Ventilation system (sport function)	Heat recovery + presence detection	Heat recovery + presence detection	Heat recovery general
	PV panels	Thin film panel (CdTe)	Thin film panel (CdTe)	Thin film panel (CdTe)
	Lighting (changing room and entrance)	LED + daylight detection	LED + daylight detection	LED

Building 2	Measure	Min. GWP payback period	Min. CED payback period	Min. financial payback period
	Lighting (sport function)	LED + daylight detection	LED + daylight detection	LED

Table 30 Selected products for each measure of building 3.

Building 3	Measure	Min. GWP payback period	Min. CED payback period	Min. financial payback period
Label B	Insulation roof	Wood fibre	EPS	PIR
Label A	Insulation floor	EPS pearls	EPS pearls	PIF
	Insulation roof	Wood fibre	EPS	PIR
	Glazing (initial single)	HR++ glass	HR++ glass	Triple glass
	Glazing (initial double)	HR++ glass	HR++ glass	Triple glass
	Glazing (entrance)	HR++ glass	HR++ glass	Triple glass
Energy Neutral	Insulation facade	Wood fibre	Thermofoam	PUR foam
	Insulation floor	EPS pearls	EPS pearls	PIF
	Insulation roof	Wood fibre	EPS	PIR
	Glazing (initial single)	HR++ glass	HR++ glass	Triple glass
	Glazing (initial double)	HR++ glass	HR++ glass	Triple glass
	Glazing (entrance)	HR++ glass	HR++ glass	Triple glass
	Heat pump (sport function)	Refrigerant: propane	Refrigerant: propane	Heat pump air-air / air-water
	Heat pump (changing room)	Refrigerant: propane	Refrigerant: propane	Heat pump air-air / air-water
	Heat pump (tap water)	Refrigerant: propane	Refrigerant: propane	Heat pump air-air / air-water
	Ventilation system (sport function)	Heat recovery + presence detection	Heat recovery + presence detection	Heat recovery general
	Ventilation system (changing room)	Heat recovery + presence detection	Heat recovery + presence detection	Heat recovery general
	PV panels	Thin film panel (CdTe)	Thin film panel (CdTe)	Thin film panel (CdTe)
	Lighting (changing room and entrance)	LED + daylight detection	LED + daylight detection	LED
	Lighting (sport function)	LED + daylight detection	LED + daylight detection	LED

Table 31 Selected products for each measure of building 4.

Building 4	Measure	Min. GWP payback period	Min. CED payback period	Min. financial payback period
Label A	Insulation roof	Wood fibre	EPS	PIR
Energy Neutral	Insulation façade	Wood fibre	Thermofoam	PUR foam
	Insulation floor	EPS pearls	EPS pearls	PIF
	Insulation roof	Wood fibre	EPS	PIR
	Glazing (initial double)	HR++ glass	HR++ glass	Triple glass
	Glazing (entrance)	HR++ glass	HR++ glass	Triple glass
	Heat pump (sport function)	Refrigerant: Propane	Refrigerant: Propane	air-air heat pump
	Heat pump (changing room)	Refrigerant: Propane	Refrigerant: Propane	air-air heat pump
	Heat pump (tap water)	Refrigerant: Propane	Refrigerant: Propane	air-air heat pump
	Ventilation system	Heat recovery + presence detection	Heat recovery + presence detection	Heat recovery general
	PV panels	Thin film panel (CdTe)	Thin film panel (CdTe)	Thin film panel (CdTe)

Table 32 Selected products for each measure of building 5.

Building 5	Measure	Min. GWP payback period	Min. CED payback period	Min. financial payback period
Label A	Insulation roof	Wood fibre	EPS	PIR
Energy Neutral	Insulation façade	Wood fibre	Thermofoam	PUR foam
	Insulation floor	EPS pearls	EPS pearls	PIF
	Insulation roof	Wood fibre	EPS	PIR
	Glazing (sport function)	HR++ glass	HR++ glass	Triple glass
	Glazing (changing room)	HR++ glass	HR++ glass	Triple glass
	Glazing (entrance)	HR++ glass	HR++ glass	Triple glass
	Heat pump (sport function)	Refrigerant: Propane	Refrigerant: Propane	air-air heat pump
	Heat pump (changing room)	Refrigerant: Propane	Refrigerant: Propane	air-air heat pump
	Heat pump (tap water)	Refrigerant: Propane	Refrigerant: Propane	air-water heat pump
	Ventilation system (sport function)	Heat recovery + presence detection	Heat recovery + presence detection	Heat recovery general

Building 5	Measure	Min. GWP payback period	Min. CED payback period	Min. financial payback period
	Ventilation system (changing room)	Heat recovery + presence detection	Heat recovery + presence detection	Heat recovery general
	PV panels	Thin film panel (CdTe)	Thin film panel (CdTe)	Thin film panel (CdTe)

Table 33 Selected products for each measure of building 6.

