CARBON ——BASED DESIGN

RESEARCH ON THE ENVIRONMENTAL IMPACT OF RESIDENTIAL BUILDINGS

Version 2 | January 2022

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CORRECTIONS

Changes have been made in this version compared to the second version dated January 2022:

On page 40, a 2018 PBL report is quoted with: 'about 0.3 Mton CO_2 per year can be sequestered and as much avoided by replacing concrete and brick'. The PBL report has since been corrected and the word 'brick' has subsequently been replaced by the word 'steel' in this report.

This report was prepared by CITYFÖRSTER architecture + urbanism on behalf of the Rijksdienst voor Ondernemend Nederland (RVO), for the Circular Construction Economy.

WITH THANKS TO:

THE EXPERT PANEL: Slatjana Mijatovic - BPD
Menno Rubens - Cepezed
Ruben Zonnevijlle - DGBC
Peter Fraanje - TNO

Ballast Nedam, BPD, Gemeente Rotterdam, Group A, Heijmans, Lingotto, Merosch, Shift a+u, Superuse, TBI, The New Makers for making their projects available as case studies.

And W/E advisors for providing the GPR building calculation software and accompanying advice.

COLOPHON

Authors:	Martin Sobota, Isabel Driessen, Margot Holländer/MOR (CITYFÖRSTER)
Initiative:	Transitieteam Circulaire Bouweconomie
Client:	Netherlands Enterprise Agency
Guidance:	Thomas Wellink (RVO) and Menno Brouwer (RVO)
Execution\Formatting:	CITYFÖRSTER architecture + urbanism
Editors:	Byline

FIGURE 1.

BNA Chairman Jolijn Valk Photographer: Alice Lucchinelli

FOREWORD

PRACTICAL AND ACHIEVABLE

A metaphor for my vision for the future direction of architecture and the built environment comes across perfectly in the image of the most detailed picture of a human cell ever made, which I recently came across in NRC. The image looks like a futuristic urban network. A human cell is a structure in itself, which in turn can have its own structures and networks: an infinity of relationships and connections. This immediately made me think of the spatial issues we face as designers: the housing challenge, the energy transition, biodiversity, climate and circularity. Complex tasks that are in direct connection with the various scales, including the seemingly invisible ones.

When I look at such an enlarged cell, I like to see the ideal building chain in it. Making a difference on a small scale (material level) requires chain cooperation.

This brings me to the key question of this research on CO_2 metabolism in housing: how can we design and build with as little CO_2 emissions as possible? The reality, if we are honest, is that we are far from having a ready-made answer to that. For example, we all want to "be circular," but most architects, clients, and builders don't get much further than reusing materials as of yet. The inspiration and experiences of buildings like Circl in Amsterdam or the Stadskantoor in Venlo do help. And knowledge sharing for practitioners is taking off, as recently evidenced by the presentation of the book Lessons in Circularity by Hans Hammink (Cie). We could use that kind of practical analyses.

Here is another yet excellent analysis, on a larger scale, to the hands-on applicability of circular design and construction. This research is timely. The case studies, from low-rise to high-rise, are recognizable to everyone in our playing field. The policy recommendations are practical and achievable - just what we need to accelerate and scale up. The housing challenge does not lie, nor does the climate crisis. But the will is there, with everyone, as our experience with the BNA policy program "Doing Circular", also shows, in which we are active with our members and knowledge partners since 2020. Building houses on a large scale that are quality and Paris-proof: I firmly believe that we are capable of doing this, as soon as we also work on chain cooperation. Therefore, I see the recommendations in this report as a recommendation for that much-needed interplay.

To understand each other fully and to be able to innovate, we must be willing to learn from each other and dare to experiment. In a time of a "battle for space" and resurgent building frenzy, it is incredibly important to know exactly what you are building and for whom. In complicated situations and issues, there is a tendency to simplify and "flatten" it. Simplification creates the impression that we are regaining control of what we need to do. And quickly. But instead of simplifying it, we should also gather more knowledge and add to the collective education instead of suppressing it.

The detailed structure of this report includes clear guidelines and provides a basis for concrete action. I suggest that from now on we stop arguing about the facts, as they are stated blatantly in this report (a suburban home needs seven times the infrastructure compared to a highly urban home...). Let's put our energy into transitioning the construction industry from being "part of the problem" to being "part of the solution," with "net-zero building sites" as the goal. As long as we believe in the fact that everything is connected, at the scale of a human cell, and at the scale of the housing challenge, it can be done.

Jolijn Valk

BNA Chairman

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SUMMARY

CARBON-BASED DESIGN: DESIGNING BASED ON CARBON EMISSIONS

This research revolves around the role that embodied carbon plays in construction. The main questions on this subject are:

- Which parts of a building contribute the most to emissions?
- How do we reduce these?
- What would happen if we made our design decisions based on the carbon emissions they produce?

We interpreted the key terms around this topic, looked at how the **embodied carbon** emissions are calculated, placed them in a larger picture and analyzed what interactions exist. We then highlighted a number of case studies, six of which are detailed.

Based on the insights gained, we formulated 24 principles that will guide a designer in their process and enable them to make early decisions to improve the CO_2 balance of a building.

Last but not least, we have formulated a number of policy recommendations. These arose from thecontradictions we observed between, on the one side, the current practices and the current policies and regulations, and on the other side, what we believe would be the right preconditions to work towards a 'Paris-proof' construction sector.

HOW GREAT IS OUR IMPACT?

The biosphere causes 120 gigatons of CO_2 emissions per year, and the oceans release an additional 90 gigatons of CO_2.

They also absorb about the same amount. The technosphere (consisting of human activities) emits more CO_2 than it absorbs. To a large extent this is done by burning fossil fuel reservoirs, but activities such as burning lime and cement also contribute to this.

The construction sector is responsible for about 38 percent of global CO_2 emissions. Materials alone account for 11 percent of global CO_2 emissions.

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EMBODIED OR OPERATIONAL?

In recent decades, great strides have been made worldwide to reduce energy consumption during the usage phase of buildings. The more progress we make towards truly zero-energy buildings, the more relevant embodied carbon also becomes. On the one hand because their share becomes proportionally more relevant, but also because a reduction in operational consumption is often accompanied by an increase in material consumption, e.g. due to larger and more complex building systems.

On top of this, the **embodied emissions** has already been released, while **operational emissions** are spread over a building’s lifespan and increase yearly. Emissions that occur now therefore have much more of an effect on climate change than emissions that accumulate gradually over the lifetime of a building. We call this the time value of carbon.

QUANTIFYING AND CONTEXTUALIZING EMBODIED CARBON

About 65 percent of embodied carbon occurs/is emitted before or during the construction process (**cradle-to-site**). The remaining 35 percent occurs/is emitted during the maintenance and replacement of parts.

These numbers are based on our research of 24 housing projects. Since 2013, it has become mandatory in the Netherlands to make an MPG calculation when applying for a building permit. This calculation maps out the environmental performance of buildings and, in addition to CO_2 emissions, includes a number of other environmental impacts such as soil/water? acidification and harmful emissions. The different effects are then multiplied by their theoretical social **shadow costs**, leading to a normalized value of social costs in euros. These costs are then divided by the **gross floor area** in square meters and a default life expectancy of 75 years. The requirement of that ratio was adjusted from 1.0 to 0.8 in 2021 for residential new constructions. Thus, a 120 m^2 home may only cost 96 euros instead of 120 euros in social costs.

Although the method is standardized and the various certified software packages must use the same National Environmental Database, not all MPG calculations are equally readable or comparable. It is also clear that an MPG calculation without the accompanying **EPC-** or **BENG-**calculation has little meaning.

By default, the MPG only displays the various environmental impacts at the building level and thus does not provide any insight into how much CO_2 the various materials contain. In addition, the MPG standard distinguishes between floors and walls, but not between load-bearing and non-load-bearing components.

This fits with a practice in which a calculation of a final design is usually made afterwards by an external consultant. Because the requirements are still relatively easy to achieve, this does not pose a problem in practice. Most architects do not even know what an MPG calculation is. As the requirements become more stringent, the MPG will also start to play a larger role in the design process and a different data structure will become necessary.

From the 24 case studies, we singled out 6 that were best documented and that covered a wide spectrum of urban densities. For this study, we redid the calculations for our case studies and structured the information sorting it by life cycle phase and by S-layer according to Steward Brand —an approach that builds on the distinction between "structure and infill", as formulated by John Habraken in 1961. (1961, The Carriers and the People: The End of Mass Housing).

CARBON-BASED DESIGN GUIDELINES

Following those case-studies, we analyzed the most important questions for a designer:

- What are the building components with the highest embodied carbon?
- What are the alternatives and what does that mean for design and detailing?
- How does the 75-year lifespan affect design decisions??
- What happens when we try to achieve a low MPG value??
- Can we get below zero? And does that make sense?
- How does a higher investment in solar panels, for example, relate to energy consumption in the usage phase of the building?
- Does it make sense to build large homes with low MPG scores that are occupied by

only one or two people?

- Or does it make sense to invest a little more in a heavy support structure that is flexible in function and can accommodate more people, closer to a subway station?

Our research has ultimately led to a set of guidelines for Carbon Based Design. These are organized to provide guidance for a designer at different stages of the design process. The key principles are summarized below, clustered according to Steward Brand's S-layers, with some general principles up front

GENERAL PRINCIPLES: REDUCE > REUSE > RECYCLE

Energy consumption is not the same as emissions: we do not have an energy problem but an emissions problem. The energy that reaches our planet every day from the sun is 10,000 times what we need worldwide in an entire year. Yet energy generation always has negative effects. Solar panels have to be placed somewhere, meaning there is then less room for greenery. Windmills make noise and are built using rare resources, and so on.

The most environmentally friendly building is therefore the one that does not need to be built. Instead, we could For exampleinvent ways of building and living together that offer freedom, privacy and comfort, without the large amount of space, complex systems and countless gadgets that we now think we need.

In addition, the question is how we can reuse the existing structures for new needs with as much value retention as possible.

Sometimes meaningful reuse is not possible. When that is the case let's make sure that our building materials are reduced to raw materials again. For example, by avoiding the use of glue or complicated composites. That is the **cradle-to-cradle** principle.

SITE

Location and context are important to the carbon footprint. To reduce the amount of new materials, we need to look at what we already have. Urban locations are already equipped with infrastructure, a public transport network and shared facilities. Even though these aspects do not count in the MPG calculation, this is where the biggest gains can be made. Consider how much infrastructure is needed to access a building. For example, a dwelling in a rural area needs 7 times more infrastructure than a dwelling in a dense urban area. The energy linked to the use of that infrastructure (e.g. mobility) is not even taken into account here.

STRUCTURE

The supporting structure of a building contains large amounts of materials, but it also has the greatest potential lifespan. So, we need to design efficient structures that save as much material as possible, but also consider possible changes in function. This requires, for example, floors with more load-bearing capacity, or larger spans. An interesting issue is also the demountability and remountability of supporting structures. Because of its mass, a load-bearing structure is extremely suitable for storing carbon, for example by building with wood.

SKIN

The facade of a building largely regulates comfort. Window openings that provide plenty of daylight are also a weak point when it comes to retaining energy. The production of glass also requires a great deal of energy. It is therefore important for designers to design facade openings carefully. The most common wall cladding in the Netherlands is brick, which requires a relatively large amount of production energy, while also having a long lifespan in theory. Though they have a long lifespan bricks are often not exploited to their full potential. Even during the demolition process bricks are not always reused because it is easier to use a new brick than to strip an old brick of its mortar. Wood and other biobased materials can, depending on their lifespan, temporarily store CO_2 and then be returned to organic matter. In addition, bio-based materials such as loam, straw or hemp often have good physical properties for construction, which means that they have a double advantage.

In high-rise buildings, the impact of the facade in relation to the roof and base plate is even greater.

SERVICES

The energy performance of buildings is often optimized by complex and intensive building service systems. The starting point is often a relatively narrow understanding/limited idea of comfort (usually the indoor temperature) that tries to be achieved with automated measurement and control technology. In reality, however, being able to open a window is often more important for comfort. A building that is planned to have a good energy performance on paper can in practice be inadequate and even consume more energy than a conventional building.

Again, the basic principles apply: the most efficient cooling is the cooling that is not needed. This can be achieved if a building has a good orientation to the sun, employs the right materials, and makes good use of shading and natural ventilation. Carefully combined with automated and user controlled systems , such passive strategies can provide higher comfort while being more robust in unpredictable situations. Solar panels, which are by far the largest emitters, still make sense because they can ultimately make the building energy positive

SPACE PLAN

Spaces in a building often change function. A bedroom becomes a living room, which then becomes a home office which later becomes a nursery. If our floor plans can be used flexibly, walls and doors do not have to be moved. And if we do want to change interior layouts at some point, it is an advantage if the elements are demountable. These can be flexible walls and standardized elements, but they can also be materials such as wallpaper that protects the stucco.

Interestingly, cement screeds, which are often used in modern wood construction for acoustic insulation, are responsible for a large share of a building's CO_2 emissions. They are often replaced when an interior layoutis rearranged, so they also have a relatively short lifespan.

STUFF

What happens in and around buildings determines 89 percent of our emissions. Designers should devise housing where people can live healthy lives, in cities where they can work within biking distance, and where they can find meaning without unnecessary material consumption or vacations. These cities should be climate-proof and allow easy access to most necessities.

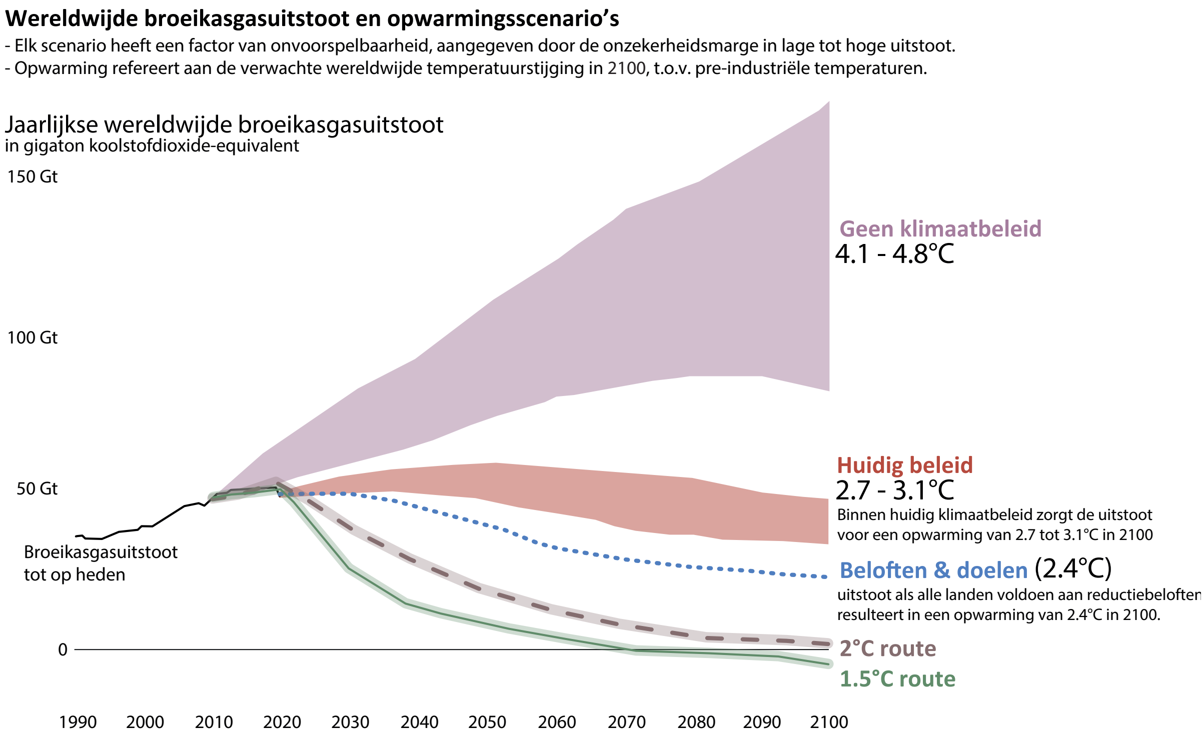
INTRODUCTION

GLOBAL WARMING

Despite global efforts to reduce **CO_2 emissions**, we are still far from the goal of keeping the global temperature rise below 2 degrees. The share of the constructi-on sector is currently estimated at 38 percent. There are huge opportunities here to reduce emissions and even contribute to the reduction of CO_2 in the atmosphere. Through this research, we want to explore the possibilities of **CO_2 emission reduction and storage** in residential construction and understand the role designers, clients, and builders can play in it.

FIGURE 2.

Future scenario of gloabal warming due to greenhouse gases. Source: Climate Action Tracker (May 2021). Based on national policies and pledges as of May 2021.



FROM NET-ZERO HOMES TO NET-ZERO CONSTRUCTION

The CO_2 emissions of a building include all emissions that arise during the use of the building and that arise during construction in the production, transport and assembly of building materials. The design of so-called net-zero **homes**, where net energy con-sumption is reduced to zero, is already the norm in many countries. But this only con-cerns the **operational emissions**. Meanwhile, the construction process and produc-tion of the building materials also have a major impact, which is still often disregarded. We call this **embodied carbon emissions**.

3 United Nations (2020). *United Nations Environment Programme Emissions Gap* Report 2020, Nairobi.

RULES OF THUMB FOR CARBON-BASED DESIGN

Through this research we want to gain insight into the CO_2 cycle and what role the construction sector plays in it. The focus is on the **embodied carbon** in residential buildings. By understanding the construction process and which parts of it have the most impact on climate change, we can adjust our design and development strategy accordingly. The earlier in the process, the better. The first step is to provide insight into the existing knowledge and thus to make us aware of the possibilities that we have as designers and developers. Then, on the basis of a number of established design principles, the possibilities for Carbon-Based Design are explained in more detail.

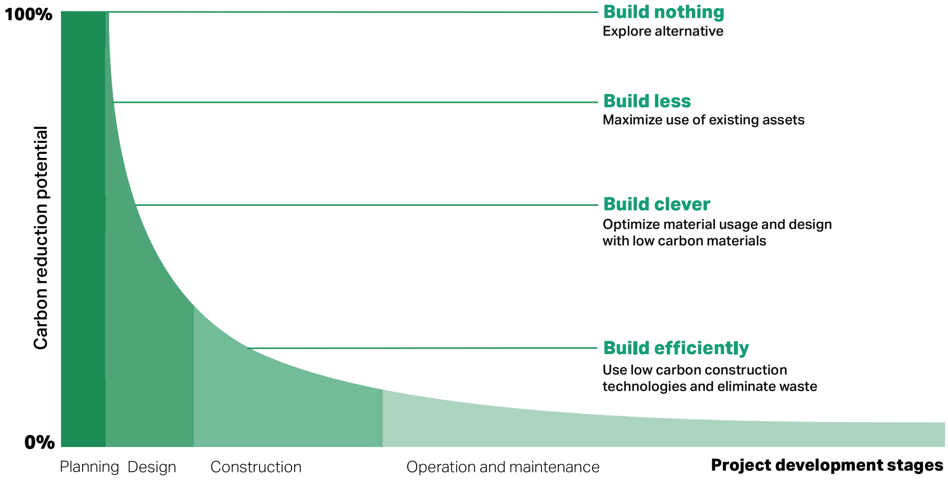


FIGURE 3.

Opportunities to reduce embodied carbon across all project phases. Bron: Churkina, G. et al. (2020). *Decarbonizing construction. Buildings as a global carbon sink.*

FROM BIGGEST POLLUTER TO CO_2 CATCHER

How can we ensure that the 1,000,000 new homes needed in the Netherlands by 2030 put as little pressure as possible on the already hard-to-achieve climate goals? Even if all future homes are built according to current agreements, that of the **BENG** (Near Zero Energy Building) and of a four percent reduction of emissions in the industry, the **CO_2 budget** for construction (in a 1.5-degree warming scenario) will run out in 2026.

Instead of building 'less badly', can we even build in a 'good' way for the environment in the future by allowing building materials to store CO_2 for a long time and thus extract it from the atmosphere? How can we as a construction industry, instead of being the problem, contribute to the solution to the enormous CO_2 emissions with all its climate consequences? These are the questions we intend to formulate answers to in the following chapters.

4 Mooij, M. (2021, Nov. 23). ***Congres Paris Proof Embodied Carbon Dutch Green Building Council***. https://www.dgbc.nl/agenda/congres-paris-proof-embodied-carbon-334

APPROACH AND METHODOLOGY

The following steps were taken to arrive at the desired design principles:

LITERATURE REVIEW

An analysis of existing literature and knowledge on the CO_2 cycle, on CO_2 emissions and capture in the atmosphere and in the built environment as well as associated calculation methods and regulations.

UNDERSTANDING THE CO_2 CYCLE

A study of the CO_2 cycle and the role of the construction industry in the cycle was done to understand our position and all aspects relating to it.

MPG AS A MEASURE OF CO_2 EMISSIONS IN A BUILDING

To apply for a building permit, an **environmental performance of buildings (MPG)** must always be calculated. The basis for this calculation is the **life cycle analysis (LCA)** of the building components and materials. We used this calculation method to provide insight into the CO_2 emissions of a building.

CASESTUDIES

Several reference projects have been collected and analyzed to understand the impact of design choices on the total embodied carbon and related CO_2 emissions of a building. These are all housing projects where different building densities were considered (high-density urban context, low-density/suburban context and rural/extra-urban context).

DESIGN PRINCIPLES

From both the literature review and the analysis of reference projects, several design principles were compiled, where minimizing CO_2 emissions is paramount.

STRUCTURE OF THE REPORT

INTRODUCTION

The background, problem statement, goals, questions, approach and method, and structure of this report are described here.

I. INTRODUCTION TO THE CO_2 CYCLE

The most important terms and concepts of the CO_2 cycle are explained and defined, whith a focus on the building level.

II. EMBODIED CARBON

A description of the impact that embodied carbon has in construction and how this is measured as well as what the current policies around these emissions are.

III. DESIGN PRINCIPLES

Several design principles have been formulated to help reduce embodied carbon in the design of housing. These design principles are organized from large to small and according to the **S-layers** from **Stewart Brand** and tested on the design strategies of CB'23 as general design principles.

IV. CASESTUDIES

The environmental impact was assessed for 24 housing projects using the **MPG-** and **EPC/BENG-** calculation. In this way, we can find out which parts of a building have the greatest impact and what effect certain design choices have. Six projects were chosen to analyze in further detail.

V. POLICY RECOMMENDATIONS

In this study, we encountered a number of limitations in current policies, in particular those related to the environmental performance of buildings, which calculate the environmental impact of the materials used in a building. This chapter describes these limitations and provides recommendations for policy developments.

VI. INDEX

An alphabetical listing of abbreviations and terms used in this report. The terms that can be searched for in the index are identified in the report by the **blue bold** text.

I.

THE CO_2 CYCLE

A NATURAL BALANCE

Almost everything we see around us is made up of carbon: we are made of it, we eat it, we burn it, and our economy runs on it. Carbon has always played an important role in our existence and always will. The short-term carbon cycle consists mainly of flows of carbon between different life forms on Earth and between the different 'spheres'. Per year, around 400 gigatons of carbon move through the short-term carbon cycle. However, CO_2 is also released through the weathering of rocks, eruption of volcanoes and especially through the biological process in the oceans.

Carbon concentrations were also higher in prehistoric times than they are today. After millions of years, however, this so-called long-term carbon cycle has reached a natural equilibrium, with the amount of carbon in the **atmosphere** (air), the **oceanosphere** (sea), the **lithosphere** (Earth's crust) and the biosphere (flora and fauna) remaining in balance and thus stabilizing the earth's temperature. These stable conditions are the basis for the world we know and the civilizations that have developed in it. However, since industrialization, humans have had an increasing impact on the CO_2 cycle, and this has led to unprecedentedly high concentrations of CO_2 in the atmosphere. We call the human impact the **technosphere**.

FIGURE 4.

Carbon-cycle. All quantities are given in gigatons C.

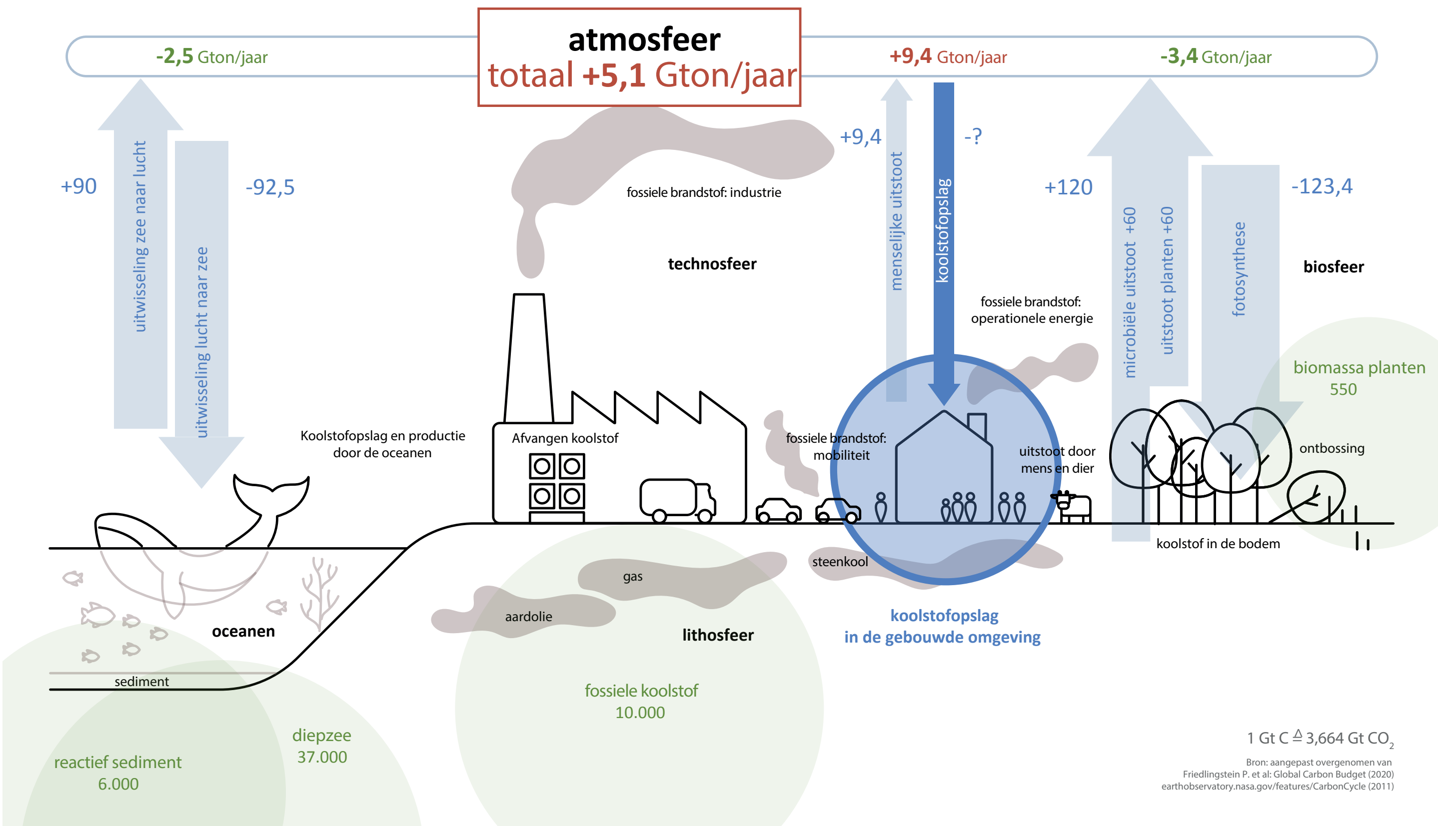
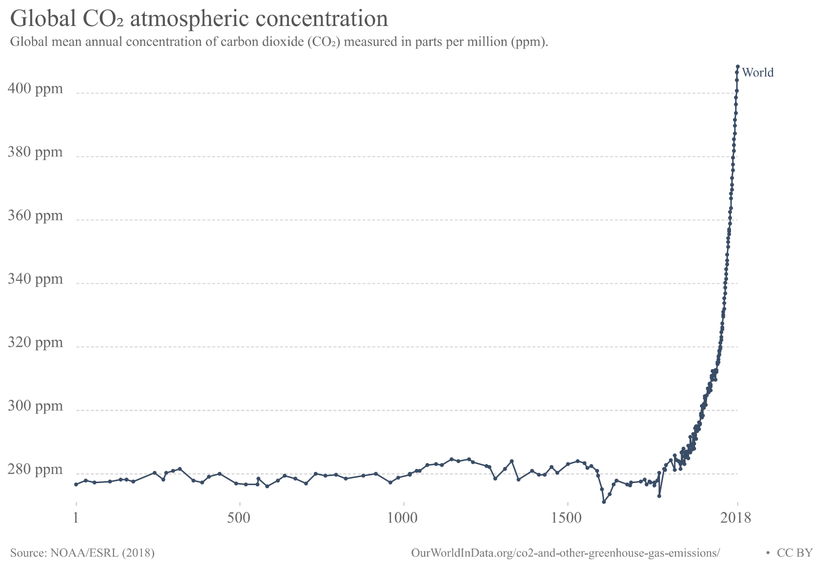


FIGURE 5.

Atmospheric CO_2-concentration over the past 2000 years (short term).



THE TECHNOSPHERE

The amount of carbon in the atmosphere and the earth's temperature are inextricably linked and constantly influence each other. Currently, human activities are disrupting the natural balance of the carbon cycle. By burning fossil fuels and clearing land, we are emitting additional carbon dioxide into the atmosphere and removing plants and trees that absorb carbon during their growth period. This releases carbon from the long-term cycle (fossil fuels created over millions of years) into the short-term cycle (carbon in the atmosphere). Of the nine gigatons of human **CO_2 emissions** per year, five gigatons are reabsorbed by plants and the oceans, but four gigatons of these human emissions remain in the atmosphere. This raises the earth's temperature, acidifies the oceans and disrupts natural plant growth. This effect is also compounded by forest fires, thawing permafrost, drying soil and deforestation. The effects of these are already being felt, but to what extent human influence is going to upset the balance on the planet depends on how we act with today's knowledge.

FIGURE 6.

Carbon sinks trough-hout history. Source: Churkina, G. et al. (2020). *Decarbonizing construction. Buildings as a global carbon sink.*

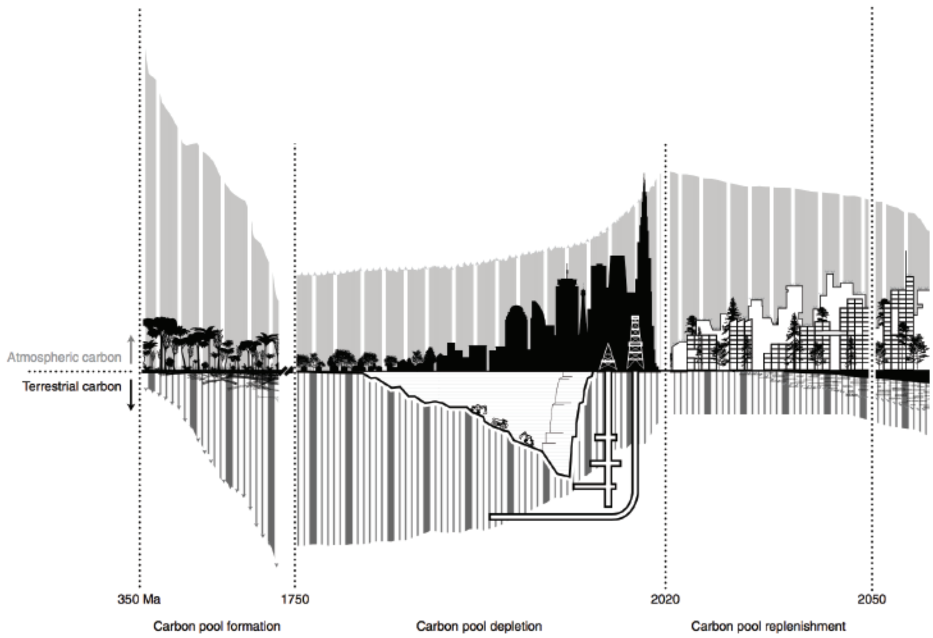
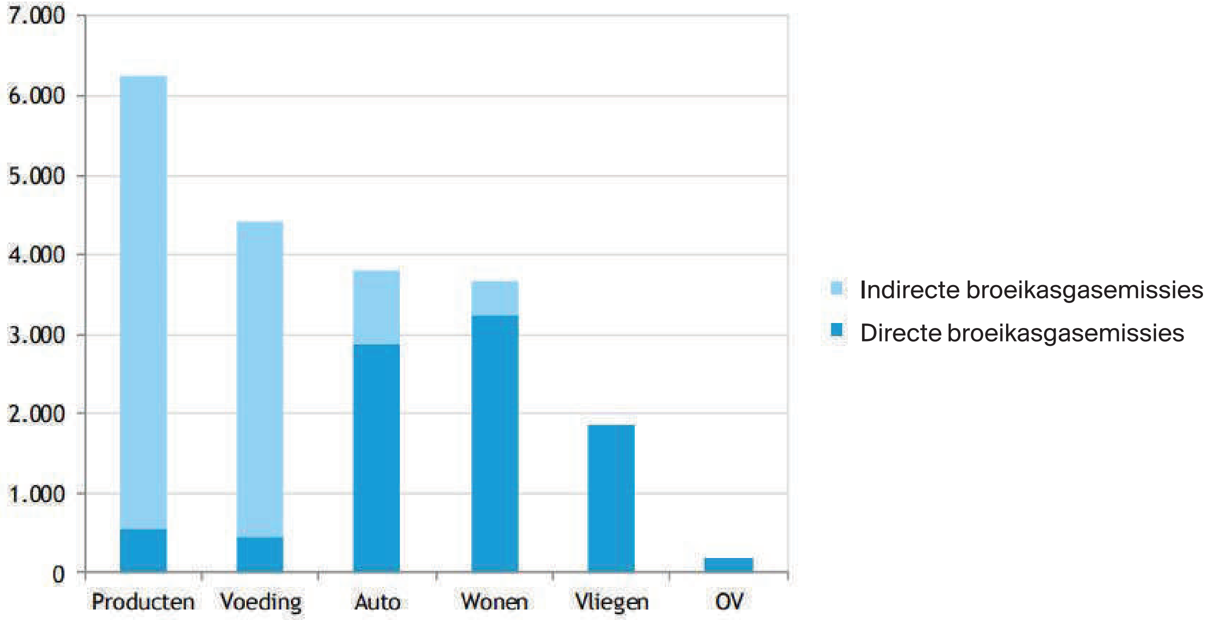


FIGURE 7.

Annual greenhouse gas emissions.

Source: CE Delft (2019), *Uitstoot broeikasgassen in Nederland. Een analyse van de sectoren en bedrijven met de meeste uitstoot.*

JAARLIJKSE BROEIKGASUITSTOOT (KG CO_2-EQUIVALENTEN) PER CATEGORIE PER HUISHOUDEN



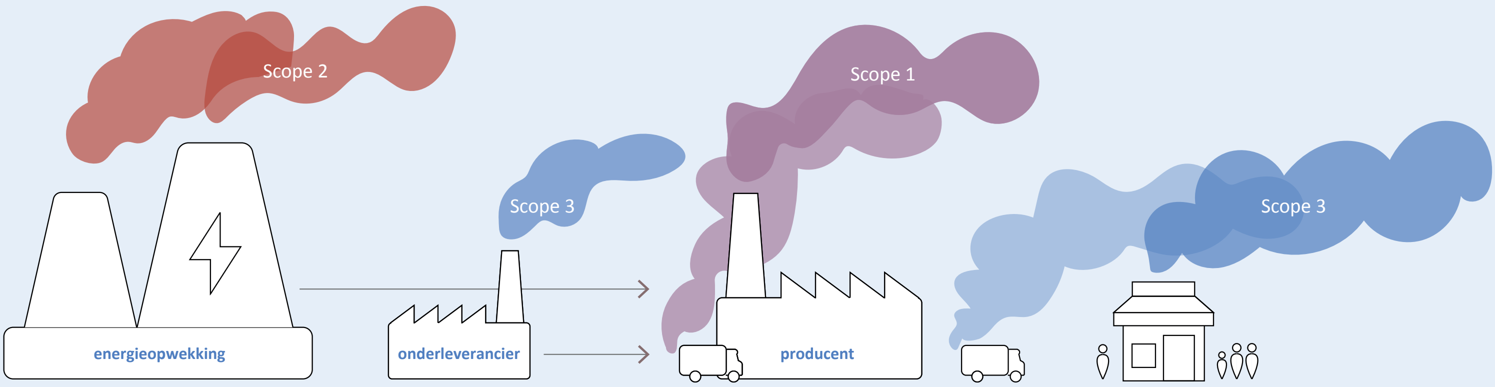
CO_2 FOOTPRINT

First of all, it is important to gain an insight into the carbon footprint of the average Dutch consumer. On average a Dutch person emits ten tons of CO_2 per year, for a household the average is twenty tons of CO_2 per year. This includes everything: from all the things we buy, the energy we use in our homes, car use and flights, to the food we consume. Housing accounts for eighteen percent of our carbon footprint. Included are the total emissions from both the construction process and materials, as well as the energy used in the home. Not included are other construction activities such as infrastructure and non-residentialconstruction.

5 Bergsma G. et al., (2020). **Top 10 milieubelasting gemiddelde Nederlandse consument.** CE Delft, Delft.

EMISSIE SCOPES 1, 2 EN 3

Greenhouse gas emissions are defined in three groups or "scopes" by the internationally recognized Greenhouse Gas Protocol (GHG Protocol). Scope 1 includes the direct emissions of a user. Think gas consumed in the home or the gasoline consumption of a car. Scope 2 includes the indirect emissions from the generation of purchased energy. This includes electricity that is consumed in the home, but whose generation takes place elsewhere. Scope 3 are all other indirect emissions linked to services or products that you as a user cannot influence. These include emissions from the production or extraction of materials for consumer products and emissions from transportation.



Uitstoot in scope 2:
Uitstoot van de door een bedrijf aangekochte elektriciteit

Uitstoot in scope 1:
Uitstoot van de faciliteiten en voertuigen van een bedrijf die onder eigen beheer vallen

Uitstoot in scope 3:
Uitstoot hoger en lager in de keten. Bijvoorbeeld:

Door leveranciers en distributeurs, zakelijk reizen door medewerkers en het gebruik van verkochte producten

A distinction has been made between direct greenhouse gas emissions, e.g. gas or energy consumption in the home and fuel consumption for the car (**scope 1&2**); and upstream or downstream emissions (for example, emissions emitted in the production of products or food consumed or purchased by consumers; **scope 3** emissions). Scope 1 and 2 are relatively easy to determine. Scope 3 requires an analysis of the entire life cycle and is therefore often left out of consideration. However, this leads to a distorted picture and possibly to an 'outsourcing' of emissions. If, for example, construction steel was to be imported from abroad, Dutch emissions could drop dramatically. However this would make no difference to global carbon emissions.

THE IMPACT OF LIFESTYLE

Without wanting to downplay the need for CO_2 emission reduction in construction, it is important to look beyond the direct and indirect greenhouse gas emissions of housing alone. When planning and designing homes, in addition to the CO_2 emission during the construction process and usage phase, we can also influence the lifestyle of the occupants. Enabling a sustainable lifestyle can result in a large reduction in the overall carbon footprint, even greater than what we can achieve by using sustainable building materials.

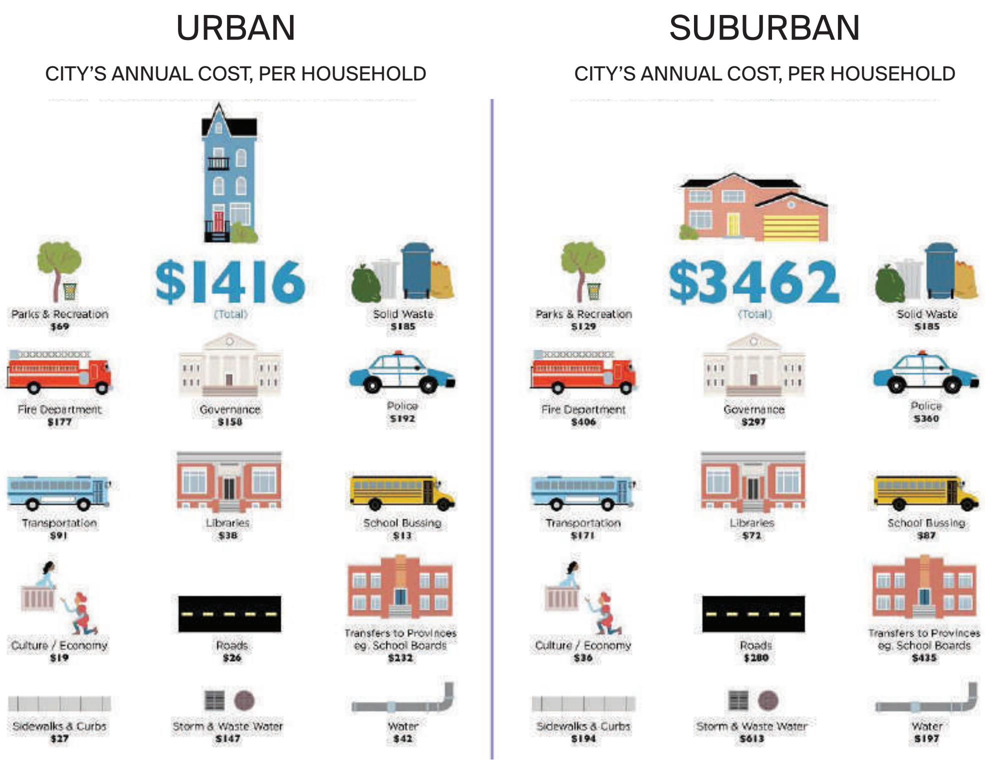
Thus, it is not necessarily better to reduce the carbon footprint of the structure as far as possible—for example through prefabricated(?)building modules (often in low-rise buildings)—if this results in more commuting and additional infrastructure as a side effect.

The focus of this report is on embodied carbon in housing, but when you include lifestyle in the design process, the trade-off can be made for a higher 'carbon investment' in the building materials if this ultimately leads to a lower footprint for the occupants. High-rise buildings for example, with a heavier construction and therefore greater 'CO_2 investment', can pay off in a low footprint of the residents if they live in an area with sufficient public transport and where cycling is the main mode of transport.

FIGURE 8.

Costs and amont of infrastructure per building density.

Source: Infographic by Sustainable Prosperity; Image via streetsblog.org, based on study of Halifax Regional Municipality in Nova Scotia.



The diagram above shows the amount of infrastructure and services needed per dwelling by building density. Similar research by the Flemish Government Architect also indicates that sprawled housing developments require up to nine times as much infrastructure as a housing in central urban areas. This information is not taken into account when applying for an environmental permit for a building project, nor in the MPG calculation, but it does have a major influence on the CO_2 impact of construction

EXAMPLE CALCULATION OF CO_2 FOOTPRINT PER HOUSEHOLD

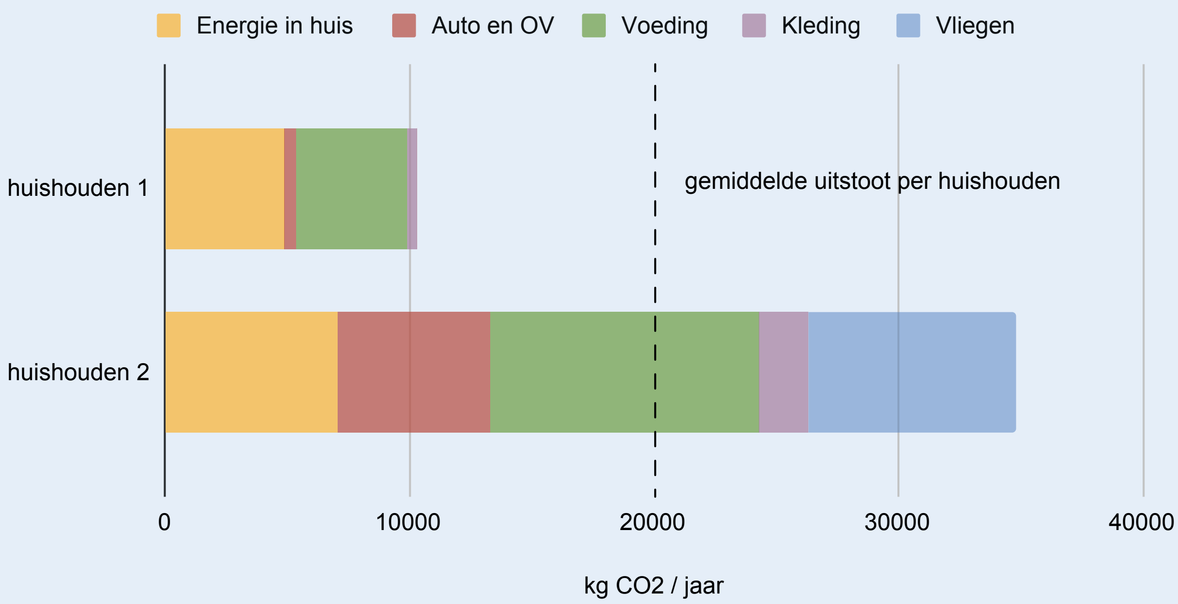
The calculation example below provides an insight into the large variations in carbon footprint of different households or individuals and how this relates to the embodied carbon of a home.

The average carbon footprint of a Dutch household is 20,000 kg of CO_2 per year . This includes transport, energy consumption, food, vacations and daily consumption. However, this is an average and the variation is very large, depending on lifestyle choices and possibilities opportunities(?).

For a four-person household that eats vegan, travels by public transport, buys second-hand clothing and goes on vacation close by, the emissions are 10,400 kg per year. A four-person household that eats meat and dairy daily, makes weekly online orders, of which one person commutes to work by car daily and the entire household flies on holiday twice a year, ends up with emissions of 34,500 kg per year. The difference is more than threefold. So, lifestyle has a highly significant impact on the carbon footprint of a person or household.

FIGURE 9.

Emissions four-person household with a sustainable lifestyle compared to households with a unsustainable lifestyle. Source: Milieucentraal (2021). *Tests en Advies op maat* (rekentool).



6 Milieucentraal (2021). ***Tests en Advies op maat***. https://www.milieucentraal.nl/over-milieu-centraal/tests-en-advies-op-maat/

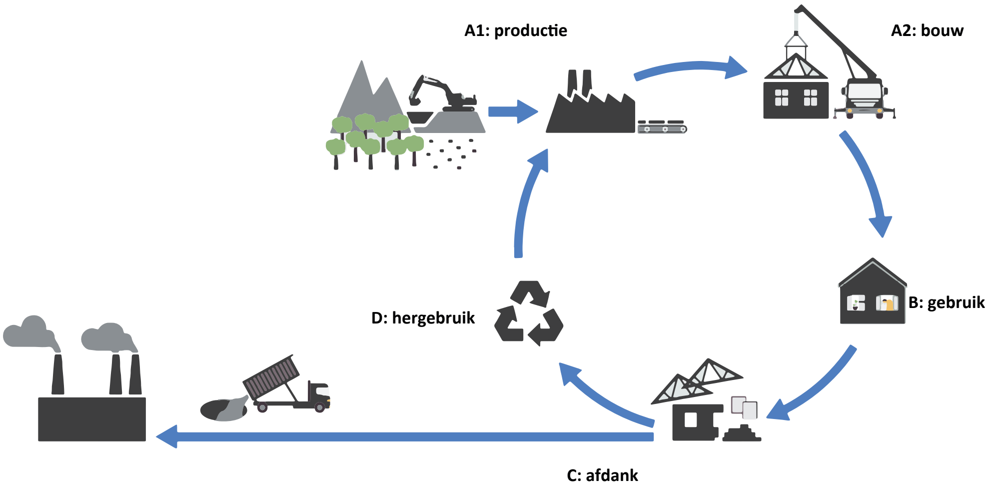
CO_2 CYCLE OF A BUILDING

The life cycle of a building consists of several phases. In each of these phases, CO_2 is emitted. The phases are divided as follows:

FIGURE 10.

Life cycle of a building.

Source: Danish Transport and Construction Agency, (2016). *Introduction to LifeCycle of Buildings; Trafik-Og Byggestyrelsen.*



A - PRODUCTION AND CONSTRUCTION PHASE

The production phase includes the extraction of raw materials, the transportation to the factory, and the processing of construction materials and products at the factory. The transportation of materials to the construction site as well as the construction activity fall into the construction phase.

B - THE USAGE PHASE

The usage phase includes the building's energy use, maintenance and repair of the building, replacement of building elements when they reach the end of their useful life, and renovations needed to keep the building usable.

C - END OF LIFE PHASE

The end of life phase includes demolition, disassembly, transport of residual materials, and waste disposal.

D - REUSE OR RECYCLING PHASE

By this we mean the reuse and repurposing of the building materials after a building has reached the end of its life cycle. The recycling phase is a very important phase to reduce emissions and is seldom used in a traditional linear building process, if at all. The transition to a circular building economy will make this phase increasingly important and largely replace the production and disposal phase

EMBODIED AND OPERATIONAL EMISSIONS

There is an important distinction between the **embodied emissions** and the **operational emissions** of a building

EMBODIED EMISSIONS

The embodied emissions of a building are all emissions generated during the production and construction phase, the maintenance and renovations in the usage phase, as well as during the disposal phase and, if applicable, the reuse phase. To summarize, the embodied emissions represent everything that is emitted to obtain the physical mass of a building.

OPERATIONAL EMISSIONS

Operational emissions are all emissions caused by the use of a building in the form of electricity, gas, water and heating. When operational energy is generated by fossil fuels or biomass, CO_2 is emitted. To reduce operational emissions, we need to minimize our consumption and switch to renewable energy.