Building 6	Measure	Min. GWP payback period	Min. CED payback period	Min. financial payback period
Label A	Insulation roof	Wood fibre	EPS	PIR
Energy Neutral	Insulation façade	Wood fibre	Thermofoam	PUR foam
	Insulation floor	EPS pearls	EPS pearls	PIF
	Insulation roof	Wood fibre	EPS	PIR
	Heat pump (sport function)	Refrigerant: Propane	Refrigerant: Propane	air-air heat pump
	Heat pump (changing room)	Refrigerant: Propane	Refrigerant: Propane	air-air heat pump
	Heat pump (tap water)	Refrigerant: Propane	Refrigerant: Propane	air-air heat pump
	Ventilation system (sport function)	Heat recovery + presence detection	Heat recovery + presence detection	Heat recovery general
	Ventilation system (changing room)	Heat recovery + presence detection	Heat recovery + presence detection	Heat recovery general
	PV panels	Thin film panel (CdTe)	Thin film panel (CdTe)	Thin film panel (CdTe)

J. Case study results - measure packages

In this appendix, the GWP, CED, and financial costs (investment), savings, and payback periods are presented for the energy labels A and Energy Neutral (EN) for all six buildings.

Table 34 GWP, CED and financial costs for the energy labels A and Energy Neutral for the six buildings.

Building	Label	Scenario	Investment						
			GWP min GWP (CO2 eq.)	GWP initial GWP (CO2 eq.)	GWP max GWP (CO2 eq.)	CED min (MJ)	CED initial (MJ)	CED max (MJ)	Financial costs (€)
Building 1 Label E	Label A	Sc.1	40,723.23	45,278.51	78,015.93	1,771,565.95	2,110,585.16	4,082,289.55	277,797.04
		Sc.2	53,770.12	61,363.09	104,796.75	1,403,093.47	1,600,451.80	2,756,452.54	243,092.54
		Sc.3	539,356.91	578,720.68	751,788.95	3,517,280.09	3,688,498.41	6,873,312.98	176,703.08
	EN	Sc.1	59,579.45	69,591.63	107,175.82	3,417,430.01	4,131,145.66	6,813,647.18	1,151,621.59
		Sc.2	72,626.34	85,676.21	133,956.64	3,048,957.53	3,621,012.29	5,487,810.18	1,116,917.09
		Sc.3	559,339.20	604,212.56	787,429.74	5,459,179.26	6,015,282.35	10,378,149.31	851,625.35
Building 2 Label E	Label A	Sc.1	40,706.10	45,255.97	77,966.34	1,773,106.94	2,112,612.78	4,086,750.31	278,382.66
		Sc.2	53,800.93	61,399.35	104,837.49	1,403,833.97	1,601,323.46	2,757,431.82	243,686.68
		Sc.3	539,403.40	578,783.76	751,850.78	3,518,534.27	3,690,193.16	6,874,981.74	177,071.27
	EN	Sc.1	57,582.31	67,024.10	104,156.21	3,397,711.11	4,103,989.41	6,786,218.12	1,120,153.01
		Sc.2	70,677.14	83,167.49	131,027.36	3,028,438.15	3,592,700.08	5,456,899.63	1,085,457.03
		Sc.3	557,403.64	601,726.15	783,694.82	5,439,160.52	5,987,764.57	10,342,664.85	823,415.80
Building 3 Label D	Label A	Sc.1	4,756.36	5,393.50	2,512.93	375,516.08	476,847.80	882,891.81	185,926.53
		Sc.2	12,212.12	14,542.41	16,637.35	245,818.28	290,313.45	328,367.06	185,981.88
		Sc.3	420,704.46	456,029.25	511,444.02	705,858.78	798,354.92	842,504.26	133,542.24
	EN	Sc.1	54,506.00	62,824.35	100,247.17	3,286,141.01	3,948,715.55	6,558,126.36	1,083,374.35
		Sc.2	66,041.92	77,059.60	124,297.29	2,934,922.36	3,464,661.34	5,321,984.69	1,046,449.93
		Sc.3	541,953.39	583,677.15	763,122.85	5,341,641.91	5,847,821.79	10,200,268.41	789,534.86

Building	Label	Scenario	Investment						
			GWP min GWP (CO2 eq.)	GWP initial GWP (CO2 eq.)	GWP max GWP (CO2 eq.)	CED min (MJ)	CED initial (MJ)	CED max (MJ)	Financial costs (€)
Building 4 Label C	Label A	Sc.1	-2,709.06	-3,564.56	-7,842.03	243,676.23	320,626.61	705,378.55	111,929.65
		Sc.2	4,746.70	5,584.35	6,282.40	113,978.42	134,092.26	150,853.80	111,985.00
		Sc.3	7,934.46	10,579.28	10,579.28	208,885.46	278,513.94	278,513.94	70,430.93
	EN	Sc.1	14,708.41	18,009.58	14,878.49	2,156,243.95	2,666,532.36	4,125,793.74	950,293.83
		Sc.2	25,790.17	31,678.67	37,823.80	1,829,682.47	2,215,594.66	2,965,521.89	917,485.57
		Sc.3	456,184.18	497,989.28	565,003.40	3,018,139.58	3,522,074.26	4,825,688.16	702,714.65
Building 5 Label C	Label A	Sc.1	-2,709.06	-3,564.56	-7,842.03	243,676.23	320,626.61	705,378.55	111,929.65
		Sc.2	4,746.70	5,584.35	6,282.40	113,978.42	134,092.26	150,853.80	111,985.00
		Sc.3	7,934.46	10,579.28	10,579.28	208,885.46	278,513.94	278,513.94	70,430.93
	EN	Sc.1	15,167.94	18,580.16	15,567.78	2,159,169.55	2,670,164.97	4,130,182.14	1,076,567.41
		Sc.2	26,249.69	32,249.24	38,513.09	1,832,608.07	2,219,227.28	2,969,910.29	1,043,759.15
		Sc.3	456,644.28	498,561.12	565,923.59	3,021,068.82	3,525,714.89	4,831,546.63	797,644.71
Building 6 Label C	Label A	Sc.1	-2,709.06	-3,564.56	-7,842.03	243,676.23	320,626.61	705,378.55	111,929.65
		Sc.2	4,746.70	5,584.35	6,282.40	113,978.42	134,092.26	150,853.80	111,985.00
		Sc.3	7,934.46	10,579.28	10,579.28	208,885.46	278,513.94	278,513.94	70,430.93
	EN	Sc.1	9,865.61	11,814.84	7,614.29	2,107,238.52	2,599,832.97	4,052,285.59	987,744.40
		Sc.2	20,947.37	25,483.92	30,559.59	1,780,677.04	2,148,895.28	2,892,013.74	954,936.14
		Sc.3	451,336.23	491,783.22	555,658.98	2,969,101.37	3,455,302.76	4,738,936.19	718,540.21