Since the 1990s, increasing attention - as well as increasingly stringent requirements - has been paid to the energy consumption of buildings. Initially through the **EPC (Energy Performance Coefficient)** and, since 2020, new buildings must meet the requirements for **BENG (Near Zero Energy Buildings)**, which brings operational energy consumption to near zero. Although there was much resistance and doubt about the feasibility of these ambitions, it appears that the construction industry has adapted quickly and innovatively to meet these goals. Policy has a major impact and thus plays an important role in the transition to a sustainable construction sector. However, good operational performance is often achieved through high material investments in the initial phase. This largely shifts emissions to the production and construction phase.

FIGURE 11.

the life cycle phases of a building in which material-related emissions are emitted are shown in blue.

Source: EN 15804.

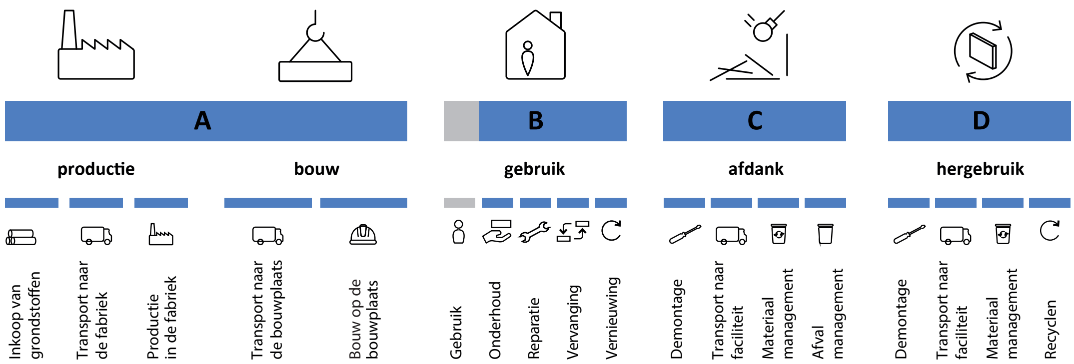
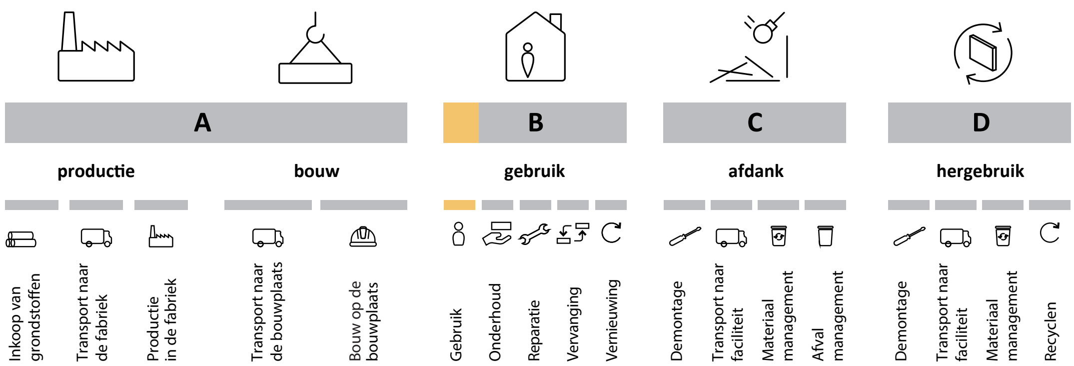


FIGURE 12.

The life cycle phases of a building in which operational emissions are emitted are shown in orange.

Source: EN 15804



EPC: ENERGY PERFORMANCE COEFFICIENT

The energy performance coefficient expresses the energy performance of a home. This refers to operational energy; it does not include embodied energy. This index was used from 1995 to 2020 and was mandatory to submit with a building permit application. At the start in 1995 a house had to meet the requirement of at least 1.4,while in the last years until 2020 it was 0.4. A value of 1 is equivalent to how an average home performed in 1990. Thus, a home with an EPC value of 0.4 consumes forty percent of the energy that the same home would have consumed in 1990. As of January 1, 2021, EPC has been replaced by BENG.

BENG: (BIJNA ENERGIENEUTRALE GEBOUWEN): NEAR ZERO ENERGY BUILDINGS

BENG establishes the energy performance requirements for new buildings in the Netherlands. All permit applications for new constructions (residential and non-residential) after January 1, 2021, must meet the BENG requirements. The assessment method used is NTA 8800. The BENG requirements replace the EPC. The energy performance in BENG is determined on the basis of three individually achievable requirements

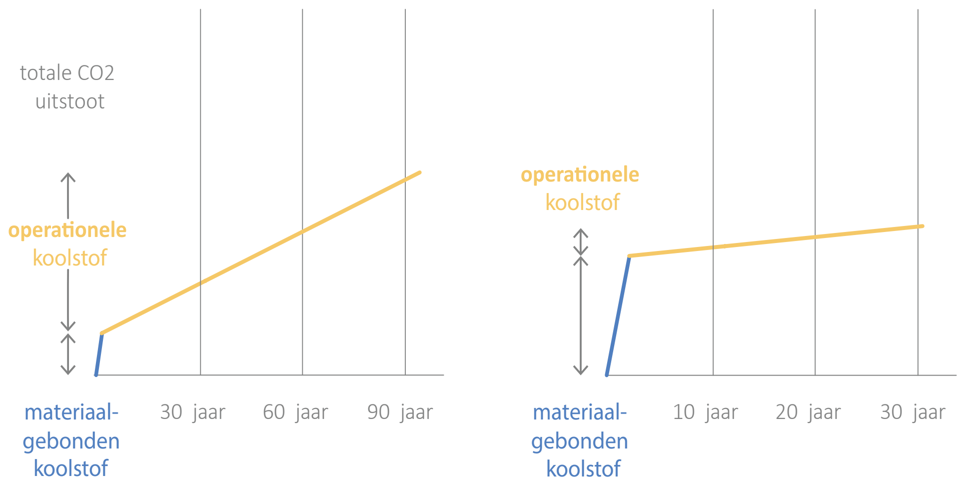
1. The maximum energy demand in kWh per m^2 of useable area per year ($kWh/m^2/yr$).
2. The maximum primary fossil energy consumption, also in kWh per m^2 of useable area per year ($kWh/m^2/yr$).
3. The minimum renewable energy share in percent. (%).

EEMBODIED AND OPERATIIONAL EMISSIONS

Embodied and operational emissions cannot be assessed separately. For example, low embodied carbon in a building can be achieved by using less building materials (in left graph below). However this may result in the building not being well insulated and therefore consuming more energy for heating and cooling. In the first few years, emissions will be low because few emissions occurred during construction, but over all the years that the relatively high operational emissions are (re)emitted, that difference shrinks and the total emissions end up being higher compared to that of a well-insulated building with higher embodied carbon (figure on the right).

FIGURE 13.

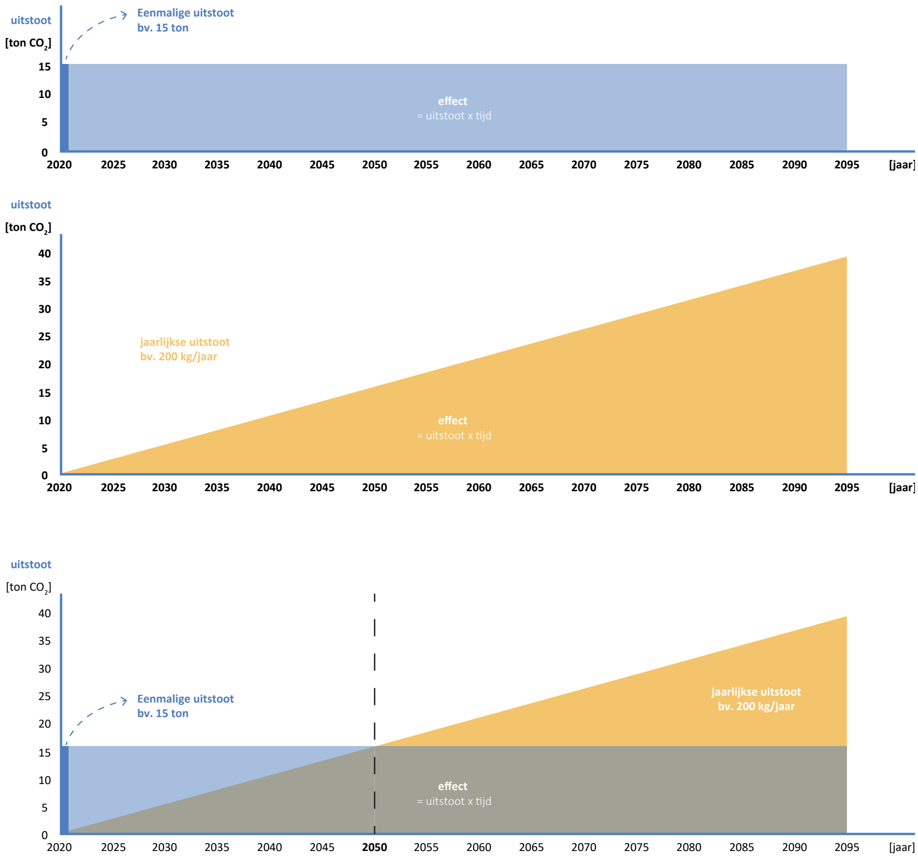
operational energy and material-related energy on a 90-year timeline. Left: low embodied carbon with high operational carbon. Right: high embodied carbon with low operational carbon.



The tendency to get operational emissions down as far as possible has caused a relative but also an absolute growth in embodied carbon. Large quantities of petroleum-based insulation materials, heavy mechanical installations and large quantities of solar panels are used to minimize the energy consumption of buildings. At the same time, the lifespan of buildings is becoming shorter in some cases, because optimizing them for specific functions makes repurposing them more difficult. Because these so-called net-zero homes often disregard embodied carbon, they seem at first to be a very good thing, although the total emissions per year of use over the lifespan of the building may not necessarily be lower

FIGURE 14.

The effect of emissions over time: damage accumulation. The longer the CO_2 is in the atmosphere, the more damage it does.



TIME VALUE OF CARBON

Embodied emissions are released for the most part at the beginning of the construction process, while operational emissions are emitted evenly throughout a building's life cycle. The time factor is important to consider. The damage that emissions cause to our planet is not equivalent to the absolute amount of **CO_2 Emissions**. The longer CO_2 stays in the atmosphere, the more damage it causes. The CO_2 that we emit today causes damage over a longer period of time than the CO_2 we emit in twenty years (principle of linear accumulation of damage from Werner Sobek).

In the graph above, a building with an equal absolute amount of embodied emissions (15,000 kg once during construction in year 0) and operational emissions (200 kg per year over 30 years = 15,000 kg total) is plotted on a 30-year timeline. The 15,000 kg of embodied emissions is present in the atmosphere for the entire thirty years, while the operational emissions slowly increase and is only present in the total amount in the atmosphere after thirty years. Over these thirty years, the operational emission caused half as much damage as the embodied emissions. This is also called "the time value of CO_2" or the principle of "linear damage accumulation".

CLIMATE IMPACT = EMISSIONS X TIME

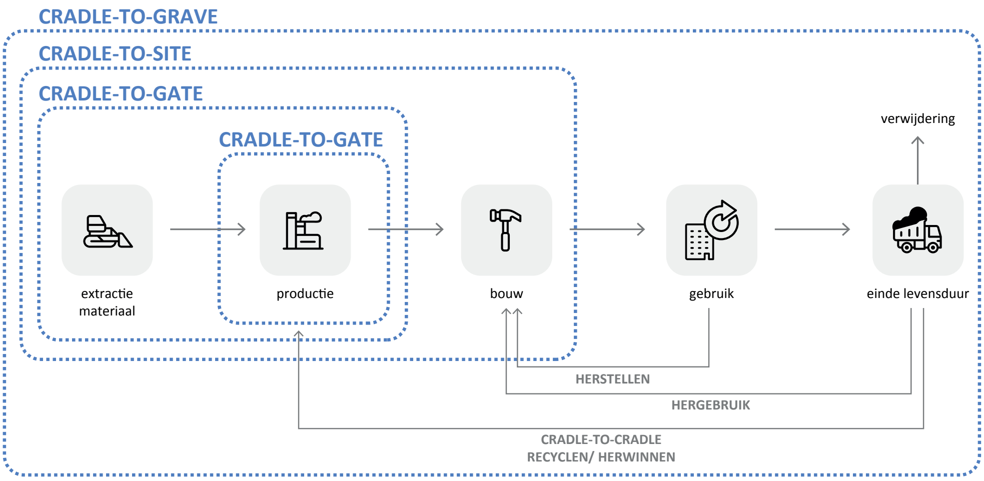
II. EMBODIED EMISSION

HOW CAN WE QUANTIFY EMBODIED CARBON?

The embodied carbon of a building can be measured by looking at the emissions in the life cycle of the components. These emissions are calculated by means of a **life cycle assessment (LCA)**. The results of aa product's LCA can be recorded in an **Environmental Product Declaration (EPD)**. A product's life cycle assessment looks at all the emissions a product has caused from **'cradle-to-grave'**. In a linear economy, this includes everything from raw material extraction to waste disposal. In the transition to a circular economy, we will begin to look at life cycles as **'cradle-to-cradle'**, where a discarded product can be reused or serve as a raw material for a new product. In preparing an LCA, only the part **'cradle-to-gate'** is to be determined with certainty. The construction, use and disposal phases will be different for each construction project and are therefore entirely based on assumptions.

FIGURE 15.

Life cycle analysis. Source: Baumann, H., Tillman, A. (2004). Hitch *Hiker's Guide to LCA. An Orientation in Life Cycle Assessment Methodology & Applications.*



The EPD describes the unit of the element (e.g., m^2), the various factors of environmental impact, and the **environmental cost indicator (MKI)**. By means of the MKI, different products can be compared with each other. Naturally, the material specifications, such as load-bearing capacity or fire safety and insulation performance, must be similar in order to make a fair comparison in terms of environmental costs.

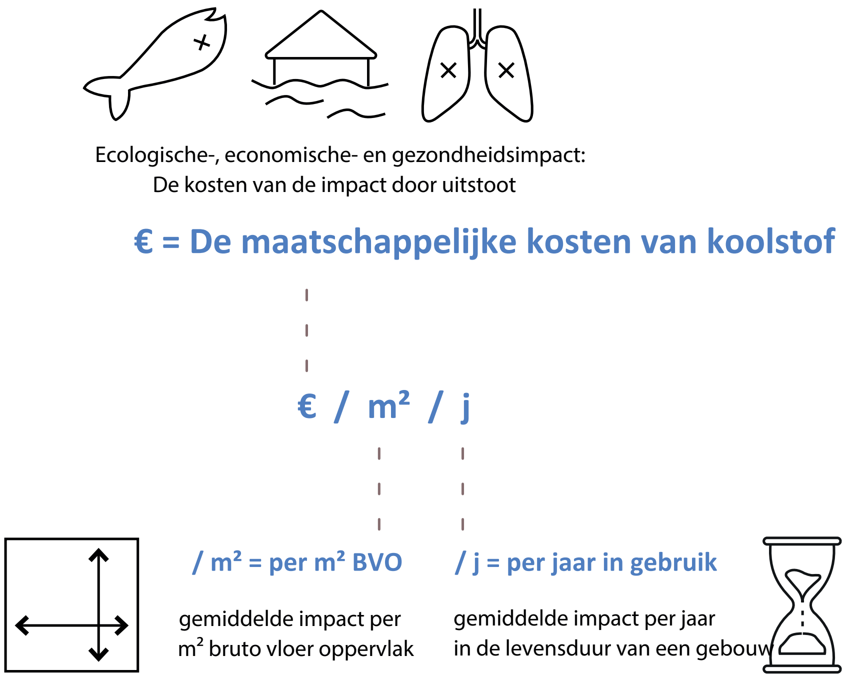
In addition to the environmental impact, the expected life span is also considered. This is important in a construction project where many different products are used. A product with a lifespan of 15 years must be replaced five times if the building has a lifespan of 75 years. The environmental impact of this product must logically be counted five times compared with a product with a life span of 75 years in the same building.

THE ENVIRONMENTAL PERFORMANCE OF A BUILDING (MPG)

The **environmental performance of a building** represents the environmental impact of a building. This concerns the environmental impact of the construction process and the materials, not the impact of the operational energy consumed during the usage phase. An MPG calculation is mandatory for any application for an environmental permit for new office buildings (larger than 100 m^2) and new homes. The MPG is calculated by taking the environmental impact from the **EPD**s per building material and multiplying it with the quantity in which they have been applied in the building. This is done with a calculation tool (e.g. One Click LCA, GPR Materiaal, MRPI, MPG Calc, DuboCalc). The MPG is expressed as a fictitious price in euros, i.e. the **shadow costs**. This involves normalizing the various environmental impacts such as CO_2 emissions, heavy metal loads and the like through the assumed social costs of these impacts. These are then added together and divided by the **gross floor area in** square meters and the **life span** of the building . The unit of the MPG shadow cost then becomes euro per square meter per year. In this way, different buildings, with varying surface areas and lifespans, can be compared.

FIGURE 16.

Unit of MPG. Schaduwc osts per square meter per year.



An MPG calculation is often made by an external party who is not directly involved in the design process. If the design does not meet the MPG requirements, this expert can make recommendations to the designer, for example, on adapting materials in order to ultimately meet the requirements. This calculation is often made late in the design process, so that major design adjustments are no longer possible. Nowadays this is not a pressing problem because the requirements are relatively easy to meet. However, as the MPG requirements become more stringent in the future, this problem will become all the more critical.

LCA: LIFE CYCLE ASSESSMENT

An LCA calculates the environmental impact of all the processes and raw materials needed to make a product. A life cycle assessment can be done for a material, product, and building, but also for a process or a company. It is a method to quantify the total environmental impact of a product or service. In this way, insight can be gained into the critical elements and alternatives can be examined. The result of an LCA can be used to determine a sustainability strategy and to communicate environmental performances to customers or suppliers.

The difference between an LCA and a carbon footprint is that a carbon footprint only quantifies greenhouse gas emissions, while an LCA considers multiple environmental impact categories, including land use, water use and acidification.

EPD: ENVIRONMENTAL PRODUCT DECLARATIONS

An EPD consists of the results of a life cycle assessment of a product. The manufacturer is responsible for preparing an EPD of its products. However, this is not mandatory. An EPD contains all information and details about the environmental impact over the entire life cycle of a product according to standard EN 15804+A2.

NMD: NATIONAL ENVIRONMENTAL DATABASE

The National Environmental Database contains all EPDs available in the Netherlands. This database is managed by the NMD Foundation, formerly the Building Quality Foundation (SKB). For a building product to be included in the NMD, the following requirements must be met:

- The life cycle assessment for the preparation of the SPD must be performed by an LCA expert recognized by the NMD Foundation
- An annual fee must be paid to include the EPD in the NMD.

For these reasons, far from all existing product-specific EPDs are included in the database. As a solution to this, product-generic EPDs are available, these are however subject to an additional thirty percent environmental impact, as no product details are available.

MKI: ENVIRONMENTAL COST INDICATOR

A life cycle assessment calculates the environmental impact of a material, product or structure. These environmental impacts (multiple numbers with different units) can be converted into one integral number: the environmental costs, expressed in euros. These environmental costs are also called shadow costs.

MPG: ENVIRONMENTAL PERFORMANCE OF BUILDINGS

Since 2013, an MPG calculation must be submitted for every new building permit applied for in the Netherlands. This is calculated by the amount of building materials in the project multiplied by the environmental impact as calculated in the EPD. To quantify the shadow costs, the total environmental cost of the building (MKI) is divided by the gross floor area (BVO) and the estimate life span of the building. The results are always in euro/m^2/year. Since July 1, 2021, the MPG value of new constructions must be below 0.8 to apply for a building permit. The MPG can be used to compare the environmental impact of different buildings. It does not include operational emissions.

PRODUCT-SPECIFIC EPD IS MORE ACCURATE THAN GENERIC DATA.

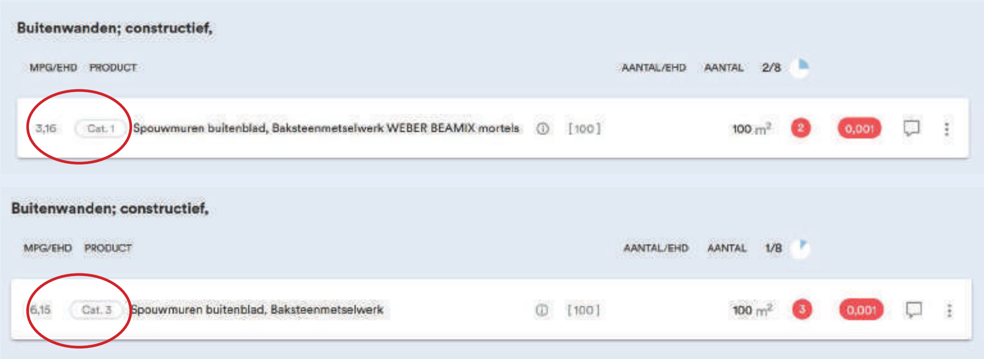
The National Environmental Database distinguishes three categories of building materials:

Category 1:	Based on data provided by manufacturers. Verified by accredited LCA experts.
Category 2:	Based on data from industry associations and supplier groups, independent of specific manufacturers. Verified by accredited LCA experts and representative of the Dutch market.
Category 3:	Generic data independent of manufacturers, unverified and based on averages. A thirty percent "penalty" is applied to the environmental impact of that particular element.

The most reliable data are the category 1 products. Unfortunately, there are still few category 1 products present in the database and therefore many category 2 and 3 products are applied. It is therefore difficult to see what the actual environmental impact of a building is because generic EPDs are used instead of product-specific EPDs.

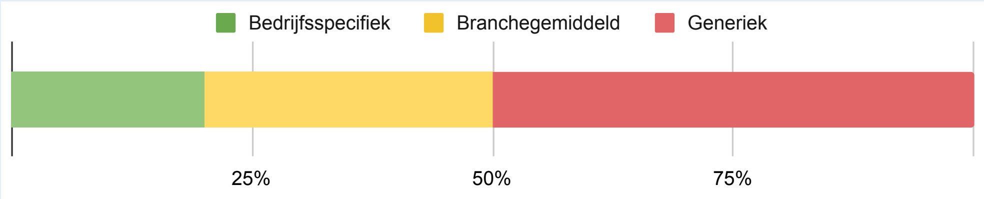
FIGURE 17.

Comparison category 1- and category 3-product in the National environmental database. Source: Nationale Milieudatabase.



The example above shows the same product, entered in the database as a category 1 and category 3 product. The environmental impact is almost twice as high for the category 3 product. Thus, when the product-specific EPD (cat 1) is not present in the database, the MPG score will be higher regardless of the actual emissions. Also, choosing an environmentally friendly variant of a material therefore has less effect if a category 1 EPD is not available.

The current version of the National Environmental Database (Reference Date 23-09-2021) consists of twenty percent Category 1, thirty percent Category 2 and fifty percent Category 3 products.



The Netherlands is one of the first countries in Europe (besides France, Sweden and Denmark) where a **LCA** in the form of the **MPG** is required by law. The MPG became a legal requirement in 2013, although the requirements are still relatively low. The plan is to adjust them step by step. As of July 1, 2021, a building must meet the requirement MPG < 0.8. Previously, the requirement was MPG < 1, which was achievable for almost any design without additional effort.

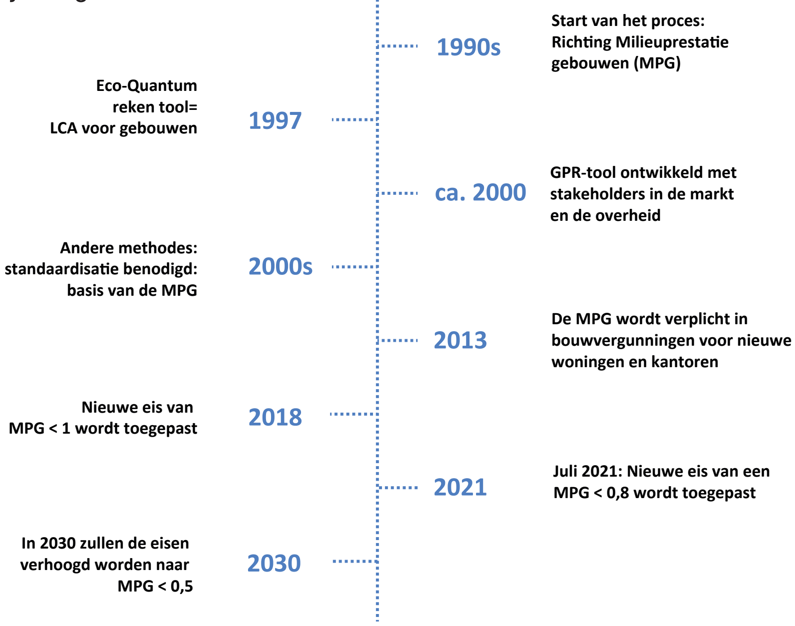


FIGURE 18.

Development of the MPG in the past and the future.

ENVIRONMENTAL IMPACT

In a **MPG**-calculation, various environmental effects are evaluated. Apart from CO_2 many other environmental effects can be distinguished, such as acidification, ozone layer depletion, depletion and toxicity. The heading 'climate change' doesn't only include CO_2 emissions, it also includes other greenhouse gases, such as methane and nitrogen. For ease other emissions are usually denoted in CO_2 equivalent, alsoknown as the **global warming potential (GWP)**. This allows different greenhouse gases to be easily compared. For example, a ton of methane emissions are ten times more harmful to the environment than a ton of CO_2 emissions. The GWP of a ton of methane is therefore equal to ten tons of CO_2 equivalent.

On average, the global warming potential, i.e. the CO_2 equivalent, covers forty percent of the environmental impacts included in the MPG calculations of the projects we examined for this study.

FIGURE 19.

Environmental effects from an example MPG calculation.

	Schaduwkosten	Milieueffecten	
Emissies	**€ 144,991,-**		
Klimaatverandering	€ 60,137,-	1,202,739	kg CO2 eq.
Aantasting ozonlaag	€ 3,-	0.1022	kg CFC-11 eq.
Humane toxiciteit	€ 43,482,-	483,128	kg 1.4-DB eq.
Zoetwater aquatische ecotoxiciteit	€ 394,-	13,148	kg 1.4-DB eq.
Mariene aquatische ecotoxiciteit	€ 5,624,-	56,239,058	kg 1.4-DB eq.
Terrestrische ecotoxiciteit	€ 521,-	8,680	kg 1.4-DB eq.
Fotochemische oxidantvorming	€ 1,504,-	752	kg C2H4 eq.
Verzuring	€ 21,558,-	5,389	kg SO2 eq.
Vermesting	€ 11,768,-	1,308	kg PO4 eq.
Uitputting	**€ 1,136,-**		
Uitputting abiotische grondstoffen	€ 5,-	32	kg Sb eq
Uitputting fossiele energiedragers	€ 1,131,-	7,066	kg Sb eq
Totaal	**€ 146,127,-**		

III. DESIGN PRINCIPLES

GENERAL PRINCIPLES

The Netherlands is working toward a circular building economy. This means using as few primary raw materials as possible. As a general principle, we can say that minimum resource use equals minimum CO_2 emissions. To achieve this, designers need to design in a different way and manufacturers need to innovate.

In addition to reducing the use of primary raw materials, we need to start reusing existing materials as much as possible. For example, a disassembled steel structure or carpet tiles. Also, switching to renewable building materials will have a big benefit in a building's carbon footprint. Consider biobased materials that in some cases sequester even more CO_2 than they emit.

CO_2-CAPTURE BY PHOTOSYNTHESIS

CO_2 is captured by the natural process of photosynthesis, which also releases oxygen, and converted into carbohydrates. When a tree grows, it absorbs CO_2 from the air, which is sequestered in the mass of the tree. When the tree dies, the CO_2 is released again during the decay process. When you use wood as a building material you can think of this as CO_2 being stored in the building material. When the tree is cut down for timber production and a new tree is planted in its place, the new tree will absorb CO_2 from the atmosphere, while the felled tree is used as building material. In this way, the CO_2 supply in the felled tree is stored for a long time in the building instead of being emitted into the atmosphere during the decay process. This principle applies to all biobased materials.

Fig. 1. Mean carbon stocks ($Mg \cdot ha^{-1}$) and fluxes ($Mg \cdot ha^{-1} \cdot year^{-1}$) in a wood-production and wood-use chain. The figure shows the stocks (boxes) and fluxes (solid arrows for carbon originating from forest, broken arrows for fossil carbon) for Scots pine sites when a 90-year rotation length is applied.

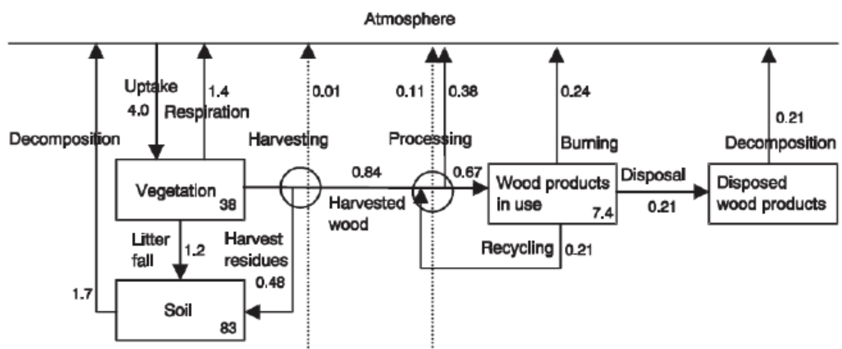


FIGURE 20.

Diagram van de CO_2-balans door fotosynthese in houtbouw. Bron: Kriegh, J., et al. (2021). *Carbon-Storing Materials: Summary Report.*

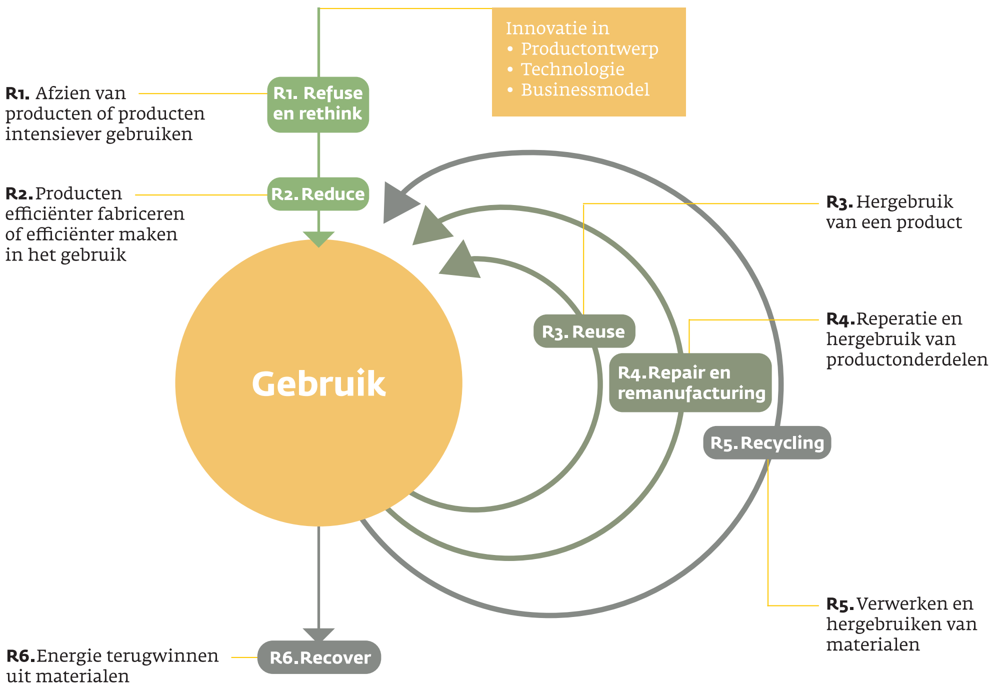
R-LADDER

The **R-Ladder** creates a hierarchy of principles for sustainable use of materials and energy, with the end goal being a circular economy. The principles are: Refuse and Rethink; Reduce; Reuse; Repair, Refurbish, Remanufacture and Repurpose; Recycle; Recover. They are ordered by rank of impact, with the first principle having the greatest possible positive impact and the last principle being the least desirable. But all six principles are better than a linear process where the residuals are landfilled at the end of their useful life.

FIGURE 21.

R-ladder. The higher up R-ladder, the lower the resource use. Source: Planbureau voor de Leefomgeving, (2019). *Circulaire economie in kaart.*

R-ladder met strategieën van circulariteit



The **R-ladder** is often used to determine the degree of circularity. We use the same **R-ladder** to qualify the found design principles. For this purpose, we use a simplified version containing the following three steps:

- **REDUCE:** (R1 en R2) - Reducing consumption and production and making and using products in a smarter way.
- **REUSE:** (R3 en R4) - Extending the life of products and components.
- **RECYCLE:** (R5 en R6) - Putting to use materials that would otherwise be landfilled.

8 Rijksdienst Voor Ondernemend Nederland. (2021, April 28). ***R-ladder - strategieën van circulariteit.*** https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/circulaire-economie/r-ladder

DESIGN STRATEGIES OF WORKING GROUP CB'23

Platform CB'23 has the ambition to establish national, industry-wide agreements regarding circular construction before 2023. To this end, a guidebook has been prepared containing various design principles for circular construction. These translate the R-ladder into more concrete guidelines for construction. Because circular building and CO_2 reduction go hand in hand, we designate these as basic strategies

REDUCE

1. DESIGNING FOR PREVENTION

This strategy focuses on avoiding the use of construction products, elements or materials by abstaining form building, trying to cleverly combine different functions or providing a different solution.

REDUCE

2. DESIGNING FOR LIFE CYCLE IMPACT REDUCTION

In this strategy, the effect of circular materials is evaluated by understanding their environmental impact and environmental performance both in the usage phase and at the end of life.

REUSE

3. DESIGNING FOR FUTURE-PROOFING

Making the design adaptable for future needs and requirements is central to this strategy.

REUSE

4. DESIGNING WITH REUSED OBJECTS

This strategy involves the reuse of building products or building components/elements, before or after their production.

RECYCLE

5. DESIGNING WITH SECONDARY RAW MATERIALS

This revolves around designing with raw materials that have been previously used or with waste material from another product system.

RECYCLE

6. DESIGNING WITH RENEWABLE RESOURCES

This strategy is about designing with only or as many building materials from renewable sources as possible. Renewable raw materials are grown, naturally replenished or naturally cleaned.

9 Platformcb23. (2021). ***Circulair ontwerpen: Werkafspraken voor een circulaire bouw.*** https://platformcb23.nl (accessed 30/6/2021)

LIFESPAN

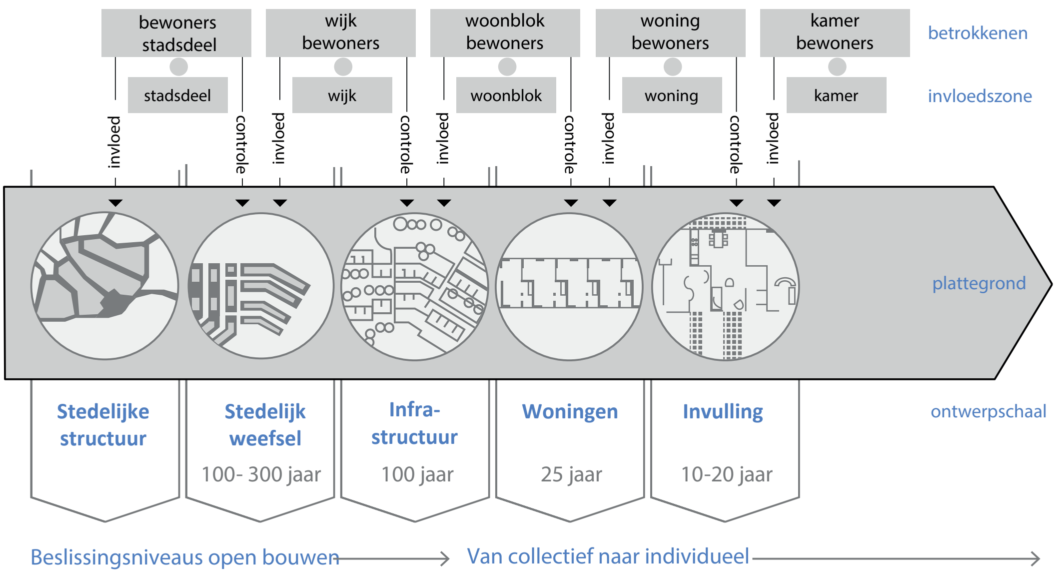
The lifespan of a building element is the time a product is in use, from purchase to disposal. In environmental impact calculations, lifespan is an important factor. The emissions of a product with an expected lifespan of ten years must be multiplied by five if you want to compare it to a product with an expected lifespan of fifty years. After all, the first product will have to be replaced four times during the lifetime of the second product. For this reason, the environmental impact is given in CO_2 equivalents per square meter per year. However, it should be kept in mind that the actual life span can only be determined at the end of the usage phase. It is therefore quite possible that a material has a much higher or lower environmental impact than previously calculated, because the building will be out of use much earlier or later than previously estimated.

John Habraken wrote in the 1960s about the "open building" principle. He made a distinction between the support and the infill of a building, where the support (supporting structure) is seen as permanent and public and the infill as temporary, personal and replaceable. Considering different building elements separately according to their lifespan is a valuable insight in the transition to a circular and sustainable building economy.

FIGURE 23.

Parts of a city with different life spans modeled on.

Source: J. Habraken (1961). *De Dragers en de Mensen: Het Einde van de Massawoningbouw.*



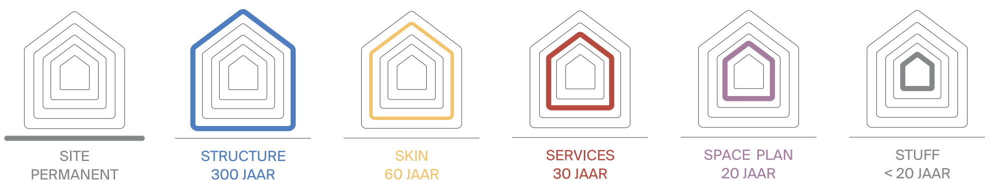
.THE LAYERS OF STEWART BRAND

A similar model was penned in 1994 by Stewart Brand, in which he breaks down a building into elements. These are also called the S layers and are; site, structure, skin, services, space plan and stuff. His principles are also based on the lifespan of different elements and products in construction, as John Habraken formulated earlier. Lifespan and CO_2 impact are closely linked. For this reason, the design principles described in this chapter are classified according to Stewart Brand's 'Shearing layers'.

FIGURE 22.

The S-layers of a building.

Adapted from: S. Brand (1994). *How Buildings Learn. What Happens After They're Built.*



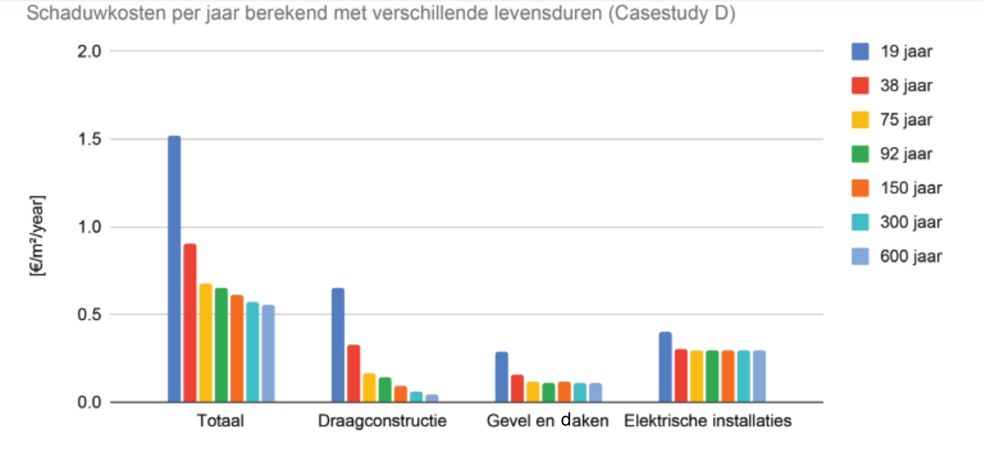
EXTENDING THE LIFE OF A BUILDING

1. SHADOW COSTS (€/M²/YEAR) DECREASE NON-LINEARLY.

Suppose a building has a lifetime of 10 years and an associated shadow cost of 100 euros. When the lifespan is doubled, the shadow costs are halved. With a 40-year lifespan, we have a quarter of the shadow costs left. At a life span of 50 years, the shadow costs become 20 Euros per year. It can be seen that with the extension of the lifespan from 10 to 20 years there is a reduction of 50 euros per year, while with the extension from 40 to 50 years there is only a reduction of 5 euros per year.

This means that extending the life of a building from 75 to 92 years (as in case study D) does not have a major impact on the MPG score. What we do not see reflected in the score, however, is that a longer building life also has the effect that no new building needs to be developed in the same period (this saves more CO2 impact). When comparing two scenarios, demolition and new construction (1) versus a building with a longer lifespan (2), it can be said about the first scenario, "Since the existing building has been demolished, and with it its embodied carbon, this embodied carbon can be added to the embodied carbon of the new building."

As a matter of fact, there is no monitoring of this aspect. If a building is demolished before the end of its assumed lifespan, there are no consequences.



2. ENVIRONMENTAL IMPACT OVER TIME VARIES BY COMPONENT

The embodied carbon of the supporting structure (measured in shadow costs per year) decreases significantly with a longer building life. This is not the case for electrical systems, for example— their correlation with the building lifespan stagnates already at the step from 19 to 38 years.

Components with a relatively short lifespan of 25 years must be replaced frequently. Photovoltaic cells have one-third of their environmental impact in the production phase and two-thirds in the usage phase, particularly in the form of replacement. Glazing has a relatively similar distribution. A structural concrete floor, on the other hand, has a lot of impact in the production phase and no environmental impact during the usage phase due to its long lifespan.

SITE

The site (location) describes the context in which a building is located. This can be climatic or topographical conditions, but also different urban densities. Consider a project's surroundings when designing for a low carbon footprint. The environmental impact of a project goes beyond the building itself. Urban locations are better connected, and residents can make joint use of existing facilities.

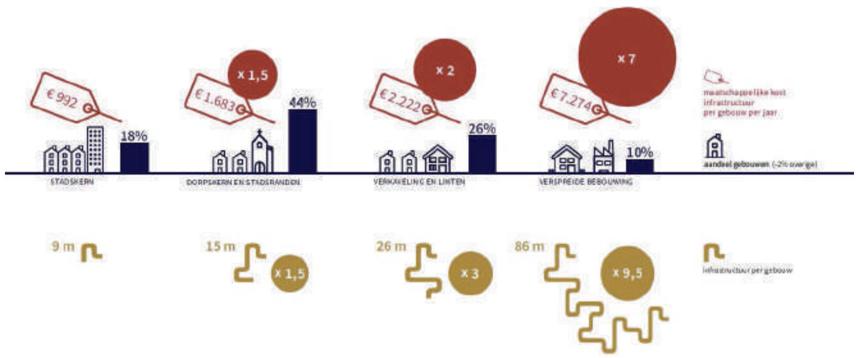
REDUCE

7. CONNECTING BUILDINGS TO THE CURRENT TECHNICAL INFRASTRUCTURE

Consider densifying existing space in our cities rather than adding new areas to the grid. The required sewers, roads, bike lanes, and lighting are items outside the building lot that are not counted in the MPG score but have significant environmental and financial costs. It takes ten times more infrastructure to connect homes in suburban areas than in inner cities.

FIGURE 24.

Social infrastructure costs per building per year (Cost of urban sprawl). Source: Van Broeck, L. (2019, April 2). Vlaams Bouwmeester. www.vlaamsbouwmeester.be



REDUCE

8. CREATING COMMON SPACES AND FACILITIES

A densely populated environment supports the emergence of a sharing economy. Both spaces and facilities can be shared. When multiple users share things, they are used more intensively. Individual use of space, a major factor in social costs, may therefore decline. Building for communities can also be a possible solution for another problem. Many elderly and single people still live in their old family homes. An attractive offer with smaller individual homes and, for example, a shared guest room for the grandchildren could motivate them to free up their family home for young starters, who are struggling in the housing market.

REDUCE

9. ENCOURAGING CAR-FREE MOBILITY

The perception of beauty, comfort and safety in the built environment is associated with pedestrian and bicycle mobility. Comfortable and safe bicycle paths and parking encourage the use of bicycle transportation. Pleasant sidewalks invite citizens to take longer walks. Larger goods and heavy groceries can be transported by (shared) cargo bikes instead of cars.

However, there is also much resistance to reducing the use of cars in our cities and not all measures have the intended effect. For example, it is difficult to predict the effect of closing a lane on a major road. Will more people start cycling and public transport improve, or will the city end up more congested? Rotterdam, for example, has opted for a pragmatic approach: "Because models cannot always predict the final effect, in 2020 we are carrying out a number of experiments with temporarily adapted traffic situations. In this way, we will experience how a road redesign works in practice."

FIGURE 25.

"Stimulating pedestrians,cyclists and public transport." Source: Gemeente Rotterdam, (2020), *Rotterdamse Mobiliteitsaanpak februari 2020.*

STRUCTURE

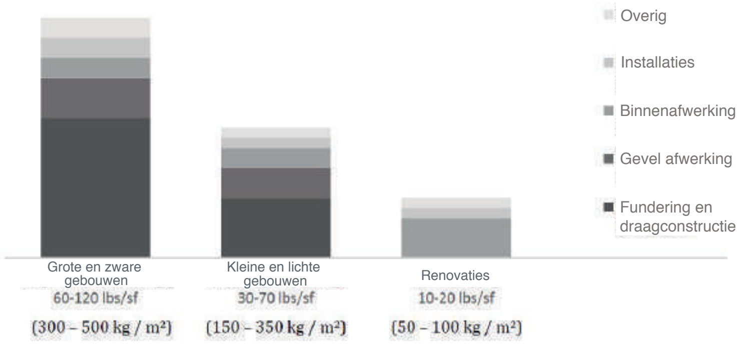
The supporting structure holds everything in place. It has the longest lifespan of any building component, determines the lifespan of the project, and has the greatest mass of any component.

AT THE BUILDING LEVEL

Large, heavy buildings are often characterized by structures with a high carbon impact. In high-rise buildings, larger structural components are required to withstand the effect of wind loads, which has less of an impact in lower buildings. A high-density building in a central location can offset the disadvantage of additional structure with the benefits of existing infrastructure and good connections. In fact, in our high-rise case studies, structure appeared to have the greatest impact. Thick concrete floors lead to a very high embodied CO_2 impact

FIGURE 26.

Carbon emissions by type of building and element. Source: King, B. (2017) *The New Carbon Architecture: Building to cool the climate.*



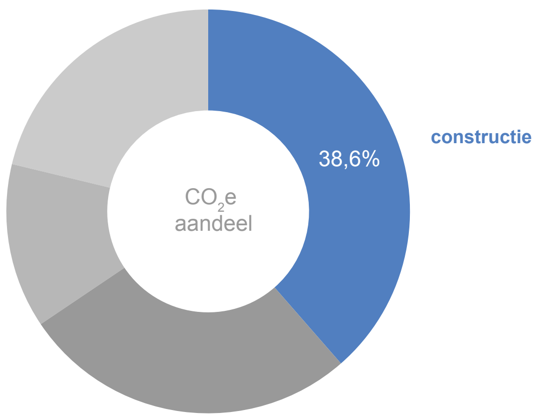
AT THE BUILDING COMPONENT LEVEL

On average, a building's structure is responsible for 38 percent of the total shadow costs. This makes the structure the largest source of emissions of all building components. What strategies can be used to reduce the impact of this part of the building?

FIGURE 27.

Average share of environmental impact of the supporting structure of the six case studies.

PV-panels are not included in this calculation.



BIOGENIC CARBON STORAGE IS NOT VISIBLE IN THE MPG SCORE.

Be aware of the potential for biogenic carbon storage. The way we calculate affects the assessment of emitted CO2. Over a period of one hundred years, the actual GWP of wooden structures is only half as much as calculated in the MPG score, as described in the 2021 TNO report "An exploration of the potential of temporary CO2 storage in wood construction". The reason is that temporary carbon capture has a positive effect on the overall environmental impact of the product. CO2 is captured for the entire lifespan of the building. Today, the MPG ignores this period of storage and mixes all positive and negative CO2 emissions into an overall score. In the long run, the MPG methodology will need to be restructured to account for CO2 uptake. The most appropriate (in our view) will be a carbon accounting tool, such as is being developed by the Dutch Green Building Council and their partners in the context of the Whole Life Carbon Approach..

HOW DOES A PROJECT QUALIFY FOR AN EXTENDED LIFESPAN IN THE MPG CALCULATION?

In our list of case studies, number 18 stands out because it assumed an extended lifespan of 92 years (as opposed to the commonly used standard of 75 years). It should be noted that these standard lifespans also vary from country to country. In order to be able to count on a longer lifespan, this must be made plausible. The specific requirements for this can be found in the guideline "specific building lifespan" in which various life-extending aspects are listed.

MPG-SCORE [€/M²/YEAR]

The adaptability of a building affects the final lifespan of the building in the MPG calculation. Due to the longer lifespan (larger denominator through which shadow costs are divided), the environmental impact of a building is slightly reduced. However, this is also determined per building element. For example, building service systems are replaced every 25 years. Therefore, if the building life is extended by 25 years, the systems go into a new cycle and have no effect on the MPG. It is also assumed that the same systems will be used again.