Table 35 GWP, CED and financial savings for the energy labels A and Energy Neutral for the six buildings.

Building	Label	Scenario	Saving per year				
			GWP (CO2 eq./y)	CED (MJ/y)	Financial costs min (€/y)	Financial costs initial (€/y)	Financial costs max (€/y)
Building 1 Label E	Label A	Sc.1	7,839.39	130,215.72	9,044.17	19,542.07	30,039.97
		Sc.2	7,839.39	130,215.72	9,044.17	19,542.07	30,039.97
		Sc.3	7,839.39	130,215.72	9,044.17	19,542.07	30,039.97
	EN	Sc.1	28,050.40	464,411.06	39,976.52	86,471.19	132,965.85
		Sc.2	28,050.40	464,411.06	39,976.52	86,471.19	132,965.85
		Sc.3	28,050.40	464,411.06	39,976.52	86,471.19	132,965.85
Building 2 Label E	Label A	Sc.1	9,567.14	159,310.72	10,959.07	23,717.31	36,475.55
		Sc.2	9,567.14	159,310.72	10,959.07	23,717.31	36,475.55
		Sc.3	9,567.14	159,310.72	10,959.07	23,717.31	36,475.55
	EN	Sc.1	36,453.81	606,831.87	50,339.95	109,180.92	168,021.88
		Sc.2	36,453.81	606,831.87	50,339.95	109,180.92	168,021.88
		Sc.3	36,453.81	606,831.87	50,339.95	109,180.92	168,021.88
Building 3 Label D	Label A	Sc.1	6,228.61	104,430.93	6,981.28	15,176.70	23,372.12
		Sc.2	6,228.61	104,430.93	6,981.28	15,176.70	23,372.12
		Sc.3	6,228.61	104,430.93	6,981.28	15,176.70	23,372.12
	EN	Sc.1	23,950.09	397,429.25	30,608.54	66,188.28	101,768.03
		Sc.2	23,950.09	397,429.25	30,608.54	66,188.28	101,768.03
		Sc.3	23,950.09	397,429.25	30,608.54	66,188.28	101,768.03
Building 4 Label C	Label A	Sc.1	2,951.82	49,491.18	3,294.20	7,161.30	11,028.40
		Sc.2	2,951.82	49,491.18	3,294.20	7,161.30	11,028.40
		Sc.3	2,951.82	49,491.18	3,294.20	7,161.30	11,028.40
	EN	Sc.1	26,571.59	442,770.39	32,584.53	70,608.84	108,633.15
		Sc.2	26,571.59	442,770.39	32,584.53	70,608.84	108,633.15
		Sc.3	26,571.59	442,770.39	32,584.53	70,608.84	108,633.15

Building	Label	Scenario	Saving per year				
			GWP (CO2 eq./y)	CED (MJ/y)	Financial costs min (€/y)	Financial costs initial (€/y)	Financial costs max (€/y)
Building 5 Label C	Label A	Sc.1	2,968.07	49,763.61	3,312.33	7,200.72	11,089.11
		Sc.2	2,968.07	49,763.61	3,312.33	7,200.72	11,089.11
		Sc.3	2,968.07	49,763.61	3,312.33	7,200.72	11,089.11
	EN	Sc.1	22,704.08	378,611.54	28,392.61	61,567.21	94,741.81
		Sc.2	22,704.08	378,611.54	28,392.61	61,567.21	94,741.81
		Sc.3	22,704.08	378,611.54	28,392.61	61,567.21	94,741.81
Building 6 Label C	Label A	Sc.1	2,954.53	49,536.58	3,297.22	7,167.87	11,038.52
		Sc.2	2,954.53	49,536.58	3,297.22	7,167.87	11,038.52
		Sc.3	2,954.53	49,536.58	3,297.22	7,167.87	11,038.52
	EN	Sc.1	20,534.14	342,084.49	26,641.70	57,705.89	88,770.07
		Sc.2	20,534.14	342,084.49	26,641.70	57,705.89	88,770.07
		Sc.3	20,534.14	342,084.49	26,641.70	57,705.89	88,770.07

Table 36 GWP, CED and financial payback periods for the energy labels A and Energy Neutral for the six buildings.