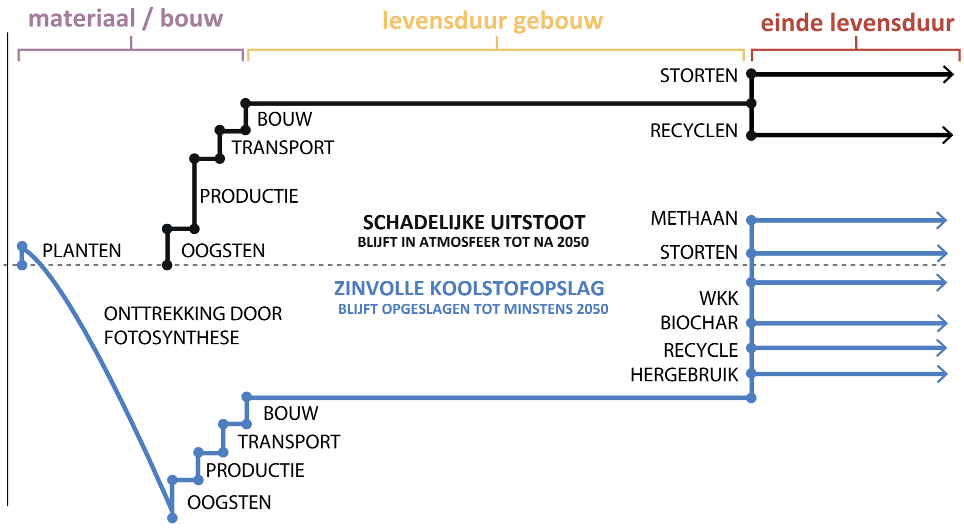
REDUCE

10. STORING CARBON IN THE STRUCTURE

Biogenic carbon storage reduces the concentration of CO_2 in our atmosphere. Plants store CO_2 as they grow. When we then use them as building materials, the carbon remains stored in our buildings. Wood construction is a frequently cited example and is seen as a significant opportunity in Dutch housing construction. A 2016 study by W/E engineers estimated that "with a sixfold increase in the number of low-rise residential buildings using timber frame construction and an increase in the use of wood in public works, about 0.3 Mton of CO_2 per year could be sequestered by 2030 and as much avoided in emissions by replacing concrete and steel . If this doubles by 2050 then this could rise to 0.6 Mton CO_2." [10]

FIGURE 28.

Diagram of the CO_2 balance by photosynthesis in timber construction. Source: Kriegh, J., et al. (2021). *Carbon-Storing Materials: Summary Report.*



However, there are still some systemic barriers to building with wood. For example, the above described effect of carbon capture is not yet recorded in the MPG calculation. A change in the measurement method is being investigated. (See more on this topic in the following chapters). Also, wood prices have risen sharply recently and sound insulation as well as high-rise buildings are still challenges.

Meanwhile, building with wood need not wait. Recently, we've even been seeing residential buildings built from wood in high-densities and large quantities. Two examples are the HAUT building in Amsterdam, a 73-meter-high cross-laminated timber structure, and more than five hundred earthquake-resistant timber-frame houses in Groningen.

REUSE

11. RENOVATION INSTEAD OF NEW CONSTRUCTION

Renovations can dramatically reduce embodied CO_2 emissions and their effects compared to new construction. In the former, an existing structure is used. In the latter, the structure is new. But the benefits of renovation are twofold. On the one hand, through the lower amount of embodied CO_2 emissions: "Renovating a building releases somewhere between 50 to 75 percent less carbon than building a new one does." The diagram below compares three new buildings with varying energy demands with one renovated building.

On the other hand, embodied carbon is emitted at the start of a building's lifespan, which is much more damaging to the climate. The principle of the time value of carbon (TVC) is explained in the introduction on page 25.

Poorly performing and vacant buildings in particular lend themselves to renovation and/ or redevelopment and should replace demolition and new construction where possible.

FIGURE 29.

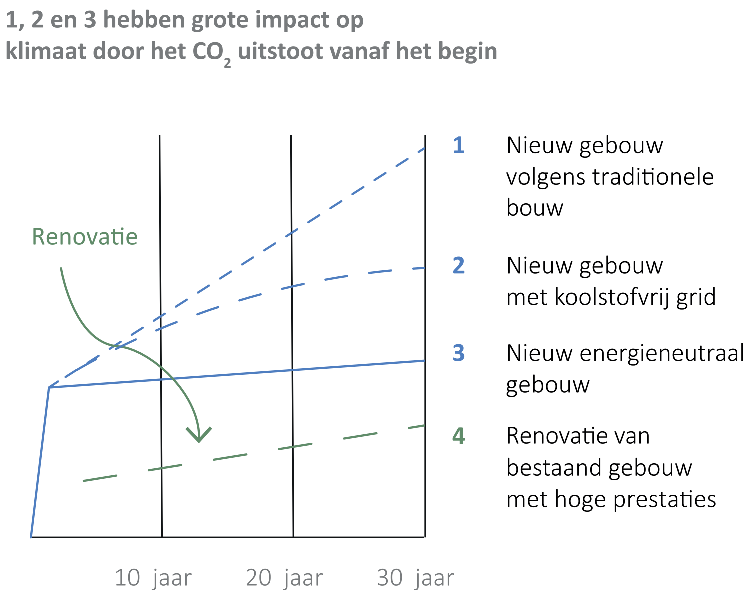
Good news, it is possible to achieve both low operating emissions, as having low material-related emissions.

Source: King, B. (2017) *The New Carbon Architecture: Building to cool the climate.*

FIGURE 30.

Life-extending factors. Source: W/E adviseurs (2013). *Richtsnoer 'Specifieke gebouwlevensduur'. Aanvulling op de Bepalingsmethode Milieuprestatie Gebouwen en GWW-werken (MPG).*

Uitgangspunt: gemiddelde levensduur
Levensduurverlengende aspecten
Hoge interne belevingswaarde
Hoge functionaliteit
Bijzonder daglicht enóf uitzicht
Hoog comfort
Hoge externe belevingswaarde
Landmark
Krachtige identiteit
Groot accommoderend vermogen
Toekomstgerichtheid
Indelingsflexibiliteit
Flexibele verkaveling
Aanpasbaar bouwvolume



It is also financially more advantageous to choose to renovate existing structures. Building a new structure can take more than one-third of the economic investment compared to the total construction cost. Make full use of this investment by renovating rather than demolishing.

Despite all the benefits of renovation, it can be a more complex task for designers than starting with an empty lot. In particular, a complex transformation from another function into housing can feel like uncharted territory. This requires us to rethink the design process and redefine the values we are looking for. Even the policies are different when it comes to renovation. It can be a learning process, but in the end, we can use those factors to our advantage. The existing condition that might feel like a constraint at first glance can fuel creativity and provide the basis for memorable, sustainable and treasured architecture that is sensitive to its surroundings.

A successful example is the Lee Towers (Marconi Tower) in Rotterdam. "The three well-known Europoint towers at the Marconi Square in Rotterdam were designed in the early 1970s by Skidmore, Owings and Merrill (SOM). Two Europoint towers were abandoned after the municipal services left. We have transformed these towers into 883 full service rental properties."

REUSE

12. EXTENDING THE LIFESPAN OF THE STRUCTURE

Open floor plans and generous floor heights make a building suitable for different functions. Research at TU Eindhoven shows that these qualities extend the lifespan of a structure because they "have a positive effect on the flexibility and adaptability of buildings.'

The variable load specified in Dutch building regulations for office spaces is 2 to 5 kilonewtons per square meter (kN/m^2). For residential buildings, 1.5 to 2 kN/m^2 applies. Transforming homes into offices is therefore only an option if an over-dimensioned structure allows it. Transforming offices into homes, on the other hand, is not a problem structurally. However, it can be a challenge that some office buildings have very deep floor plans, which makes it more difficult to design a functional residential layout in terms of daylight access.

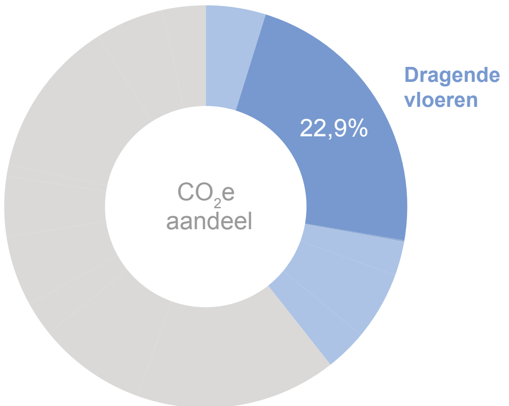
But is it worth the carbon investment? It is certainly a dilemma: either over-dimension the structure to extend its lifespan, or minimize the use of materials,reducing carbon emissions at the start of its lifespan. In his 2017 book, Barry King mentions, "We don't replace buildings because they wear out, we replace them because the land they were built on becomes more valuable, or because we don't think they look pretty anymore, or because we just want something new."

In addition to functional choices, architectural quality plays an equally important role. "Good architecture makes people feel at home somewhere, attach themselves to it and take good care of it."

FIGURE 31.

Largest polluter within the environmental impact of the supporting structure ot the six case study.

(PV-panels are not included in this calculation.)



AT PRODUCT LEVEL

Which construction material has the highest emissions? Load-bearing floors top the list in most of the case study projects we analyzed. How can we reduce their impact?

REUSE

13. DESIGN WITH EXISTING STRUCTURES

Patrick Teuffel of TU Eindhoven states that the environmental impact 'can be significantly reduced by extending the lifespan' and that we should focus on 'reuse at component and element level rather than at material level'. TNOmentions that 'as theNetherlands and Europe re moving towards a circular economy, it is recommended to investigate even longer.'[16]

However, it can be difficult to source second-hand products for a project. The conventional design process relies on demand-based component selection and a completely free choice of suppliers. The logistical effort can be great, but so can the carbon saving.

One successful example is the reuse of metal bridge trusses in the roof structure of Eindhoven's new train station.

REUSE

14. DESIGN A DEMOUNTABLE AND REUSABLE STRUCTURE

If a new structure is built, make it demountable. This can go as far as applying to an entire building, but can also involve simple repairs and replacements. Standard elements and sized will support a wider rande of applications in this regard. Components should be robust and retain their quality for reuse. .

For reuse in a new object, the structure must fire be dismantled. Joints must be suited for this purpose. It is then transferred to antoher location where it is reassembled. It is important to pay attention to the sizes and weights of the components so that they are transportable.

With good design, dismontable components can be easily reused. But certainly, for buildings designed for a long lifespan, this is only a theoretical fact. As Thomas Rau says, "Thre are no circular buildings", because we cannot be sure whether circular reuse will happen in the future. Components and amterials must therefore also be supported by new second-hand market and registered in a publicly accessible system, in order to be practicaly sourced for a second use. There are now a number of initiatives in this are, such as Madaster for registering reclaimed materials and stimating their value. RotorDC from Brussels mainly 'harvest' special building materials from old buildings and processes them to a reusable state. New Horizons and Circuloo aim for a broader market and already offer a large quantity of standard materials, such as cable ducts, pipes, tiles and plasterboard.

Plasterboard is an example of a distinct principle: in reprocessing the boards, 4.5 centimetres are cur off on both sides, making them practically new again, However, the new size is smaller than the original size. Another example of this principle is the Circl pavilion in Amsterdam. Here the columns are made longer than necessary, so that the can later be cut to size if needed.

16 Keijzer, E. et al. (2021). *Een verkenning van het potentieel van tijdelijke CO_2-opslag bij houtbouw.* TNO, Utrecht., p.2.

SKIN

De schil van het gebouw, de gevel en het dak, vormt de verbinding tussen binnen en buiten. De schil regelt de uitwisseling van warmte, lucht, vocht, licht en geluid. Deze uitwisseling wordt beïnvloed door de bouwfysische eigenschappen, het oppervlak en de oriëntatie. Openingen in de schil laten mensen door de gevel bewegen en kijken.

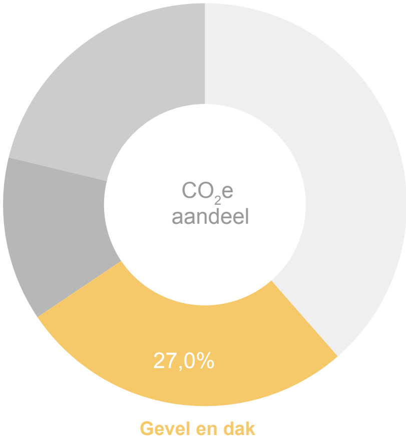
OP GEBOUWNIVEAU

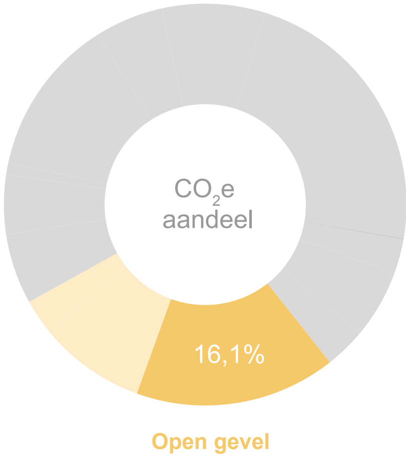
De vorm van een gebouw beïnvloedt de compactheid ervan. Een gebouw met een vierkante plattegrond is compacter en heeft minder oppervlakte te bedekken en te isoleren dan een onregelmatig gevormd gebouw.

AFBEELDING 32.

Gemiddeld aandeel milieu-impact van de gevel van de zes casestudies.

PV-panelen zijn buiten beschouwing gelaten in deze berekening.





AFBEELDING 33.

Grootste vervuiler binnen de milieu-impact van de gevel van de zes casestudies.

PV-panelen zijn buiten beschouwing gelaten in deze berekening.

REDUCE

15. CAN THE BUILDING BE MORE COMPACT?

With a smaller facade area, materials, costs and CO2 emissions can be saved. This can optimize energy performance. The taller the building, the more important compactness becomes for the embodied CO2 impact, as it affects multiple floors.

On the other hand, building volumes are also designed based on interior layout and daylight. A square floor plan will most likely contain some less desirable north-and south-facing spaces. Planning east-west oriented apartments can provide good daylighting, but usually results in elongated buildings. Compactness is not always the best option. Consider whether your design can be made more compact without compromising spatial quality.

AT THE BUILDING COMPONENT LEVEL

On average, 27 percent of emissions come from the building envelope. The roof is also a part of the building envelope and especially relevant in low-rise buildings. The higher a building is, the more important the facade becomes. It determines the architectural quality of the building in relation to its environment.

REDUCE

16. CHOOSING THE AMOUNT OF GLASS AREA CAREFULLY

Limiting glass area minimizes emissions from the façade. Operational heat losses and gains tend to increase with large glass openings. They are the biggest source of overheating in the summer. Of course, we cannot build houses without windows. But can similar quality be achieved with smaller openings? A high percentage of glass surfaces is popular in contemporary designs, especially in inner cities with high land prices. A visual connection to the outside makes interior spaces feel more generous and fills them with natural light. Glass has a sleek, modern look. For these reasons, we often see large openings in modern apartment buildings. However, these decisions have a major effect on embodied CO_2. A critical review of design decisions can have a major impact.

In our analysis, we identified the five most CO_2-emitting components from six case-studies and saw a direct correlation between the window-wall ratio and the results. The row houses with smaller openings often scored well on the list. Thus, their overall embodied CO_2 impact is effectively lower.

Glass is responsible for the largest emissions from the building envelope, accounting for over sixteen percent of the building's embodied CO_2 impact. The size of the openings is one factor, as discussed above. It also matters what type of glazing is chosen.

AT THE PRODUCT LEVEL

In general, the choice of facade products is largely based on their thermal properties. We need materials that insulate well. In closed parts of the facade, this is quite easy to do, including with low-carbon and biobased materials. Glazing, however, requires large CO_2 emissions to achieve the same thermal values.

The building code contains requirements for the thermal values of building envelopes. We can choose to follow only those requirements or strive for a higher level of insulation. Operational savings must be weighed against embodied CO_2 emissions. There is no "one size fits all" solution for the best choice, as many factors are decisive. These include the location of the building, the orientation of openings and the indoor climate system. An energy performance model should therefore be combined with the analysis of the embodied CO_2 emissions.

REUSE

17. ENCOURAGING THE REUSE OF GLAZING

Why not reuse parts, rather than recycle materials? That's a question researchers are working on. The solution is complex because "most glass in the building envelope is currently used in the form of hermetically sealed insulating glass units whose components are not easy to separate and re-use. " We are not using the full potential lifespan of the glass because sealants have a common lifespan of 25 years. At present, the "remanufacturing" of glazing is not yet a practice that is market-ready. Hopefully, we will be able to use it in construction soon.

17 DeBrincat, G. en Babic, E. (n.d.) ***Re-thinking the Life-Cycle of Architectural Glass.*** Arup, Glasgow. https://www.arup.com/perspectives/publications/research/section/re-thinking-the-life-cycle-of-architectural-glass p.19.

AT THE MATERIAL LEVEL

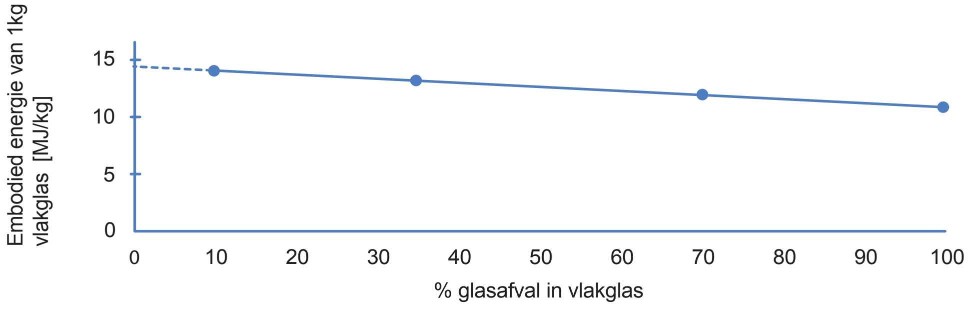
REUSE

18. SWITCHING TO CIRCULAR GLAZING

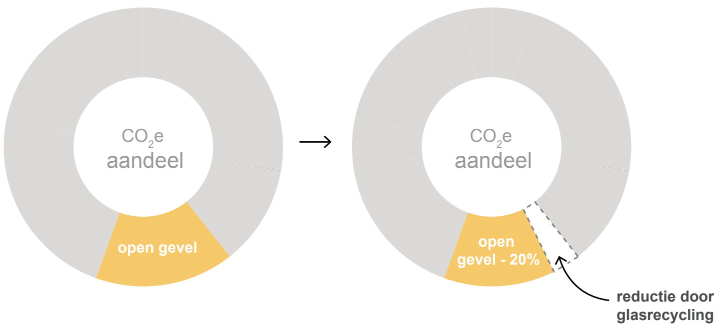
The production of one square meter of low-e double glazing results in the emission of 25kg of CO_2. Recycling glass reduces its footprint in several ways: first, it reduces landfill waste;second, the addition of recycled glass to the melting process lowers the temperature required and therefore the energy consumed in the production process (see chart below).

FIGURE 34.

Material-related energy of 1 kg of glass in relation to the percentage of recycled glass used in production. Source: DeBrincat, G. en Babic, E. (n.d.) *Re-thinking the Life-Cycle of Architectural Glass.* Arup, Glasgow.



Glass can theoretically be recycled to one hundred percent, but currently mostly ends up in landfills. Why is it not being recycled? The demolition process is the obvious bottleneck, alongside manufacturing processes that contaminate the material (e.g. lamination). 'Recycling glass back to the float line (sic: manufacturing glass) is feasible, but a new network needs to be developed and new processes introduced to ensure the quality of the recovered glass.' [17]



How can we, as designers, influence glass recycling? We can make recommendations that are not market-realistic, but deserve attention and a call to action.

First, we should be buying recycled glass. In their paper, Arup see opportunities in the procurement process: “Tender responses could require the contractors to state the level of recycled glass content from their supply chain and allow a measure between contractor returns. This could potentially have a positive effect on the promotion of increasing recycled content by the glass manufacturers”.

Second, glass should be recycled after its useful life. Service contracts and take-back contracts with facade contractors are being investigated. A study on facade leasing is underway at TU Delft. These new business models aim to clarify who manages the materials over the lifespan of a project.

MORE CATEGORY 1 PRODUCTS WITH GLAZING IN THE NMD?

The introduction of a sustainability requirement in the glass market could create competition among glass manufacturers for environmental product declarations. Glazing units with high percentages of recycled material could find their way into Category 1 EPDs in the NMD.

SERVICES

Building systems (services) are used to create a comfortable indoor environment and to supply a building with electricity and water. They include energy sources (e.g., photovoltaic cells, heat pumps) and distribution systems (e.g., piping and underfloor heating).

OP GEBOUWNIVEAU

Installaties spelen een grote rol in hedendaagse ontwerpen. Hun belang is in de loop der jaren toegenomen. Nu worden we geconfronteerd met een grote hoeveelheid materiaalgebonden energie van die installaties. We zullen dus eerst moeten kijken naar klimaatinstallaties. Welke principes helpen de totale CO_2-voetafdruk te verkleinen?

19. CHOOSE ROBUST AND PASSIVE CLIMATE DESIGN

REDUCE

To increase the efficiency of our climate design and ensure that it works well in practice, principles of so-called robust design can be applied. Robust design does not deviate too much from predicted performance and increases user satisfaction.

What makes a design robust? Positive factors include user control, low maintenance, separate systems for heating and ventilation, and most importantly, passive design.

Using passive strategies means designing a climate concept that is independent of installations. Strategies can include optimal orientation of facades, use of thermal mass, ventilation grills, or overhangs for shading. These things do have a material-related CO_2 impact, but they are usually more robust and do not need to be replaced during their lifetime, unlike building installations. We can combine passive and active measures where appropriate.

20. SHARE ENERGY LOCALLY

REDUCE

We want to be free of fossil fuels as soon as possible. The share of renewable energy in the national grid is slowly increasing but as developers and designers, we can take matters into our own hands to generate energy on the building lot.

This is more difficult for densely populated high-rise buildings than for low-density urban houses. High-rise buildings consume more energy overall and have a smaller roof area compared to the usable floor area.

The high-rise building takes electricity and heat from the city grid. It has a high total energy consumption per square meter, multiple floors and a large number of residents, while the roof area is relatively small. The amount of PV panels needed to meet the total demand simply does not fit on the roof. If there are less PV panels, we need to make energy use more efficient and reduce losses. In environments with several buildings containing a diversity of functions, an energy sharing concept can be applied. An example is De Ceuvel in Amsterdam. A local currency encourages peer-to-peer energy trading. 'The Jouliette is a blockchain-based energy token that enables individuals and communities to easily manage and share their locally produced renewable energy.'

21. MAKING BUILDING INSTALLATIONS ADAPTABLE

REUSE

The E and W installations consist of pipes, ducts and cables. They themselves do not cause major CO_2 emissions, but when planned correctly, they can support the adaptability of the spatial layout. It is more efficient in terms of material use to limit suspended ceilings and shafts by bundling installations and keeping pipes short. Long pipes, cables and tubes also lead to losses during the operation phase.

Central shafts, which allow for a variable layout of the floor plan, are a good example. With these, but also for example with meter boxes and technical rooms, it is important to build in a certain excess in order to be able to install new or different facilities later on and to place additional pipes and branches. The more accessible these shafts are, the better.

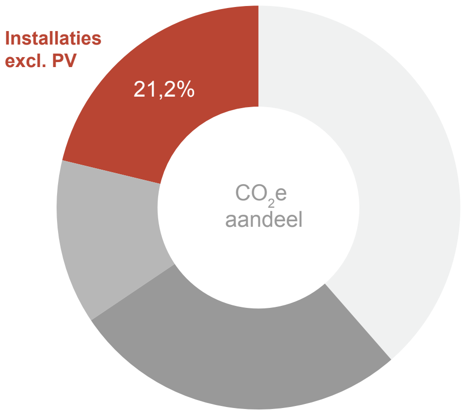
AT THE BUILDING SECTION LEVEL

21 percent of the impact of an average building, as shown in our case studies, is caused by the installations. They have a short life span of about 25 years. The longer a building remains standing, the longer we use, for example, the supporting structure, which is a long-term investment. Installations, on the other hand, are replaced regularly and continue to contribute to the material energy. They should therefore be considered "fixed costs." Passive strategies, on the other hand, which make (parts of) the installations unnecessary, can reduce the material.

FIGURE 35.

Average share of environmental impact of the facade of the six installations.

(PV-panels are not included in this calculation)



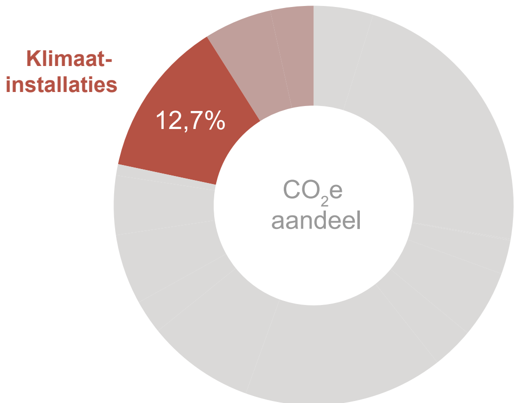


FIGURE 36.

Largest polluter within the environmental impact of the installations of the six case studies.