Building	Label	Scenario	Payback period (y)								
			GWP min	GWP initial	GWP max	CED min	CED initial	CED max	Financial min	Financial initial	Financial max
Building 1 Label E	Label A	Sc.1	5.19	5.78	9.95	13.60	16.21	31.35	9.25	14.22	30.72
		Sc.2	6.86	7.83	13.37	10.78	12.29	21.17	8.09	12.44	26.88
		Sc.3	68.80	73.82	95.90	27.01	28.33	52.78	5.88	9.04	19.54
	EN	Sc.1	2.12	2.48	3.82	7.36	8.90	14.67	8.66	13.32	28.81
		Sc.2	2.59	3.05	4.78	6.57	7.80	11.82	8.40	12.92	27.94
		Sc.3	19.94	21.54	28.07	11.76	12.95	22.35	6.40	9.85	21.30
Building 2 Label E	Label A	Sc.1	4.25	4.73	8.15	11.13	13.26	25.65	7.63	11.74	25.40
		Sc.2	5.62	6.42	10.96	8.81	10.05	17.31	6.68	10.27	22.24
		Sc.3	56.38	60.50	78.59	22.09	23.16	43.15	4.85	7.47	16.16
	EN	Sc.1	1.58	1.84	2.86	5.60	6.76	11.18	6.67	10.26	22.25
		Sc.2	1.94	2.28	3.59	4.99	5.92	8.99	6.46	9.94	21.56
		Sc.3	15.29	16.51	21.50	8.96	9.87	17.04	4.90	7.54	16.36
Building 3 Label D	Label A	Sc.1	0.76	0.87	0.40	3.60	4.57	8.45	7.96	12.25	26.63
		Sc.2	1.96	2.33	2.67	2.35	2.78	3.14	7.96	12.25	26.64
		Sc.3	67.54	73.22	82.11	6.76	7.64	8.07	5.71	8.80	19.13
	EN	Sc.1	2.28	2.62	4.19	8.27	9.94	16.50	10.65	16.37	35.39
		Sc.2	2.76	3.22	5.19	7.38	8.72	13.39	10.28	15.81	34.19
		Sc.3	22.63	24.37	31.86	13.44	14.71	25.67	7.76	11.93	25.79
Building 4 Label C	Label A	Sc.1	-0.92	-1.21	-2.66	4.92	6.48	14.25	10.15	15.63	33.98
		Sc.2	1.61	1.89	2.13	2.30	2.71	3.05	10.15	15.64	33.99
		Sc.3	2.69	3.58	3.58	4.22	5.63	5.63	6.39	9.83	21.38
	EN	Sc.1	0.55	0.68	0.56	4.87	6.02	9.32	8.75	13.46	29.16
		Sc.2	0.97	1.19	1.42	4.13	5.00	6.70	8.45	12.99	28.16
		Sc.3	17.17	18.74	21.26	6.82	7.95	10.90	6.47	9.95	21.57

Building	Label	Scenario	Payback period (y)								
			GWP min	GWP initial	GWP max	CED min	CED initial	CED max	Financial min	Financial initial	Financial max
Building 5 Label C	Label A	Sc.1	-0.91	-1.20	-2.64	4.90	6.44	14.17	10.09	15.54	33.79
		Sc.2	1.60	1.88	2.12	2.29	2.69	3.03	10.10	15.55	33.81
		Sc.3	2.67	3.56	3.56	4.20	5.60	5.60	6.35	9.78	21.26
	EN	Sc.1	0.67	0.82	0.69	5.70	7.05	10.91	11.36	17.49	37.92
		Sc.2	1.16	1.42	1.70	4.84	5.86	7.84	11.02	16.95	36.76
		Sc.3	20.11	21.96	24.93	7.98	9.31	12.76	8.42	12.96	28.09
Building 6 Label C	Label A	Sc.1	-0.92	-1.21	-2.65	4.92	6.47	14.24	10.14	15.62	33.95
		Sc.2	1.61	1.89	2.13	2.30	2.71	3.05	10.14	15.62	33.96
		Sc.3	2.69	3.58	3.58	4.22	5.62	5.62	6.38	9.83	21.36
	EN	Sc.1	0.48	0.58	0.37	6.16	7.60	11.85	11.13	17.12	37.08
		Sc.2	1.02	1.24	1.49	5.21	6.28	8.45	10.76	16.55	35.84
		Sc.3	21.98	23.95	27.06	8.68	10.10	13.85	8.09	12.45	26.97

K. Interviews with clients - questions and responses

This appendix presents the interview questions used to collect information about the criteria clients apply when selecting measure packages, measures, and products. Furthermore, an overview of the clients (Table 37) and a summary of their answers are provided in Table 38 to Table 43. Table 38 to Table 40 are used for Figure 2 in Section 4.7.1.

Measure packages

1. Have you already decided which measure package you will apply?
2. Based on which criteria did/would you choose the measure package?
3. How did/would you rank the priority of these criteria?

Measures

4. Have you already decided which measures of the package you will apply?
5. Did/would you decide to implement all measures as described? Or did/would you decide to exclude some of the measures?
    a. Yes: Based on which criteria did/would you decide to keep all measures included?
    b. No: Which measures did/would you exclude?
    c. No: Based on which criteria did/would you decide to exclude certain measures?
6. How did/would you rank the priority of these criteria?

Products

7. Have you already decided which products you will apply?
8. Based on which criteria did/would you select the products to be implemented?
9. How did/would you rank the priority of these criteria?

Sustainability

10. Is attention paid to sustainability when deciding on packages, measures and/or products?
    a. Yes: How is this done?
    b. No: Why is no attention given to sustainability?
11. Would you want to give more attention to sustainability when making decisions about the packages, measures, and/or products? And why?

Environmental impact

In the second part of the interview, I show the results of the GWP, CED, and financial costs of the products and explain these results and the method of an LCA study.

12. If you would receive an overview of the GWP and CED in future advice reports, do you think that these environmental impacts will play a role in selecting the products? And the measures? And the packages?
13. When you selected/would select the products, you mentioned criteria xxx. If you add the criteria of GWP and CED, how would you rank these?
14. When you selected/would select the measures, you mentioned criteria xxx. If you add the criteria of GWP and CED, how would you rank these?
15. When you selected/would select the measure packages, you mentioned criteria xxx. If you add the criteria of GWP and CED, how would you rank these?

Closure

16. Do you have any recommendations on how to include the environmental impacts in an understandable way?
17. What do you remember the most after this interview?

Table 37 Overview of interviewed clients.

Respondent	Organisation	Function
Client 1	Community house	Administrator of the church owned by the municipality
Client 2	School community	Advise and inform administrators, teachers and other colleagues in the field of school housing and sustainability
Client 3	Municipality	Managing, and planning maintenance actions for real estate owned by the municipality
Client 4	Municipality	Managing, maintaining, and building real estate owned by the municipality
Client 5	Governmental organisation	Advising about sustainability in projects where real estate is built or maintained by the governmental organisation

Table 38 Individual prioritisation of package criteria from the five interviewed clients.

Criteria	Client 1	Client 2	Client 3	Client 4	Client 5	Average score
Financial costs	5	5	5	5	5	5
Residual life	4	3	4	-	5	3.2
Energy savings	1	-	3	5	5	2.8
Regret-free	-	4	-	4	5	2.6
Building use	4	-	-	4	-	1.6
Political pressure	-	-	3	-	5	1.6
Environmental impact	-	-	-	-	-	-
Feasibility	-	-	-	-	-	-
CO2 savings	-	-	-	-	5	1
Simplicity	-	-	-	-	5	1
Ownership	-	2	-	2	-	0.8
Technical development	-	-	-	3	-	0.6
Residential support	2	-	-	-	-	0.4

Table 39 Individual prioritisation of measure-criteria from the five interviewed clients.

Criteria	Client 1	Client 2	Client 3	Client 4	Client 5	Average score
Financial costs	**5**	5	5	2	5	4.4
Residual life	4	4	4	4	5	4.2
Energy savings	3	3	-	3	-	1.8
Regret-free	-	-	-	-	5	1
Building use	4		4		0	1.6
Political pressure	-	-	3	-	5	1.6
Environmental impact	-	-	-	3	5	1.6
Feasibility	-	-	1	5	-	1.2
CO2 savings	-	-	-	-	5	1
Simplicity	-	-	-	-	-	-
Ownership	-	-	1	1	-	0.4
Technical development	-	-	2	-	-	0.4
Residential support	-	-	1	-	-	0.2

Table 40 Individual prioritisation of product-criteria from the five interviewed clients.

Criteria	Client 1	Client 2	Client 3	Client 4	Client 5	Average score
Reusability	-	-	-	3	-	0.6
Safety / Cybersecurity	-	-	-	4	-	0.8
Permits	-	-	4	-	-	0.8
Feasibility	-	-	-	-	5	1
Healthiness	-	-	-	5	-	1
Aesthetics	-	3	2	-	-	1
Maintainability	-	-	-	3	5	1.6
Environmental impact	3	-	-	-	5	1.6
Financial costs	5	5	3	1	-	2.8
Technical specification	4	4	5	4	-	3.4

Table 41 Individual answers of five clients on the questions related to sustainability.

Question	Client 1	Client 2	Client 3	Client 4	Client 5
Is sustainability a criterion?	Yes	No	No	Yes	Yes
On which level?	Products			Measures	Package, measures, and products
Reason/explanation					
Implementing energy saving measures		x	x		
Giving more attention to sustainability than before	X			x	
Due to our exemplary function				x	x
Trying to make the environmental impact measurable					x
Financial savings due to energy savings	X				
Reuse of installations				x	

Table 42 Individual answers of five clients on the questions related to environmental impact.

Questions	Client 1	Client 2	Client 3	Client 4	Client 5
Would the GWP and CED play a role in future projects?	Yes	Yes	Yes	Yes	Yes
What would be the new prioritisation?					
Financial costs remain most important / should remain within budget	x	x	x	x	
It should be practically feasible		x	x	x	
It is part of our ambition				x	x
Calculation of GWP and CED should be verifiable					x
Which impact would be more important?	Equal	-	CED	CED	More impacts exist

Table 43 Individual feedback from the five interviewed clients.

Feedback from respondents	Client 1	Client 2	Client 3	Client 4	Client 5
More enthusiastic about sustainability				x	
Implement in future projects	x		x	x	x
Awareness	x	x	x	x	
Difficult subject	x	x	x	x	

L. Survey for employees - questions and responses

The questions of the surveys before and after the brainstorming session are presented in this appendix. In addition, an overview of the clients (Table 44) and a summary of their answers are provided in Table 45 to Table 49.