(PV-panels are not included in this calculation)

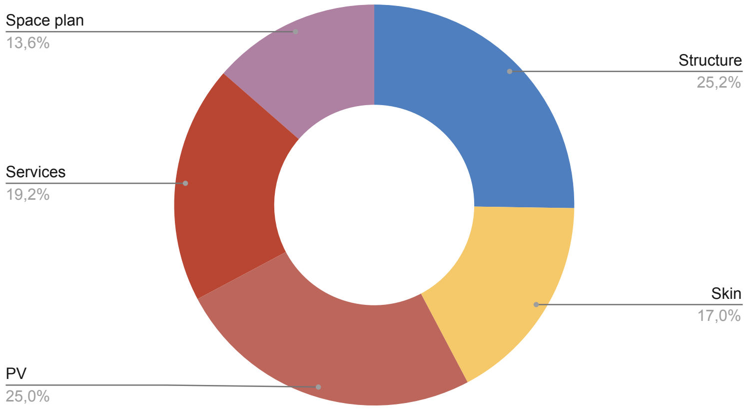
AT THE PRODUCT LEVEL

PV panels have the greatest impact of all building products. It is such a significant component that we decided to separate it from the other components. This can be seen in Figure 37. In all further comparisons, it has been excluded, because its relative amount varies very much between the

20 Alliander and Spectral. (2021). *Jouliette @ De Ceuvel.* Jouliette. https://www.jouliette.net/

FIGURE 37.

Average share of environmental impact incl. PV.



different projects. In one project, PV panels accounted for sixty percent of the total impact, while in another project, no PV panels were used at all.

Although PV panels have a very high impact, they almost always recoup this investment through the reduction in operational costs. The comparison of different projects will be fairer if PV panels are excluded from the material-related carbon comparisons. The graph above (Figure 36) shows that twelve percent of the impact is caused by climate installations. This component has been discussed in detail in the previous pages.

PV PANEL DATA USED IN THE MPG IS STILL GENERIC.

It is worth noting that PV products currently available in the **NMD** are based on generic data. The MPG calculations of our case studies use category 3 data to determine the impact of PVs. This is because the **NMD** does not include (or did not include) Category 1 or 2 options. Thus, as mentioned in the introduction on SPDs, the actual environmental impact does not correspond to the impact recorded in the MPG score.

REUSE

22. DON'T HESITATE TO USE PV

PVs are an energy-generating addition. Ordinary rooftop PV systems currently have a payback period of three to four years (with an assumed lifespan of twenty-five years), which is expected to drop to a payback period of two years in the near future. This means that operational savings will outweigh embodied carbon from that point on. Thus, over their lifetime, PVs are definitely energy positive. Overall, it is a sensible investment that reduces CO_2 emissions. However, do check the payback period of PVs for your project and remember that the frame, the underlying structure and all related systems contribute to the material-related CO_2.

The disadvantage of PV panels is that their embodied carbon show up strongly in the MPG score. Currently, all materials must be entered to calculate the MPG score. This includes the same amount of PV that is listed in the BENG calculation. In general, this is simply a matter of documentation. In this respect, one should not be blinded by the higher MPG score, because what counts is the actual carbon footprint.

For example: a case study contains PV and is energy neutral (zero-to-the-meter). It would score well in the MPG (0.32) if the PVs were not included in the calculation. However, the final score, including PV, comes out to 0.92. This would mean that this project would fail the test with the updated MPG requirements (0.8), even though it actually performs well in all respects. It is already possible within the current MPG rules to include only the PV panels that ensure that the building meets the BENG requirements. In our case studies, however, the boundary could not be clearly drawn, so we chose to disregard them entirely.

AT THE MATERIAL LEVEL

Most of the material-related CO_2 effects (eighty percent) in PV cells come from the glass sheets that cover the cells. The material is described in the subchapter "Skin. (See page 45 for more information on this).

SPACE PLAN

While the structure and envelope define the overall shape of a building, the floor plan creates different zones within this envelope. We define the "components of the floor plan" as the non-structural elements of a building. These include floor layers, ceilings, interior walls and finishes. In other words, anything that could be removed or reconfigured during a more or less extensive renovation of the building. Steward Brand calls it "floor plan," while John Habraken describes a similar category as "infill." We will refer to both names.

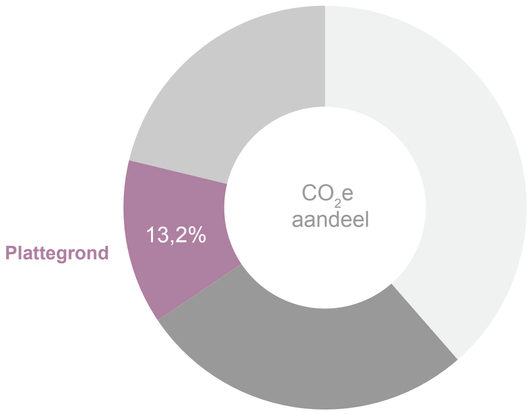
AT THE BUILDING LEVEL

Building products can be divided into those that are usually intended to last and those that need to be replaced over the years to accommodate different uses of the building. In his 1961 publication "The Carriers and the People," John Habraken defines them as "structure" and "infill." In his theories of adaptable architecture, Habraken argues for a vital architecture that gives shape to everyday life and leaves room for change. He makes a clear distinction between the carrier and the infill and emphasizes that this distinction is not only technical in nature, but primarily focuses on the possibility for personal influence. Carriers belong to the public domain and are permanent, while the infill belongs to the individual and is changeable.[21]

FIGURE 38.

Average share of environmental impact of 'space plan' of the six case studies

(PV-panels are not included in this calculation)



AT BUILDING SECTION LEVEL

Thirteen percent of the total impact, averaged across six case studies, comes from floor plan components. That is the smallest impact of the layers of Brand. However, the floor plan determines the use of a building. If it is easy to change, the building is less likely to become obsolete and be demolished. The principles formulated by John Habraken and Open Building, namely that the structure and the infill can be considered separately and should therefore be designed with other objectives in mind, are more topical than ever.

21 Habraken, N. J. (n.d.). *Open Building Legacy.* **Open Building.** https://www.openbuilding.co/legacy

REDUCE

23. KEEP THE INFILL FLEXIBLE

What infill components should we design with? Ideally, they should be moveable and rearrangeable. Designing components for a new layout can be a challenging task, as they must be light, demountable and easy to handle, while also being sturdy enough to last. In addition, the walls and floors must also be acoustically insulated. That means they need mass or a cavity to achieve the required RC value, and they need to be decoupled to stop the transmission of vibrations.

One example is the project LOFT by Sustainer Homes and The New Makers. In this concept, an empty multi-story wooden shell is created and delivered to residents without any infill. This project goes so far that even the floorboards are not installed until requested by the user. The designers describe it as follows: 'The LOFT collection offers a choice of all kinds of interior modules that you can very easily 'click in' to your loft and, after a while, also 'click out' so that they can be reused elsewhere. Think of stairs, floors, walls, but also of smart multifunctional cupboards. The parts are made of wood-like materials.

The so-called detachability index, developed by Alba Concepts, makes a start to quantify the flexibility of the structure. But also the MAT8-category of BREEAM brings several aspects into focus.

System walls and ceilings from office environments are another example. Here the turnaround time is often very high and the layout changes frequently. Often enough, it is seemingly superficial design choices that limit the life of an element. Consider a door handle and color choice from the 1990s. Was that perhaps an overly fashionable choice or will it be an aesthetic that will actually be highly valued fifty years from now?

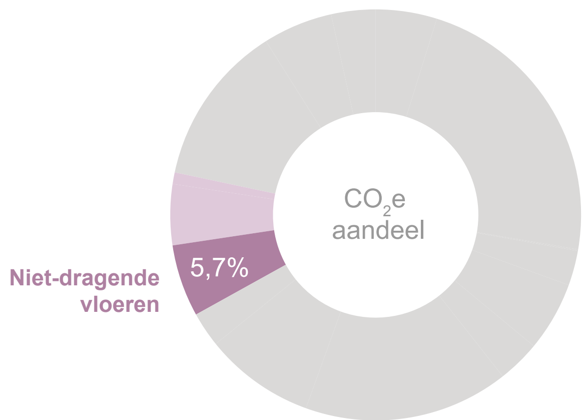
AT THE PRODUCT AND MATERIAL LEVEL

Four to five percent of the total material-related CO_2 comes from non-load bearing floors. The leveling layer has the biggest impact here.

FIGURE 39.

Largest polluter within the environmental impact of 'space plan' of the six case studies.

(PV-panels are not included in this calculation)



22 Era Contour, TBI. (2020, November 9). ***LOFT. Houtbaar.*** https://www.houtbaar.nl/loft/

REDUCE

24. AVOID CEMENT SCREEDS

All six case studies use cement screeds. These are primarily used to level the floor and acoustically decouple the floor surface from the supporting structure. It is a widely used method that is problematic because it consumes a lot of energy and is not demountable. It is common practice in Dutch housing construction to pour the cement around the load-bearing walls while plaster walls are placed on top of the cement screed. This is actually not ideal from an acoustic point of view, but already considers a later adjustment of the floor plan.

However, the underfloor heating is usually installed room by room in the cement screed. This establishes the floor plan which cannot be modified without reinstalling the cement floor and heating.

There are alternative products on the market that have been tested and proven to provide adequate acoustic properties and ease of installation. The so-called "equalization granules" are a good example of this. These pellets are made of aerated concrete granulate, but in principle different materials can be used, for example also sand. A dry screed can then be placed on top. The Recycling House in Hanover Kronsrode uses paving stones as an intermediate layer to add mass to improve acoustics. The office building Bouwdeel D(emontabel) in Delft, designed by the architectural firm cepezed, has been constructed in a completely demountable manner. The easily removable screed is of mineral granules and gypsum fiber boards.[23]

23 G. Vos et al., Rijksdienst voor Ondernemend Nederland. (2020). ***Circulaire gebouwen. Strategieën en praktijkvoorbeelden,*** p.50.

STUFF

When we design a home or residential area, we must always consider the lifestyle we are accommodating. It is difficult to quantify the carbon footprint of this because it depends on so many different factors. It is a similar problem to, say, user behavior, which is often overlooked in the energy performance of buildings.

We understand "stuff" to mean all the products brought into their homes by occupants; furniture, household appliances, and personal effects. Stuff has the greatest impact on the personal carbon footprint of an average Dutch person.

(See also a discussion of this topic on page 21)

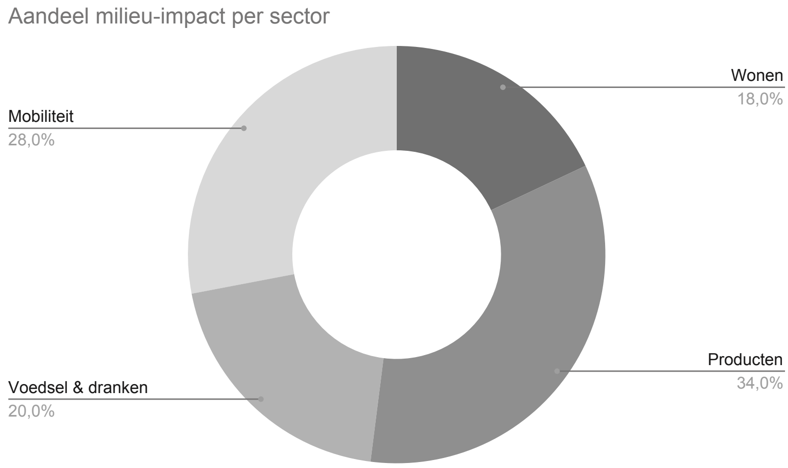


FIGURE 40.

Structure of the CO_2 footprint of an average Dutchman. Source: Top 10 milieubelasting gemiddeld Nederlandse consument - update versie 2020, CE Delft, G. Bergsma et. al, 2020.

The stuff we buy each year accounts for most of our carbon footprint. As designers of the built environment, we cannot directly influence the buying behavior of residents. However, we can consider some basic principles. More space generally means more stuff. By enabling the sharing of products, individual purchase is not necessary (e.g. fitness equipment or a drill). A well-designed home can prevent the additional purchase of products. Think of a separate air conditioner or fan, a dryer (when there is no room to hang clothes), but also a new kitchen or bathroom because the standard delivered setup does not meet the residents' needs.

24 F. Nagler (2012). Voordracht *"Einfach Bauen"*, 29. Sep. 2012.

IV. CASESTUDIES

RESEARCHING THE IMPACT OF DESIGN CHOICES

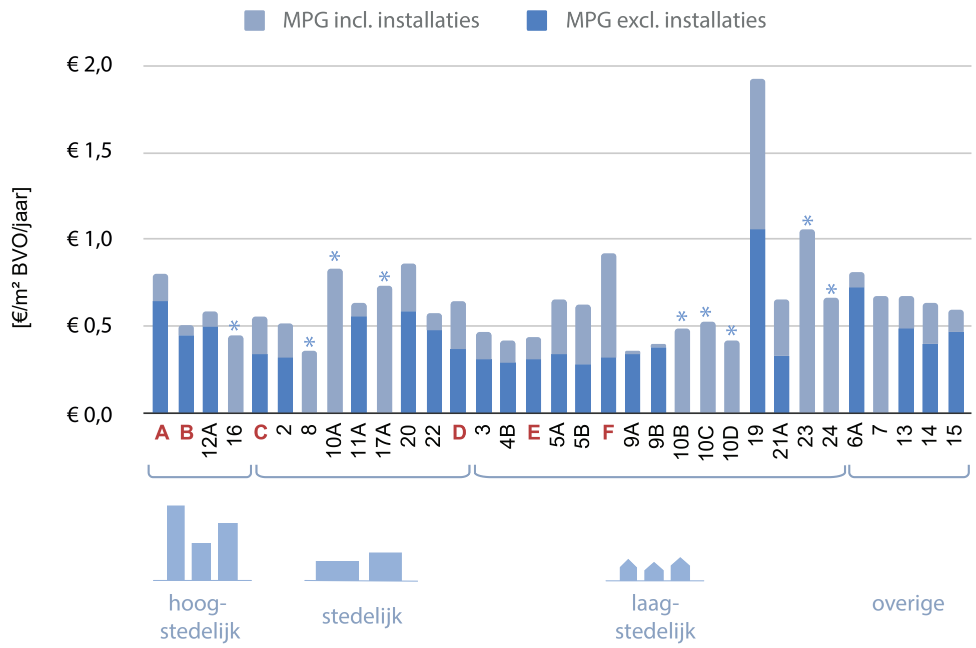
To gain more insight into the impact of design choices on total embodied carbon, research was conducted into completed housing projects. This involved examining different building typologies (high-rise, medium-rise and low-rise). The case studies were analyzed based on the MPG, EPC and BENG scores and provide practical insight into the consistency of CO_2 impacts spread across the functional building components of buildings. The analysis of the case studies led to some conclusions presented in the previous chapter.

The MPG score indicates the CO_2 impact at building level, but it is not clear enough to provide easy feedback for the design process. In this study the MPG scores of the case studies were analyzed in an alternative method so that the results can provide insight for designers during the process. This relates to the design principles formulated in Chapter 3. A number of observations and conclusions arise from the analysis of the case studies and are explained later in this chapter.

FIGURE 41.

Overview of the shadow costs of all reference projects.

*no separate information about installations available.



OVERVIEW OF THE CASE STUDIES

Within the framework of this research, 24 case studies were collected and compiled into a comparative overview. Six projects with three different urban densities were then selected that are best documented and most interesting within the framework of this research. We deliberately did not choose outliers, but rather projects that are representative of how building is done today. We did choose an 'ordinary' and an 'ambitious' project per urban density, i.e. with a fairly high and a fairly low MPG score.

The main topics analyzed are the MPG score, EPC score and BENG score, all in relation to the usable floor area. The purpose of the analysis is to interpret relationships of the CO_2 impact of different building components. Some questions could be answered with this, such as: Which part of a design would have the greatest positive CO_2 impact? How can this be minimized? Would this be more likely to be the windows or more likely to be components of the supporting structure? Or is a greater reduction in CO_2 impact achievable when choosing other installation concepts?

The different case studies were compared with each other. This showed, for example, that the projects had different CO_2 impacts within the facade category. Does this have to do with the overall shape of the building, the floor plan layout or the facade finish?

In addition to the qualitative data collection, the case studies were also categorized into different building typologies: high-rise, medium-rise and low-rise. The matrix below shows a shortlist of the selected case studies that were studied in more detail. The six most representative and best documented projects (one relatively high scoring and one relatively low scoring per typology) were finally selected for this study. To assess the projects, the building plans and their location were studied, in addition to data from MPG, EPC and BENG scores.

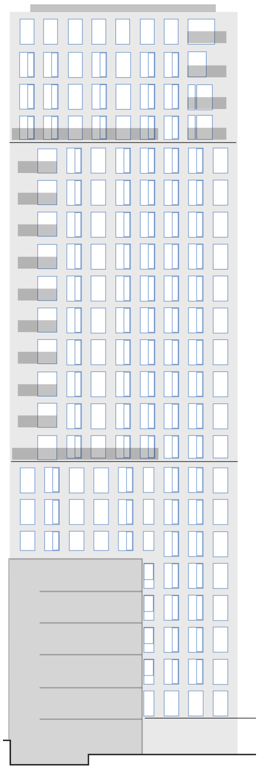
FIGURE 42.

Categorizing the case studies by density.

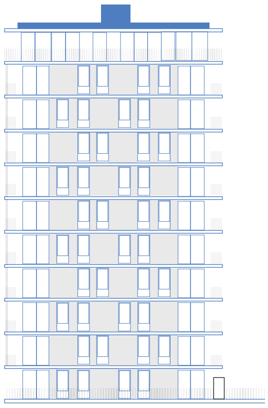
dichtheid	casestudy
hoogstedelijk meer dan 7 verdiepingen	A, B, 12, 16
stedelijk tot 7 verdiepingen	C, 2, 8, 10a, 11a, 17a, D, 20, 22,
laagstedelijk geschakeld of vrijstaand	3, 4b, E, 5a, F, 9a, 9b, 10b, 10c, 10d, 19, 21a, 23, 24
overige	6a, 7, 13, 14, 15

FIGURE 43.

Facade views of the six analyzed reference projects.

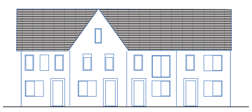


Casestudy A

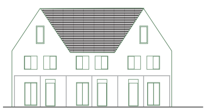


Casestudy B

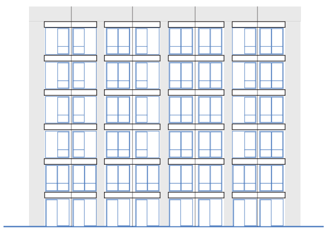
Casestudy C



Casestudy E



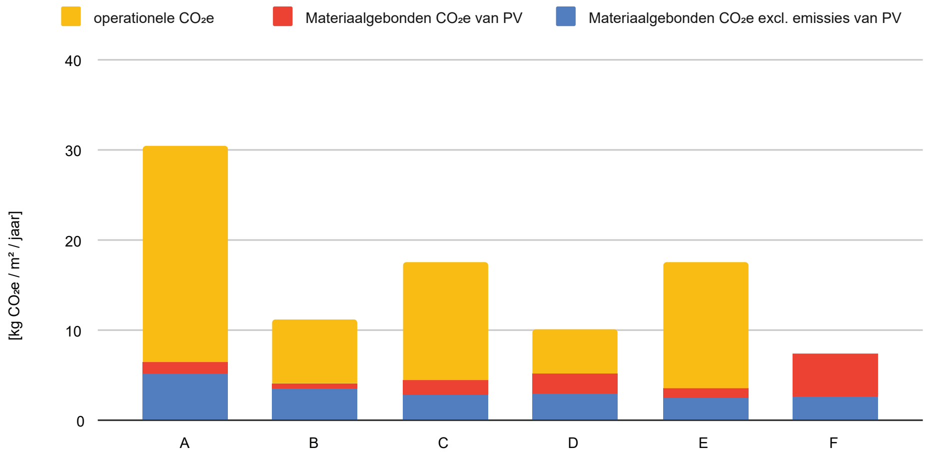
Casestudy F



Casestudy D

FIGURE 44.

Overview of the total CO2 emissions of the six selected reference projects.



explanation:

The exact amount of embodied CO2 emissions from the PV panels could not be determined from the MPG calculations. The exact amount of embodied CO2 emissions of the entire building is given. The emissions from the PV panels have been estimated by calculating with the same percentage as the share of shadow costs of the PV panels in the total MPG score.

OPERATIONAL VS. EMBODIED CARBON

The graph above shows a comparison of the total emissions per square meter per year between the six selected reference projects. A distinction has been made between the embodied carbon of the building, the 'embodied carbon' of the PV panels and the operational emissions. The two embodied carbon together (in blue and red) form the basis for the MPG score.

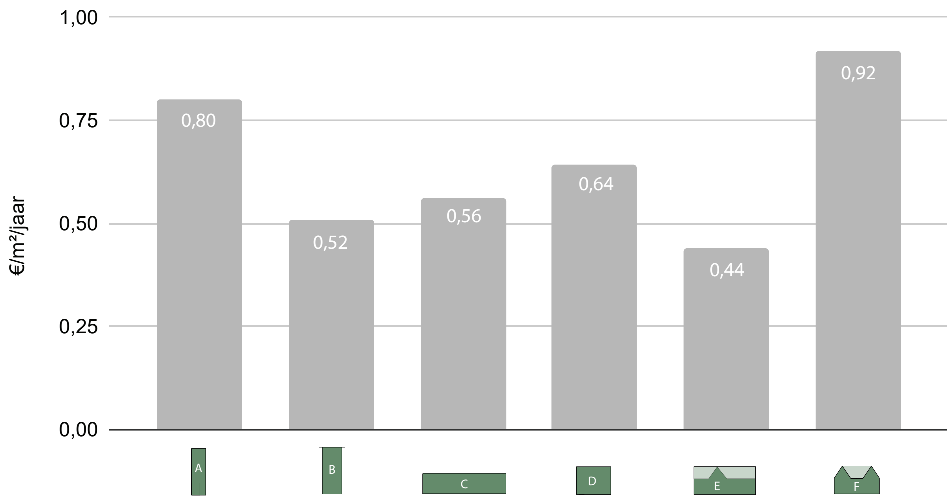
It is clear from this graph that operational emissions are often higher than embodied carbon per year. However, there are a number of factors to keep in mind here.

Although embodied carbon are calculated as emissions per year, almost all emissions occur at the time of construction, i.e., at the beginning of the life cycle. Operational emissions, on the other hand, are emitted over the life of the building. Often a standard life span of 75 years is used, but there is no guarantee that the building will actually be in use for 75 years. In the event of early demolition, the embodied carbon will be much higher if the calculation is made per year.

In addition, it is also important to consider the time factor of CO_2 emissions. The longer the CO_2 is present in the atmosphere, the more damage it does. The amount of emissions emitted during the construction process do more damage than the same amount of emissions spread out over 75 years.

FIGURE 45.

Shadow costs of six selected case studies.



METHODOLGY

The available information on the selected reference projects were not homogeneous. Nevertheless, the table above summarizes the available data in order to compare the different values of the projects.

Case study D is the only one to have a BENG calculation for operational emissions, while the other projects calculated with EPC. In order to compare the BENG score with the EPC, BENG 1 (energy demand) was compared with the primary energy consumption of the EPC scores. A limitation in this is that in the latter 'non-building equipment' is included, while in BENG this is not the case. The CO_2 emissions of the BENG 2 score (fossil energy consumption) were subtracted and multiplied by the average emissions of the Dutch energy grid. We therefore expect some inaccuracies in this.

The information available in the different EPC calculations also did not match. Some calculations referred to 'primary energy use', while others referred to 'energy use for building-related equipment' and 'energy use for non-building-related equipment'. These have been equated to make a comparison possible.

Another factor that needs to be commented on is the subjective analysis of the floor plans. It is interesting to include the lifestyle missions in the analysis, because it is related to the living situation of the residents.

The number of square meters per person has been increasing for years in the Netherlands. Not necessarily because we live in bigger houses, but because the size of the average household is getting smaller. There are more and more households of one or two people. So, isn't it necessary to design new forms of housing as well? After all, the environmental performance is expressed in €/**m²** not in €/**person**

If we want to reduce CO_2 emissions, we should not make the same mistake as the car industry. It has used innovation and increased engine efficiency to build bigger cars, not to reduce real consumption. How can we better match supply and demand? On the one hand, we could create affordable housing for first-time buyers and students who might be able to live with a small room to themselves and shared amenities. On the other hand, we could devise housing options for empty-nesters, freeing up their large single-family home for first-time buyers with a desire to have children.

For this study, we estimated the number of occupants per dwelling so that we could determine the square footage per person. This was done by counting the number of bedrooms in the homes. Of course, not every room (besides the living room) will actually be used as a bedroom.

COMPARATIVE TABEL

FIGURE 46.

Data overview of the six chosen reference projects.