Survey questions before the brainstorming session:

1. What criteria do you use to put together a measure package?
2. How would you rank these criteria?
3. To what extent do you pay attention to sustainability while putting together measure packages? (score between 1 and 7)
4. Please, describe an example of how you pay this amount of attention to sustainability.

Survey questions after the brainstorming session:

1. What insights did you gain from the brainstorming session?
2. Now that you have gained these insights: To what extent do you feel that you did consider sustainability when putting together measure packages? (score between 1 and 7)
3. Please, explain your previous answer.
4. How would you rank the following criteria? (energy saving, financial costs, feasibility, client demand, efficient use of fossil fuels, sustainable energy generation, architectural style, CO2 savings, and environmental impact (GWP and CED))
5. Would you have made different choices for the measure packages if the GWP and CED had been available? (yes, maybe, no)
6. Please, explain your answer.

Table 44 Overview of employees who participated in the surveys.

Respondent	Function / Experience
Employee 1	Determining energy labels and advising energy-saving measures. Expertise in construction and installations
Employee 2	Advising projects related to energy transition and sustainability
Employee 3	Started the training to become able to determine energy labels and advise about energy-saving measures
Employee 4	Determining energy labels with Vabi software and advising about energy-saving measures
Employee 5	Determining energy labels and advice on energy-saving measures. Expertise in advising installation-related solutions
Employee 6	Determining energy labels with Vabi software and advising about energy-saving measures
Employee 7	Experience in advising about buildings and installations by considering sustainability
Employee 8	Advising clients about building constructions and installations
Employee 9	One of the drivers of sustainability and circularity of Antea Group

Table 45 Individual prioritisation of criteria when putting together a measure package. Answered by eight employees prior to the brainstorming session.

Criteria	Emp.1	Emp.2	Emp.3	Emp.4	Emp.5	Emp.6	Emp.7	Emp.8	Average score
Energy saving	9	9	9	8	9	9		9	7.8
Financial costs		7		8			9	7	3.9
Feasibility						7	8	8	2.9
Client demand				9		6	7		2.8
Efficient use of fossil fuels	7					9			2.0
Sustainable energy generation	6					9			1.9
Architectural style					8				1.0
CO2 savings				8					1.0
Surroundings					7				0.9

Table 46 Individual prioritisation of criteria when putting together a measure package. Answered by six employees after the brainstorming session.

Criteria	Emp.1	Emp.3	Emp.6	Emp.7	Emp.8	Emp.9	Average score
Energy saving	9	9	9	7	9	5	8.0
Financial costs	8	5	7	7	6	6	6.5
Feasibility	8	7	5	8	9	7	7.3
Client demand	5	7	8	6	6	6	6.3
Efficient use of fossil fuels	8	9	5	2	9	3	6.0
Sustainable energy generation	8	9	7	9	9	5	7.8
Architectural style	3	6	6	4	9	8	6.0
CO2 savings	9	9	8	7	9	2	7.3
Environmental impact	9	9	8	8	9	9	8.7

Table 47 Individual answers of eight employees on the questions related to sustainability. Answered prioir to the brainstorming session.

Question	Emp.1	Emp.2	Emp.3	Emp.4	Emp.5	Emp.6	Emp.7	Emp.8
The extent of attention to sustainability (out of 7)	2	7	7	6	7	7	5	7
Give an example								
Measure packages (saving energy) contribute to sustainability		X		x			x	x
Besides energy saving, considering other aspects of sustainability				x				
Client demand							x	
Solutions without using fossil fuels					x			
Lower the environmental footprint	x		x					

Table 48 Individual answers of six employees on the questions related to sustainability. Answered after the brainstorming session.

Criteria	Emp.1	Emp.3	Emp.6	Emp.7	Emp.8	Emp.9
The extent of attention to sustainability (out of 7)	4	4	3	4	6	5
Explain your answer						
Too much focus on client demand	x			x		x
Insight in CO2 reduction entire lifecycle instead of only use phase	x	x			x	x
Focus now on saving on financial costs. Saving in other aspects is necessary in the future			x			

Table 49 Individual insights from six employees after the brainstorming session.

Insights of employees	Emp.1	Emp.3	Emp.6	Emp.7	Emp.8	Emp.9
The current calculation method does not always consider the impact of the entire lifecycle, while this will become important in a circular economy					x	x
Difficult subject			x	x	x	
The most CO2 reduction during the use phase (due to energy saving) is not always the best solution.		x				
Financial costs remain challenging		x				
Clients are not always aware of environmental impacts. Therefore, they should be advised about this subject	x	x	x			
Advise clients on conventional and alternative products	x					

M. Examples of GWP and CED in future advice reports

This appendix provides an example of how to visualise the GWP, CED, and financial costs by using symbols. This is done for the insulation materials, as shown in Table 50 to Table 54. The more leaf symbols, the lower the GWP, CED. Therefore, the objective is to select the products with the greatest number of symbols for the GWP and CED. Furthermore, the more coin symbols, the more financial costs.

Table 50 Visualisation of the GWP, CED, and financial costs of insulation materials using symbols.

Measure	Product	GWP*	CED*	Financial costs**
Insulation cavity	PUR foam	🍃🍃	½	🪙🪙🪙
	Thermofoam	🍃🍃🍃🍃🍃	🍂🍂🍂🍂🍂	🪙🪙🪙½
	EPS pearls	🍃🍃🍃🍃½	🍂🍂🍂🍂½	🪙🪙🪙½
Insulation facade	Rock wool	🍃🍃🍃	🍂🍂🍂½	🪙🪙🪙🪙½
	Glass wool	🍃🍃🍃🍃½	🍂🍂🍂🍂🍂	🪙🪙🪙🪙½
	PUR foam	🍃🍃	½	🪙🪙🪙
	Thermofoam	🍃🍃🍃🍃🍃	🍂🍂🍂🍂🍂	🪙🪙🪙½
	Hemp fibre	🍃🍃🍃🍃½	🍂🍂🍂🍂½	🪙🪙🪙🪙🪙
	Wood fibre	🍃🍃🍃🍃🍃	🍂🍂½	🪙🪙🪙🪙🪙
Insulation floor	PIF	½	🍂	½
	PUR foam	🍃🍃	½	½
	EPS pearls	🍃🍃🍃🍃½	🍂🍂🍂🍂½	½
Insulation roof	PIR	🍃🍃🍃🍃	🍂🍂🍂	🪙🪙🪙
	EPS	🍃🍃🍃🍃½	🍂🍂🍂🍂½	🪙🪙🪙🪙🪙
	Wood fibre	🍃🍃🍃🍃🍃	🍂🍂½	🪙🪙🪙🪙🪙

**The more leaf symbols, the lower the GWP and CED impact.*
***The more the coin symbols, the higher the financial costs.*

Table 51 Visualisation of the GWP, CED, and financial costs of glazing using symbols.

Measure	Product	GWP*	CED*	Financial costs**
Glazing	HR++ glass	½	½	🪙½
	Triple glass	🍃🍃🍃🍃	🍂🍂🍂🍂	½
	Vacuum glass	🍃🍃🍃🍃🍃	🍂🍂🍂🍂🍂	🪙🪙🪙🪙🪙

**The more leaf symbols, the lower the GWP and CED impact.*
***The more the coin symbols, the higher the financial costs.*

Table 52 Visualisation of the GWP, CED, and financial costs of heat pumps using symbols.

Measure	Product	GWP*	CED*	Financial costs**
Heat pump	Air-air heat pump	🍃🍃🍃🍃½	🍃🍃🍃🍃½	🪙🪙🪙🪙🪙
	Air-water heat pump	🍃🍃🍃🍃½	🍃🍃🍃🍃½	🪙🪙🪙🪙🪙
	Refrigerator: Propane	🍃🍃🍃🍃🍃	🍃🍃🍃🍃🍃	½
	Refrigerator: CO2	½	½	½

**The more leaf symbols, the lower the GWP and CED impact.*
***The more the coin symbols, the higher the financial costs.*

Table 53 Visualisation of the GWP, CED, and financial costs of PV panels using symbols.

Measure	Product	GWP*	CED*	Financial costs**
PV panel	Mono crystalline	½	½	🪙🪙🪙🪙
	Poly crystalline	🍃🍃½	🍃🍃½	🪙🪙🪙🪙½
	Thin film panel (CdTe)	🍃🍃🍃🍃🍃	🍃🍃🍃🍃🍃	🪙🪙🪙🪙½
	Thin film panel (CIGS)	🍃🍃🍃🍃	🍃🍃🍃🍃	½
	Thin film panel (A-Si)	🍃🍃½	🍃🍃½	½

**The more leaf symbols, the lower the GWP and CED impact.*
***The more the coin symbols, the higher the financial costs.*

Table 54 Visualisation of the GWP, CED, and financial costs of lighting using symbols.

Measure	Product	GWP*	CED*	Financial costs**
Lighting	LED	½	½	½
	LED + daylight detection	🍃🍃🍃🍃🍃	🍃🍃🍃🍃🍃	🪙🪙🪙🪙🪙
	LED + presence detection	🍃🍃🍃½	🍃🍃🍃½	🪙🪙🪙

**The more leaf symbols, the lower the GWP and CED impact.*
***The more the coin symbols, the higher the financial costs.*

The tables above have been constructed by using ranges of the GWP, CED, and financial costs per half a symbol. These ranges are presented in Table 55 to Table 57. When a product's value falls within a range, the corresponding number of symbols are awarded.

Table 55 Ranges of GWP used to define the number of symbols.