Materiaalgebonden energie

Casestudies	A (hoogstedelijk)	B (hoogstedelijk)	C (stedelijk)	D (stedelijk)	E (laagstedelijk)	F (laagstedelijk)
MPG-score [€/m²/jaar]	0,8	0,52	0,56	0,64	0,44	0,92
MPG-score exclusief impact van PVs [€/m²/jaar]	0,69	0,50	0,42	0.34	0,31	0,32
Materiaalgebonden CO_2 [kg/m²]	480	308	345	469	263	555
Materiaalgebonden CO_2 exclusief impact van PVs [kg/m²/jaar]	5,1	3,5	2,6	3,0	2,5	2,6
CO_2e van totale MPG-score [%]	45	39	41	38	39	37
Levensduur van het gebouw toegepast in de MPG-berekening [jaar]	75	75	75	92	75	75

Energieprestatie

Casestudies	A (hoogstedelijk)	B (hoogstedelijk)	C (stedelijk)	D (stedelijk)	E (laagstedelijk)	F (laagstedelijk)
EPC-score BENG-score [kWh/m²]	0,53 -	0,2 -	0,4 -	- 9,75	0,4 -	0 -
Primair energieverbruik [kWh /m²/jaar]	39	14	63	50 *	54	30
Operationele emissies [kg CO_2e/m²/jaar]	24	7	13	4-5	14	0
PV / BVO	1,1%	0,6%	7,6%	12,7%	0%	29,5%
PV oppervlakte [m²]	403	42	264	350	0	46

* alleen energiebehoefte voor verwarming en koeling

Layout

Casestudies	A (hoogstedelijk)	B (hoogstedelijk)	C (stedelijk)	D (stedelijk)	E (laagstedelijk)	F (laagstedelijk)
Gemiddeld appartement oppervlakte [m²]	94	99	87	41	151	159
Oppervlakte van het appartement [m²]	67-166	94-159	83-102	34-48	151	159
Geschatte aantal potentiële slaapkamers per appartement (gemideld)	3	3	1	1	3-4	3
Geschatte aantal potentiële inwoners per appartement (gemiddeld)	4	4	3	2	4	5
Oppervlakte per inwoner (gebaseerd op geschatte woonsituatie) [m²]	28	38	35	21	38	32
Oppervlakte van balkon [m²]	12-143	18-64	9-11	0-8	0	0
BVO gebruikt in MPG [m²]	9731	6792	3466	2761	170	156

The following pages show some comparisons between the six case studies. The different parts of the building, expressed in the S layers of Brand, are considered one by one and a number of observations are described. The case studies are also sorted according to urban density (two per density), so conclusions are also drawn relative to the data of different densities..

DISSECTING DIFFERENT BUILDING COMPONENTS

The MPG score is a cumulative score that shows the embodied carbon of building products and processes. As a designer, however, it is more interesting to see in detail the consequences of certain design decisions. We have therefore restructured the data from the six case studies in the following way:

The first figures below show the MPG results as they are normally displayed. This is convenient in terms of input, but for a designer it would be even more interesting to know exactly where the greatest environmental impact comes from. For example, the flooring category is responsible for 38.9 percent of the environmental impact, but is this in the load-bearing part, the screed or the screed, for example? The second image shows a more detailed version of the same MPG data.

Gevel

Casestudies	**A (hoogstedelijk)**	**B (hoogstedelijk)**	**C (stedelijk)**	**D (stedelijk)**	**E (laagstedelijk)**	**F (laagstedelijk)**
Raam U waarde [W/m^2·K]	1,32	1,30	1,1	ca, 1,1	1,6	1,6
Dichte geveldelen Rc waarde [m^2·K/W]	4,5	4,5	4,5	5,5	4,5	4,5
Open vs dicht *						
Glas type	Drievoudigglas	HR+ dubbel + 5m^2 glazen deuren	HR dubbel	HR++ dubbel	HR++ dubbel	HR++ dubbel
Glas oppervlakte [m^2]	3502	1162	870	482	14	17,4
Type gevelbekleding	Baksteen	Baksteen	Baksteen	Hout	60% baksteen+ 40% hout	70% Baksteen+ 30% Hout
Oppervlakte gevelbekleding [m^2]	3618	1797	1407	800	115	165
Totale oppervlakte glas + gevelbekleding [m^2]	7120	2959	2277	1282	129	183
Verhouding glas / (totaal glas + gevelbekleding) [%]	49,2%	39,3%	38,2%	37,6%	10,9%	9,5%
Vormfactor (gevel / BVO)	0,73	0,44	0,66	0,46	0,76	1,17

Draagstructuur

Casestudies	**A (hoogstedelijk)**	**B (hoogstedelijk)**	**C (stedelijk)**	**D (stedelijk)**	**E (laagstedelijk)**	**F (laagstedelijk)**
Constructief materiaal	beton (meestal) + HSB	beton	kalkzandsteen + HSB + beton	CLT (meestal) + beton	kalkzandsteen + HSB + beton	kalkzandsteen + beton

Installaties

Casestudies	**A (hoogstedelijk)**	**B (hoogstedelijk)**	**C (stedelijk)**	**D (stedelijk)**	**E (laagstedelijk)**	**F (laagstedelijk)**
Warmtepomp			X	X	X	X
Warmtelevering extern	X	X				
Warmtapwater levering extern	X	X				
E-boiler			X		X	X
Warmtedistributie leidingen		X	X	X	X	X
Vloerverwarming	X		X	X	X	X
Wandverwarming						
Vloerkoeling	X			X		
WTW unit		X				
Luchtdistributie toe- en afvoer		X				
Ventilatie type D	X			X		
Ventilatie type C			X		X	
Balansventilatie kanalen	X					
Koelmachine	X					

FIGURE 47.

Data overview of the six chosen reference projects.

REORGANIZING THE MPG SCORE

For this study, we reorganized the environmental impact according to Steward Brand's S-layers. This shows the impact of the different architectural parts of a building and also corresponds better to the different experts present in a design team (architect,

FIGURE 48.

MPG score per component as shown in a standard MPG calculation.

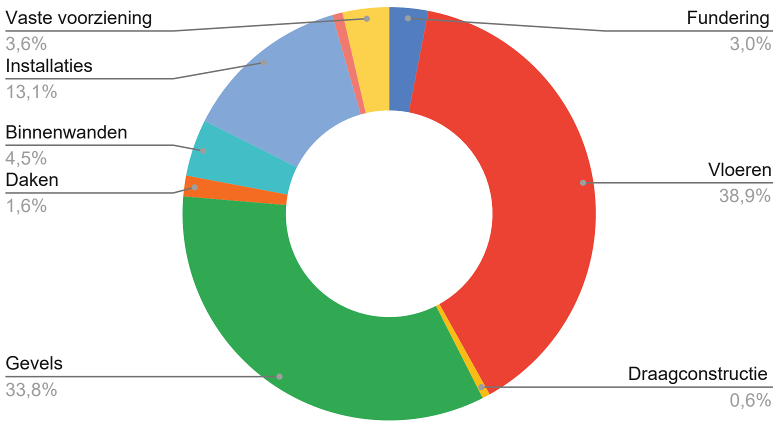
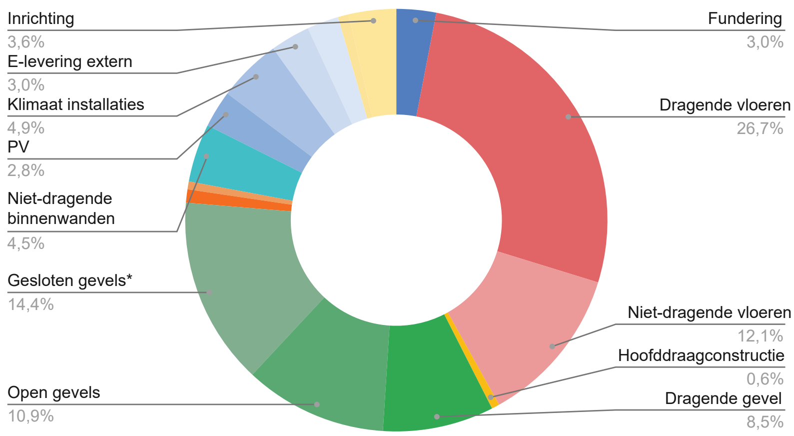


FIGURE 49.

MPG score per component shown in a detailed overview

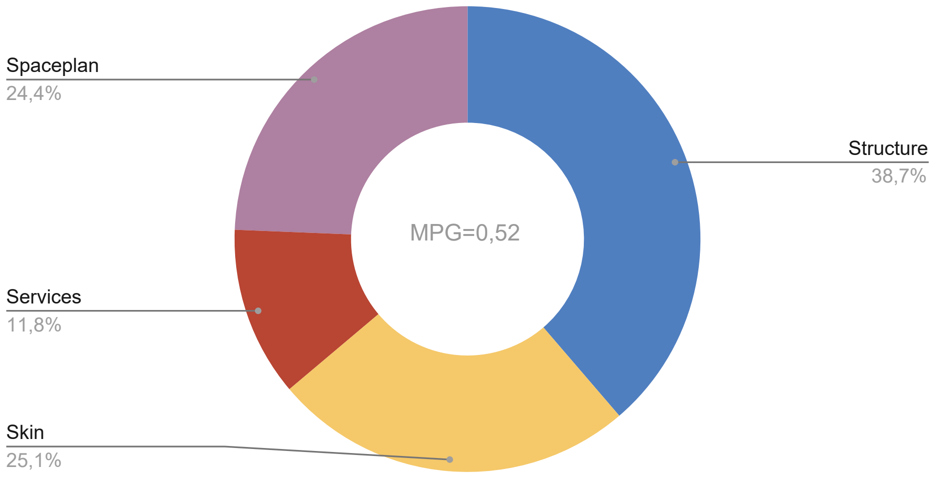


structural engineer, installer). Also, the typical lifespan differs for each building component.

Lifetime is important because it provides information on recurring emissions. Some products are used once and require little maintenance or repair (e.g., structural components in a residential building), while other components have a short life span (multiple repairs or even replacements are required). Information on product life cycles can also be found in the individual SPD. However, it is often laborious to look up this data and compare it with each other. The different layers of Stewart Brand give a rough indication

FIGURE 51.

MPG score categorized by Stewart Brand's layers.

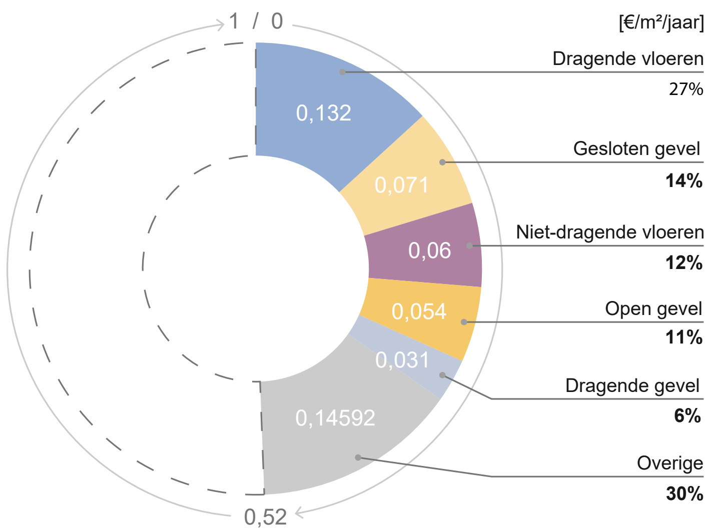


without going into further detail of building components.Naast de indeling in verschillende S-lagen zijn twee overige grafieken beoordeeld: de vijf gebouwonderdelen met de grootste milieu-impact en de verschillende levenscyclusfasen.

Onderstaande grafiek met de vijf grootste uitstoters laat zien welke producten de grootste bijdrage leveren aan de milieu-impact. De grafiek toont de effecten in de eenheid van de MPG-score, €/m²/jaar, in relatie tot een MPG-score van 1. Op die manier kunnen we de absolute aantallen van verschillende projecten met elkaar vergelijken.

FIGURE 50.

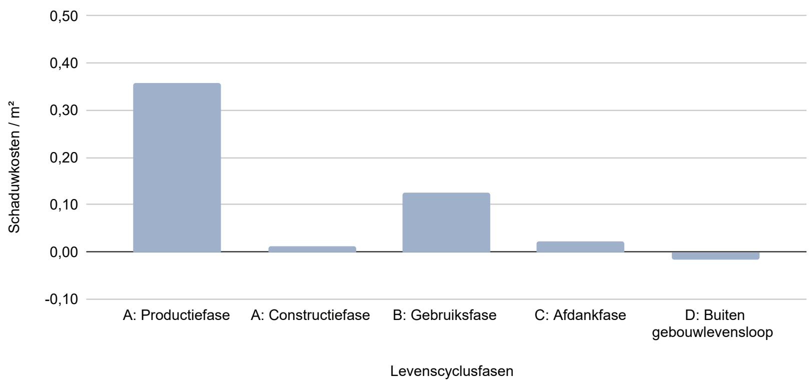
MPG score of the five building parts that cause the highest emissions.



The emissions per life cycle phase, shown in the bar chart below (production, construction, use and disposal phases) is information that can also be extracted from an MPG calculation. As mentioned in the introduction, it is good to know when emissions occur during the life of a building component. The carbon impact comes from the products and their lifetimes. For example, façade components and installations have large emissions in the usage phase (a lot of maintenance required), while the emissions of a supporting structure almost all occur in the production phase

FIGURE 52.

MPG score by lifecycle stage.



THE ROLE AND IMPACT OF PV PANELS.

The analysis shows that PV panels have a large impact on the MPG score. The embodied carbon of PV panels are comparatively very large and their lifetime is quite short, namely 25 years. An MPG score can easily increase by 30 percent or more if PV panels are included in the calculation.

However, PV panels generate renewable energy that can replace so-called gray energy. Grey energy is normally supplied by the grid to which all buildings are connected. The payback time of PV panels (seen from the CO_2 balance) is usually less than two years. In other words, the investment of embodied carbon is recouped by the renewable energy it produces. PV panels therefore have a so-called positive CO_2 balance.

However, the application of PV panels should not lead to a lack of effort in other areas. The designer must always make smart choices regarding the energy consumed. Firstly, reduce energy demand, secondly, use energy efficiently and thirdly, generate renewable energy.

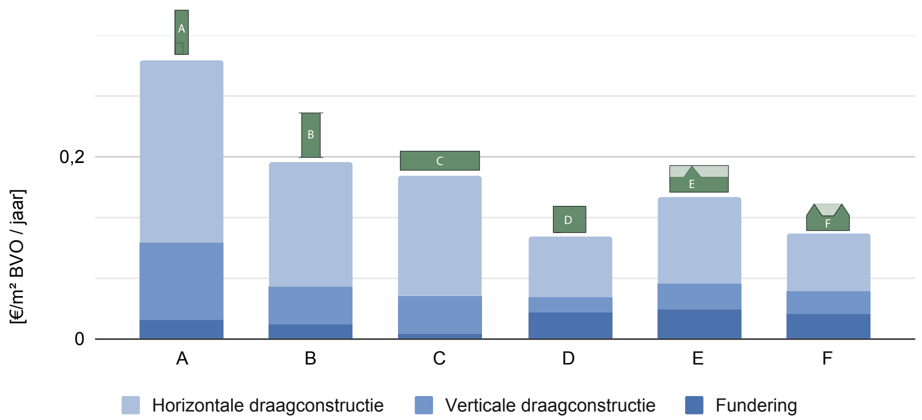
It is worth noting that PV panels are quantified in the MPG, EPC and BENG score as well: the number of PV panels required to achieve the required EPC or BENG score is also input for the MPG score.

The environmental impact of PV panels should always be explained by comparing embodied carbon with operational emissions. The MPG score might be very high and therefore not seem favorable with respect to CO_2 impact. However, if a large part comes from PV panels, it can be concluded that the building does have a favorable CO_2 balance.

COMPARISON BY LAYER

FIGURE 53.

Support structure comparison of the six case studies.



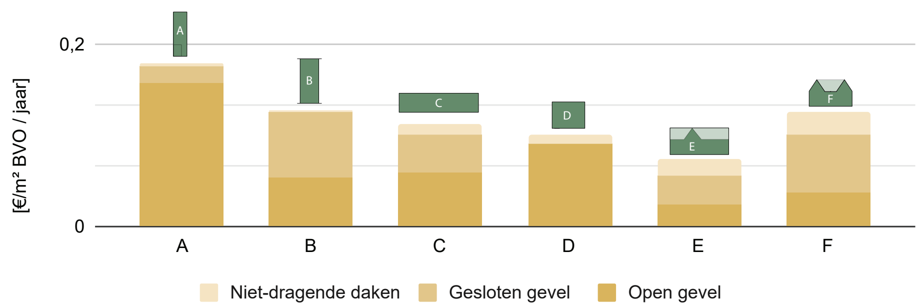
STRUCTURE (SUPPORTING STRUCTURE)

The largest component in terms of mass and emissions is the support structure of a building. Only PV panels have higher embodied carbon. The average environmental impact of load-bearing floors is 23 percent of total CO_2 emissions.

It can be observed that especially structural floors have a larger share in total emissions in high-rise projects, as can be seen in case studies A and B. This is due to thicker floors, probably because of larger spans and increasing wind loads. The foundation has a particular impact on low-rise projects, because here a relatively large amount of surface foundation is required in relation to the usable floor area. Only cases B and C do not have pile foundations, but stand on beams (B) or a slab and basement (C). None of the case studies have a structural skeleton of columns and beams. Instead, they had a slab and floor structure.

FIGURE 54.

Façade comparison of the six case studies.

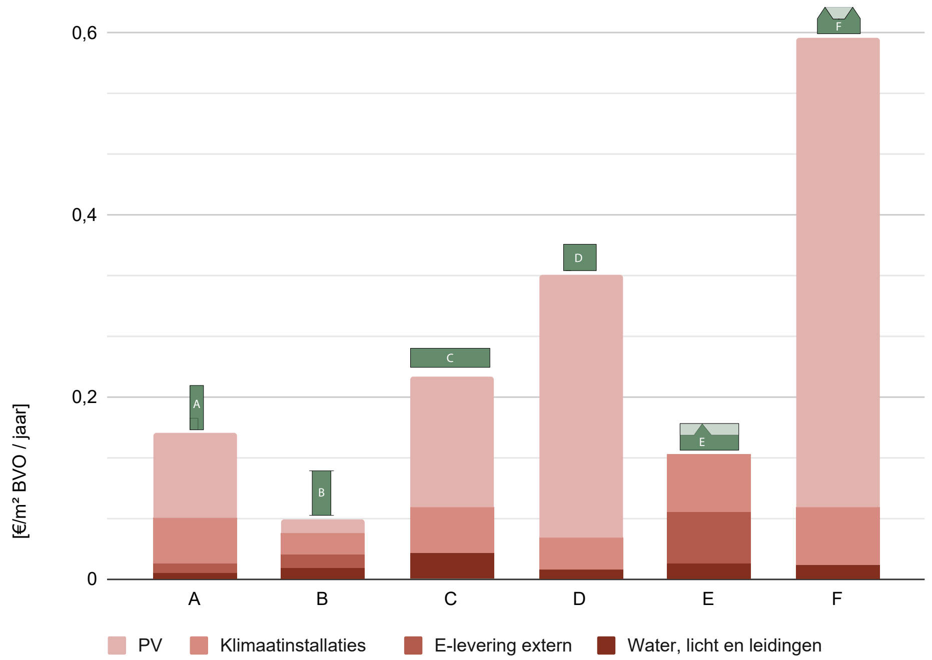


SKIN (FAÇADE)

In the facade, most of the emissions clearly come from the transparent parts. On average, the façade has the second highest environmental impact, after the supporting structure. In case study A, for example, this distribution is clearly visible. Cases E and F have a smaller ratio of open to closed façade sections and therefore a lower environmental impact from glazing. The use of brick has a limited negative impact on the MPG score. Some (unpainted or preserved) European wood claddings have a positive impact, despite their shorter lifespan and the need for maintenance and repairs (cases D and E). In addition, the type of brick product chosen also has an impact on total emissions. Consider the various alternatives that are available such as the narrow brick, brick strips and dry stacking systems..

FIGURE 56.

Installations comparison of the six case studies.

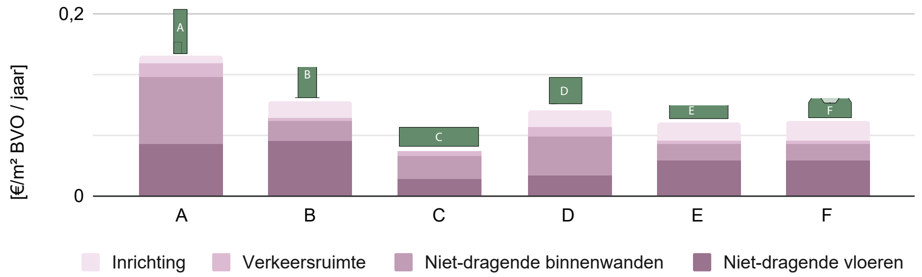


SERVICES (INSTALLATIONS)

The largest environmental impact of all building components comes from PV panels, as discussed earlier. Other important observations relate to the possible installations. There are different applications for the indoor climate and heat supply of a building. Therefore, no specific component can be designated with the highest emissions. 'External energy' shows the impact of materials used in the energy grid and energy-generating devices, such as wind turbines. When the consumption of those sources (electricity and district heating) is applied in a project, their impact is entered in the MPG. For the project E (terraced house), the impact is visible.

FIGURE 55.

Floor plan comparison of the six case studies.



SPACE PLAN (PLAN)

On average, the non-load bearing floors are responsible for five to six percent of the total environmental impact. When looking in more detail at the products used, we see that the screed (sand cement screed) is the largest contributor. A sand-cement floor is poured into the structure, which also reduces the disassembly of the floor and other components (for example, structural floor slabs and walls). In terms of non-structural walls, project A shows that more than seven percent of the impact is in metal stud walls with drywall. This is due to the short product life (25 years compared to gypsum blocks with a life of 60 years). Sanitary and kitchen components have very similar impacts in all case studies. The reason: in the NMD (in version 2.3) there are only a few options to choose from.

SHADOW COSTS IN THE S-LAYERS FROM BRAND

The different colors in the graphs on the following pages show the distribution of environmental costs (excluding the impact of PV). A whole circle equals an MPG score of 1. This shows the relative difference per case study between the different layers (what is the difference in impact between supporting structure and services), but also the absolute difference per layer (what is the impact of the supporting structure in case A versus case B).

What stands out is that the two high-rise projects (A and B) have a relatively high total score of 0.5 and 0.69. In both projects, the supporting structure has a large impact. This is because the floors are quite thick and made of concrete.

The other four projects (C, D, E and F) have similar overall MPG scores between 0.34 and 0.42 (excluding PV). However, for each case there are large differences between the different layers. Case C, for example, has a supporting structure with an impact similar to the two high-rise projects. Case C and E score quite high in the installations category (excluding PV). There is no clear reason for this, as the interaction between the installations, the materials and the configuration of a building is quite complex. This requires more research and also a comparison between the operational energy performance and the embodied carbon.

Case E scores quite low in terms of the building envelope, which is mainly due to the small size of the facade openings and the wooden cladding. Case C has a much lower score in the floor plan category, because kitchens and bathrooms were kept out of the calculation.

In the following chapters, we will elaborate on the specific layers and describe each project in more detail.

TOP 5 BIGGEST EMISSIONS

Which materials or elements are the biggest culprits? Are the largest emissions always in the same section? Figure 58 on page 70 shows the largest emissions by project based on the more detailed categorization.

First, the high impact of PV (although included in this comparison) is striking. In three of the six cases, solar panels are on one, in four of the six within the top 5. In case A and B (high-rise) the load-bearing floors are clearly on one. The reason for this is the material and the greater thickness of the floors compared to other cases. In high-rise buildings, higher horizontal forces (wind load) and larger spans are likely reasons for this. Case C has a similar absolute impact of the load-bearing floors. However, this impact is pushed down by the solar panels.

The open façade sections also rank high in the comparison, especially in the high and mid-rise building projects, due to quite generous façade openings. In case A, these make up 49 percent of the entire facade and are in triple glass up to and including 24 mm thickness. In comparison, case B has 39 percent open façade and double glazing (16 mm). It can be assumed that the closed façade sections insulate the building better, so the windows with a lower insulation value suffice. Case E and F have fewer openings overall and use partially wood instead of brick for the closed sections. However, they also have more total area relative to volume which is reflected in an overall more even distribution of environmental impact. Case E uses the least glass and brick.

Another high emission source is the non-load bearing floors. Averaged across all six cases, the proportion is 0.04€/m^2/year, which works out to about nine percent of the total MPG score (excluding PV).

FIGURE 57.

Shadow costs classified in the S-layers of Brand (excl. material-related environmental effect of PV).