Nr of GWP symbols	Thermal insulation	Glazing	Heat pump	PV panel	Lighting system	Mechanical ventilation
5.0	-1.62 - 0.73	35.72 - 39.75	1,577.90 - 1,639.37	432.70 - 537.67	685.99 - 740.12	1,729.96 - 1,777.45
4.5	0.73 - 3.08	39.75 - 43.78	1,639.37 - 1,700.84	537.67 - 642.63	740.12 - 794.24	1,777.45 - 1,824.94
4.0	3.08 - 5.43	43.78 - 47.82	1,700.84 - 1,762.31	642.63 - 747.60	794.24 - 848.37	1,824.94 - 1,872.43
3.5	5.43 - 7.77	47.82 - 51.85	1,762.31 - 1,823.78	747.60 - 852.56	848.37 - 902.50	1,872.43 - 1,919.92
3.0	7.77 - 10.12	51.85 - 55.88	1,823.78 - 1,885.26	852.56 - 957.52	902.50 - 956.63	1,919.92 - 1,967.41
2.5	10.12 - 12.47	55.88 - 59.91	1,885.26 - 1,946.73	957.52 - 1,062.49	956.63 - 1,010.75	1,967.41 - 2,014.90
2.0	12.47 - 139.39	59.91 - 63.94	1,946.73 - 2,008.20	1,062.49 - 1,167.45	1,010.75 - 1,064.88	2,014.90 - 2,062.39
1.5	139.39 - 159.53	63.94 - 67.97	2,008.20 - 2,069.67	1,167.45 - 1,272.41	1,064.88 - 1,119.01	2,062.39 - 2,109.88
1.0	159.53 - 179.68	67.97 - 72.01	2,069.67 - 2,131.14	1,272.41 - 1,377.38	1,119.01 - 1,173.13	2,109.88 - 2,157.37
0.5	179.68 - 199.82	72.01 - 76.04	2,131.14 - 2,192.61	1,377.38 - 1,482.34	1,173.13 - 1,227.26	2,157.37 - 2,204.86

Table 56 Ranges of CED used to define the number of symbols.

Nr of CED symbols	Thermal insulation	Glazing	Heat pump	PV panel	Lighting system	Mechanical ventilation
5.0	13.67 - 38.28	227.43 - 253.1	366,970.42 - 381,266.86	1,6177.8 - 20,102.14	18,363.38 - 19,834.46	289,000.36 - 301,769.40
4.5	38.28 - 62.90	253.1 - 278.76	381,266.86 - 395,563.30	20,102.14 - 2,4026.47	19,834.46 - 21,305.54	301,769.40 - 314,538.44
4.0	62.90 - 87.51	278.76 - 304.43	395,563.30 - 409,859.74	2,4026.47 - 27,950.81	21,305.54 - 22,776.62	314,538.44 - 327,307.48
3.5	87.51 - 112.13	304.43 - 330.09	409,859.74 - 424,156.17	27,950.81 - 31,875.15	22,776.62 - 24,247.71	327,307.48 - 340,076.52
3.0	112.13 - 136.75	330.09 - 355.76	424,156.17 - 438,452.61	31,875.15 - 35,799.49	24,247.71 - 25,718.79	340,076.52 - 352,845.56
2.5	136.75 - 161.36	355.76 - 381.42	438,452.61 - 452,749.05	35,799.49 - 39,723.82	25,718.79 - 27,189.87	352,845.56 - 365,614.60
2.0	161.36 - 186	381.42 - 407.09	452,749.05 - 467,045.48	39,723.82 - 43,648.16	27,189.87 - 28,660.95	365,614.60 - 378,383.64
1.5	186 - 210.59	407.09 - 432.76	467,045.48 - 481,341.92	43,648.16 - 47,572.50	28,660.95 - 30,132.03	378,383.64 - 391,152.68
1.0	210.59 - 235.21	432.76 - 458.42	481,341.92 - 495,638.36	47,572.50 - 51,496.84	30,132.03 - 31,603.11	391,152.68 - 403,921.72
0.5	235.21 - 259.82	458.42 - 484.09	495,638.36 - 50,9934.80	51,496.84 - 55,421.18	31,603.11 - 33,074.19	403,921.72 - 416,690.76

Table 57 Ranges of financial costs used to define the number of symbols.

Nr of financial symbols	Thermal insulation	Glazing	Heat pump	PV panel	Lighting system	Mechanical ventilation
0.5	41.3 - 63.00	684.52 - 714.44	126,495.95 - 130,670.31	1,419.22 - 13,040.90	1,128.48 - 1,156.69	236.25 - 257.59
1.0	63.00 - 84.69	714.44 - 744.37	130,670.31 - 134,844.68	13,040.90 - 2,4662.57	1,156.69 - 1,184.9	257.59 - 278.94
1.5	84.69 - 106.39	744.37 - 774.29	134,844.68 - 139,019.05	2,4662.57 - 36,284.25	1,184.9 - 1,213.12	278.94 - 300.29
2.0	106.39 - 128.09	774.29 - 804.21	139,019.05 - 143,193.42	36,284.25 - 47,905.92	1,213.12 - 1,241.33	300.29 - 321.63
2.5	128.09 - 149.78	804.21 - 834.14	143,193.42 - 147,367.78	47,905.92 - 5,9527.6	1,241.33 - 1,269.54	321.63 - 342.98
3.0	149.78 - 171.48	834.14 - 864.06	147,367.78 - 151,542.15	5,9527.6 - 71,149.27	1,269.54 - 1,297.75	342.98 - 364.33
3.5	171.48 - 193.18	864.06 - 893.99	151,542.15 - 155,716.51	71,149.27 - 82,770.95	1,297.75 - 1,325.96	364.33 - 385.67
4.0	193.18 - 214.87	893.99 - 923.91	155,716.51 - 159,890.88	82,770.95 - 943,92.62	1,325.96 - 1,354.18	385.67 - 407.02
4.5	214.87 - 236.57	923.91 - 953.84	159,890.88 - 164,065.25	943,92.62 - 10,6014.30	1,354.18 - 1,382.39	407.02 - 428.37
5.0	236.57 - 258.27	953.84 - 983.76	164,065.25 - 168,239.61	10,6014.30 - 117,635.97	1,382.39 - 1,410.60	428.37 - 449.72