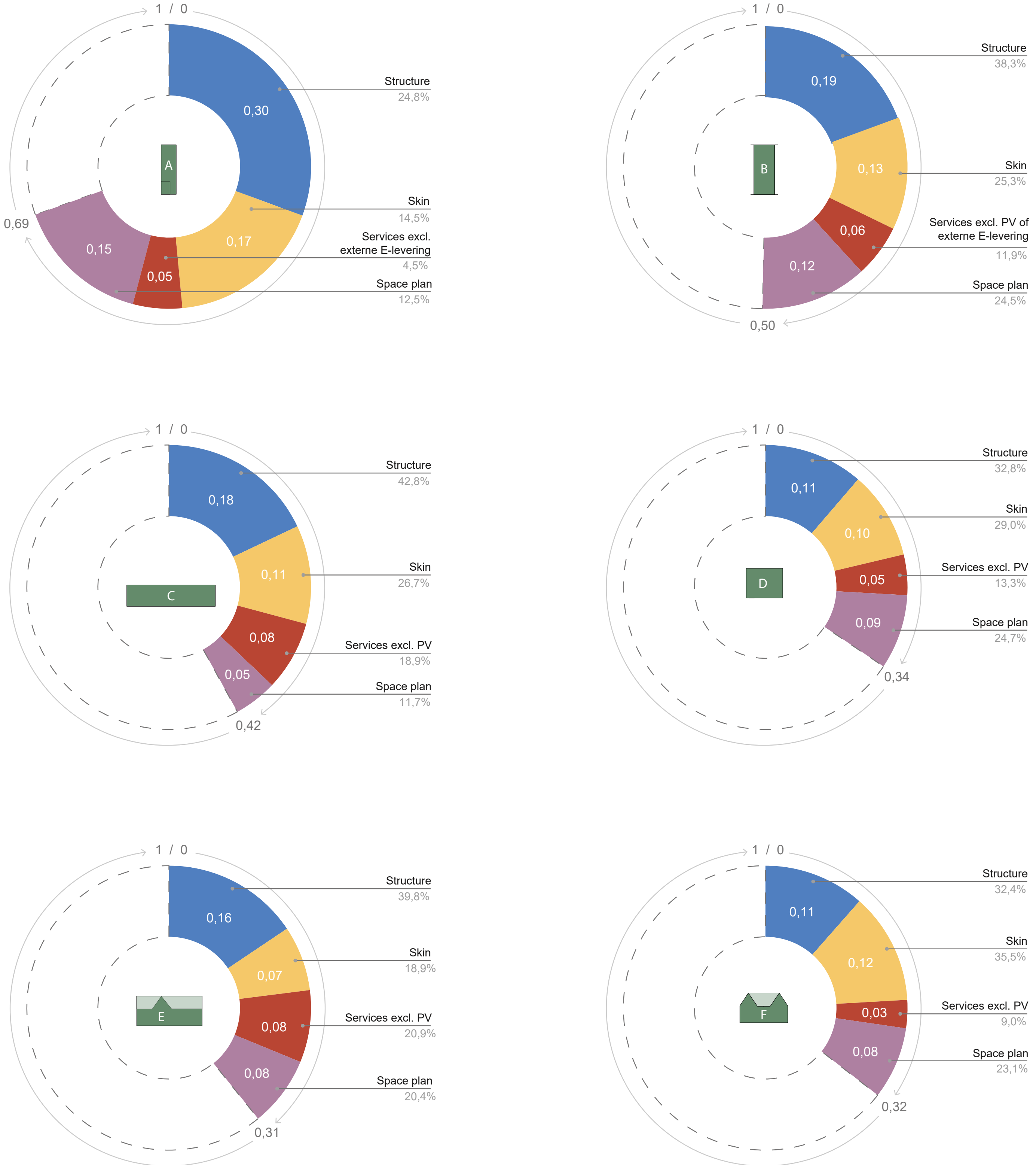
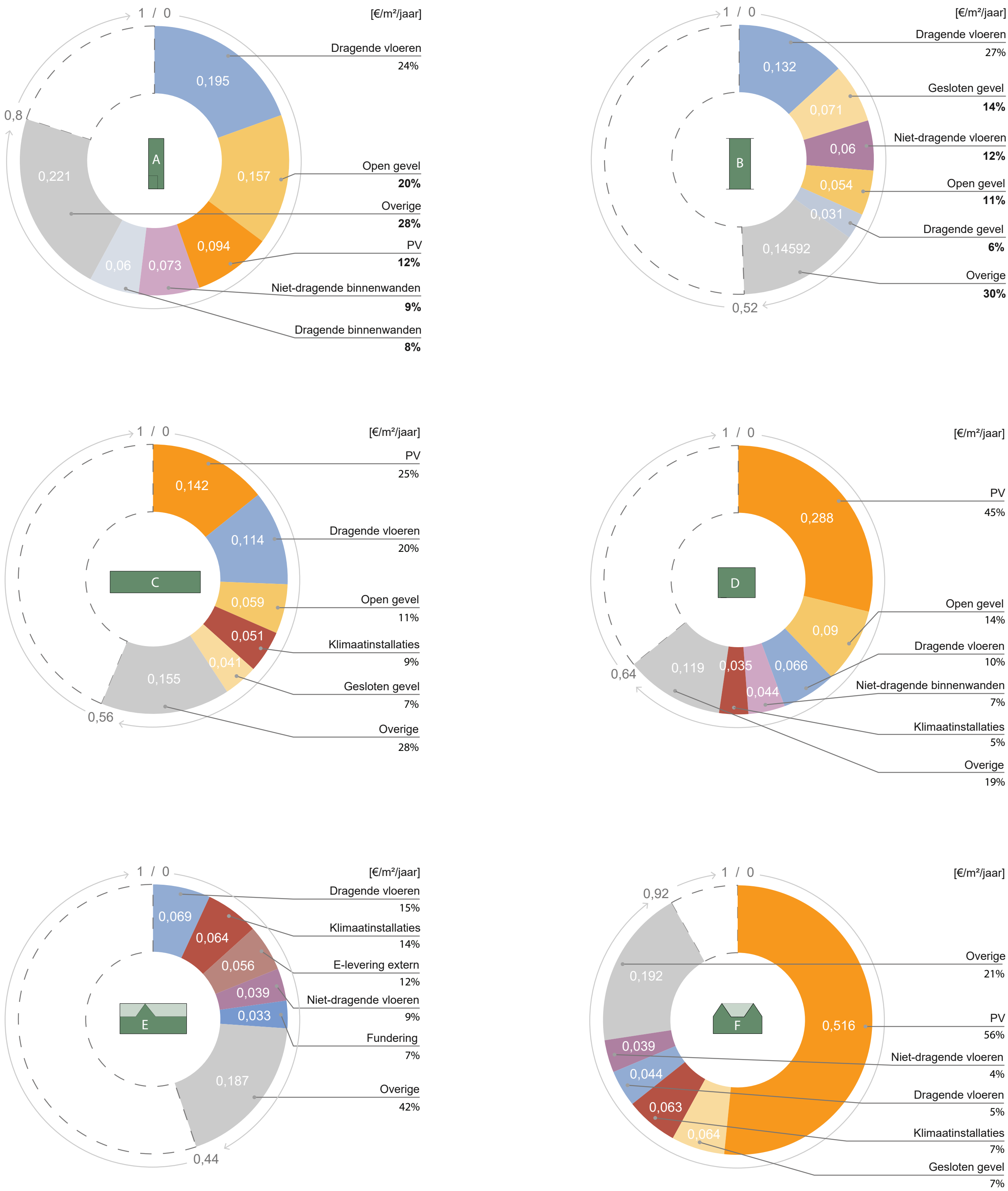


FIGURE 58.

The top 5 largest emissions of the analyzed reference projects.



LIFE CYCLE

The shadow costs by life cycle stage are compared in Figure 59 on page 71. We see that the distribution is quite similar. Most of the emissions fall in the production phase. In the MPG methodology, this phase includes only the initial construction. For example, a concrete support structure falls entirely into this phase because it remains in place over its entire 75-year life. However, if a product is replaced during the usage phase, then the emissions are attributed to the usage phase. Thus, using elements with high emissions and short lifetimes increases emissions in the usage phase. Therefore, extending the lifetime of the building as a whole does not contribute to the reduction of the MPG score. Examples are PV panels or façade glass.

The construction and disposal phases show relatively few emissions. The end-of-life phase sometimes even shows negative emissions, for example when materials are burned and energy is gained (thermal recycling) or they can prevent emissions in some other way. This then concerns phase D: outside of building lifecycle.

ENVIRONMENTAL IMPACTS

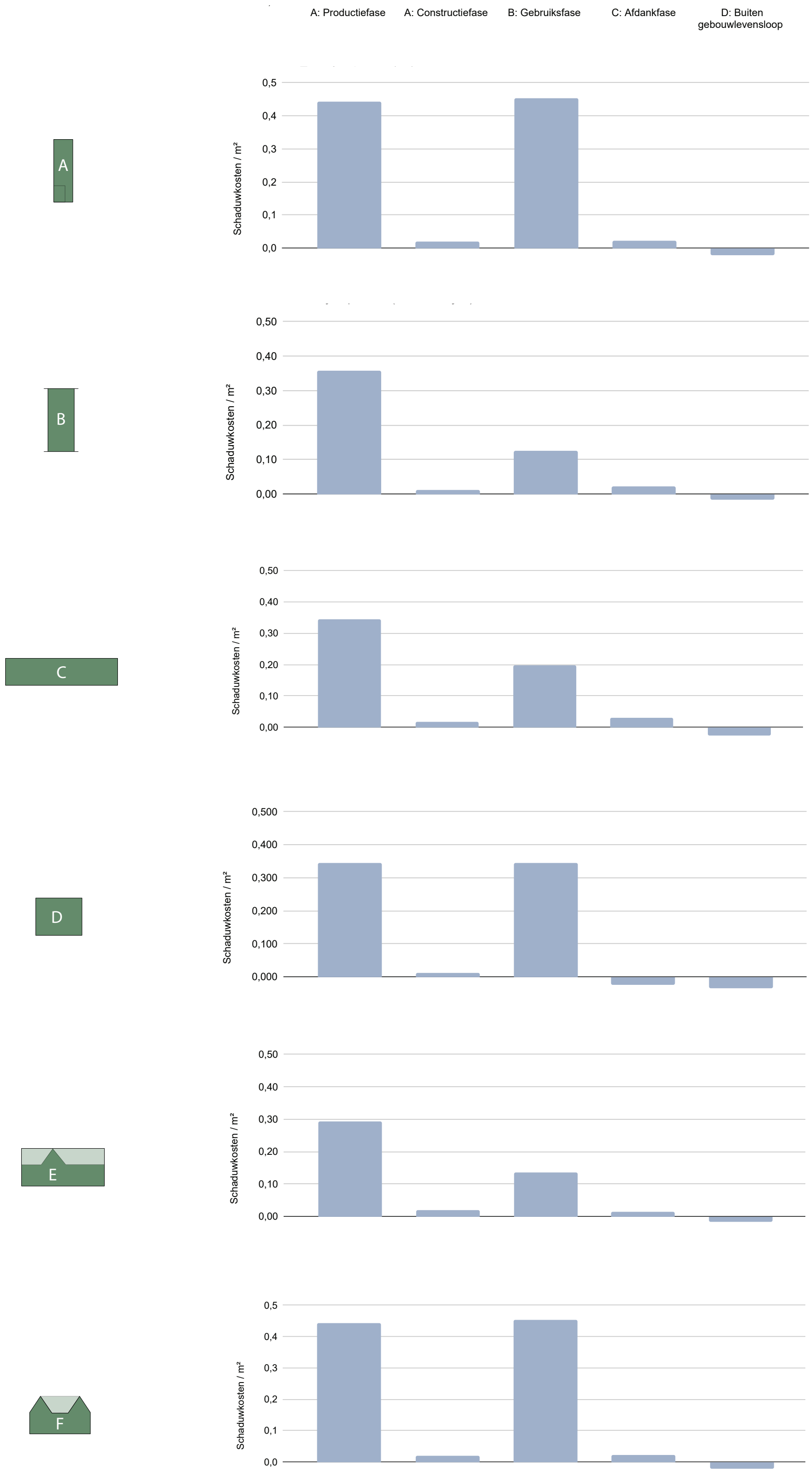
(next page)

Figure 60 on page 73 shows the different environmental impacts per case as indicated in the MPG. Added together, these are the shadow costs of the building per square meter per year. Our main interest in this study is the global warming potential (GWP), which is expressed in CO_2 equivalents. This is not only the emission of CO_2, but also, for example, methane, which is also a greenhouse gas. CO_2 emitted high up in the atmosphere counts more heavily.

On average, the GWP for our cases is around forty percent, as it was for the longlist of 24 cases. This makes it possible to compare the various cases on the basis of their MPG score, even though that is not exactly the same as the actual CO_2 emissions.

FIGURE 59.

Shadow costs per life cycle stage.



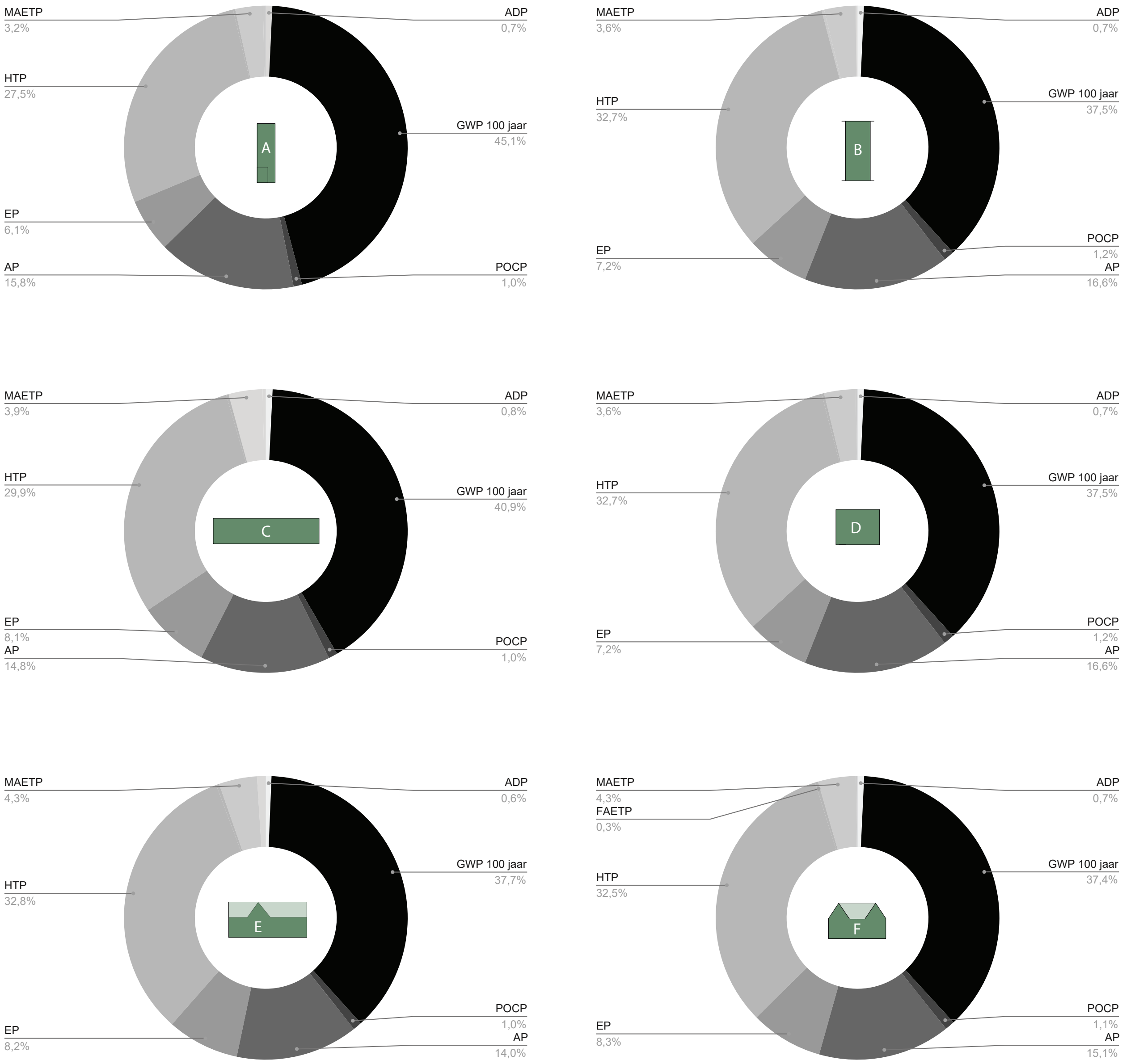


FIGURE 60.

Environmental impacts of the analyzed reference projects.

ENVIRONMENTAL IMPACTS IN THE MPG

- GWP 100 years - Climate Change
- POCP - Photochemical Oxidant Formation
- AP - Acidification
- EP - Vermesting
- HTP - Human toxicity
- FAETP - Freshwater aquatic ecotoxicity
- MAETP - Marine aquatic ecotoxicity
- ADP - Depletion of abiotic resources (excluding fossil energy carriers)
- ADP - Depletion of fossil energy carriers
- ODP - Ozone Depletion
- TETP - Terrestrial Ecotoxicity

CASESTUDY A – HIGHRISE BUILDING

This reference project concerns a 22-storey residential tower. On the first floor and second floor, there are commercial spaces. In addition, there are storage spaces on these floors. The residential tower is part of a larger complex where there is also parking and green areas on the lower floors.

The apartments in this building have floor areas between 67 and 1 66 m^2, excluding the outdoor spaces, which have floor areas between 12 and 143 m^2. The average apartment has three bedrooms. The area per square meter of living space per person amounts to 28 m^2, assuming four residents per apartment.

The material of the main supporting structure is concrete. All of the floors, roof floor and internal load-bearing walls are constructed of concrete. About half of the exterior walls are also concrete, while the other half are constructed of wood-frame elements.

FIGURE 61.

Data overview of reference project A.

Materiaalgebonden energie	
MPG-score [€/m²/jaar]	0,8
MPG-score exclusief impact van PVs [€/m²/jaar]	0,69
Materiaalgebonden CO_2 [kg/m²]	480
Materiaalgebonden CO_2 exclusief impact van PVs [kg/m²/jaar]	5,1
% CO_2e van totale MPG-score	45
Levensduur van het gebouw toegepast in de MPG-berekening [jaar]	75

Energieprestatie	
EPC-score	0,53
Primair energieverbruik [kWh/m²/jaar]	39
Operationele emissies [kgCO_2e/m²/jaar]	24
PV / BVO	4,14%
PV oppervlakte [m²]	403

Layout	
Gemiddeld oppervlakte appartement [m²]	94
Oppervlakte van het appartament [m²]	67-166
Oppervlakte van balkon [m²]	12-143
Geschatte aantal potentiële slaapkamers per appartement (gemiddeld)	3
Geschatte aantal potentiële inwoners per appartement (gemiddeld)	4
Oppervlakte per inwoner (gebaseerd op geschatte woonsituatie) [m²]	28
BVO gebruikt in MPG	9731

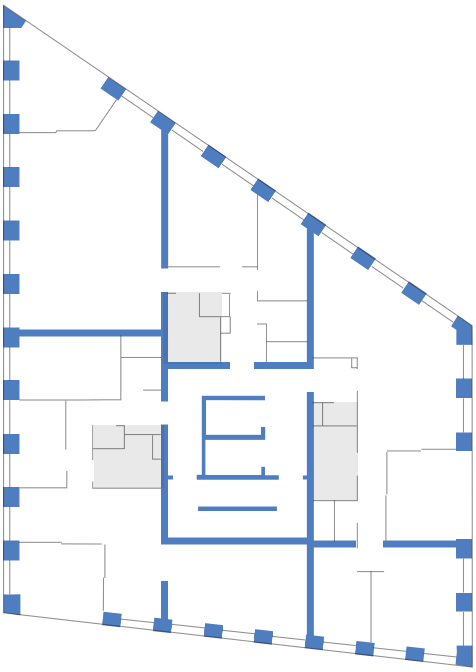
Gevel	
Raam U waarde [W/m²·K]	1,32
Dichte geveldelen Rc waarde [m²·K/W]	4,5
Open vs dicht *	
Glas type	Drievoudigglas
Glas oppervlakte [m²]	3502
Type gevelbekleding	Baksteen
Oppervlakte gevelbekleding [m²]	3618
Totale oppervlakte glas + gevelbekleding [m²]	7120
Glas / (Totaal glas + gevelbekleding) [%]	49,2%

Draagstructuur	
Constructief materiaal	beton (meestal) + HSB

Installaties	
Warmtepomp	
Warmtelevering extern	X
Warmtapwater levering extern	X
E-boiler	
Warmtedistributie leidingen	
Vloerverwarming	X
Wandverwarming	
Vloerkoeling	X
WTW unit	
Luchtdistributie toe- en afvoer	
Ventilatie type D	X
Ventilatie type C	
Balansventilatie kanalen	X
Koelmachine	X

FIGURE 62.

Floor plan reference project A.



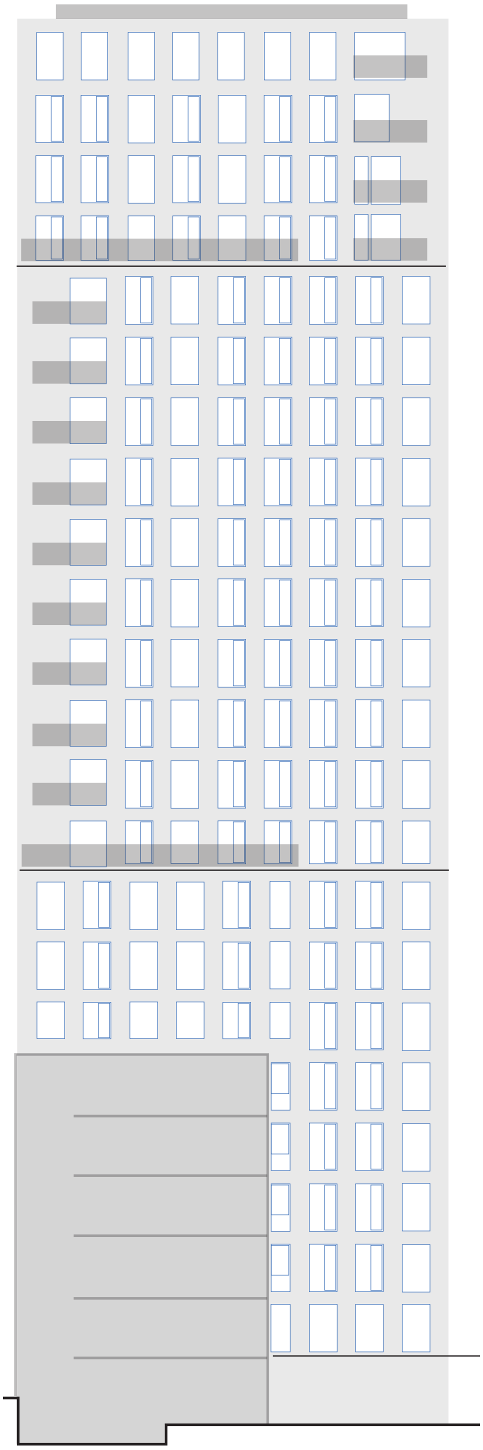


FIGURE 63.

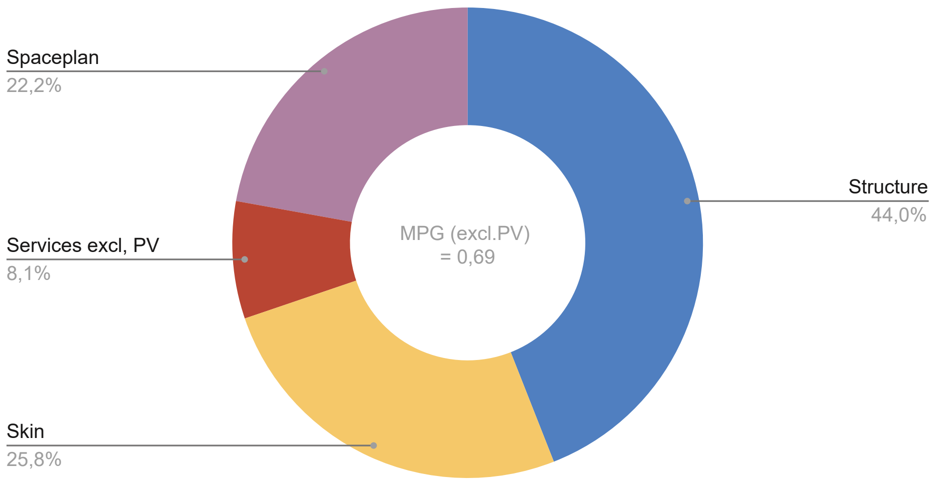
facade reference project A.

This reference project has a high MPG and EPC score. Although PV panels produce renewable energy, the fossil fuel energy consumption is 24 kg CO_2e per square meter: this is the highest of all reference projects. The ratio between the total usable floor area and the applied square meters of PV panels is low: this is logical in high-rise projects, because the roof area is often small.

In the categories of supporting structure, facade and floor plan, the shadow costs are higher than in the other reference projects. The biggest impact comes from the supporting structure. The chosen material (concrete) and the thickness of the floor is the main cause of this, similar to reference project B.

FIGURE 64.

MPG score broken down to the S-layers excluding PV panels.



Like case B, this building has fairly thick load-bearing floors, making this the largest individual element contribution. The reason is probably a higher horizontal load due to wind and possibly larger spans.

We also see a great influence of the open facade sections. This project has fairly generous window sections. Also, the glass is triple to meet the overall facade insulation requirements.

It would be interesting in a further study to compare in detail the energy calculations with the material calculations to see how the window sections can be optimized with respect to daylighting, indoor/outdoor relationship, shading, etc. It may also be possible to replace the third layer of glass with another element, such as a foil or filler.

FIGURE 65.

MPG score by lifecycle stage.

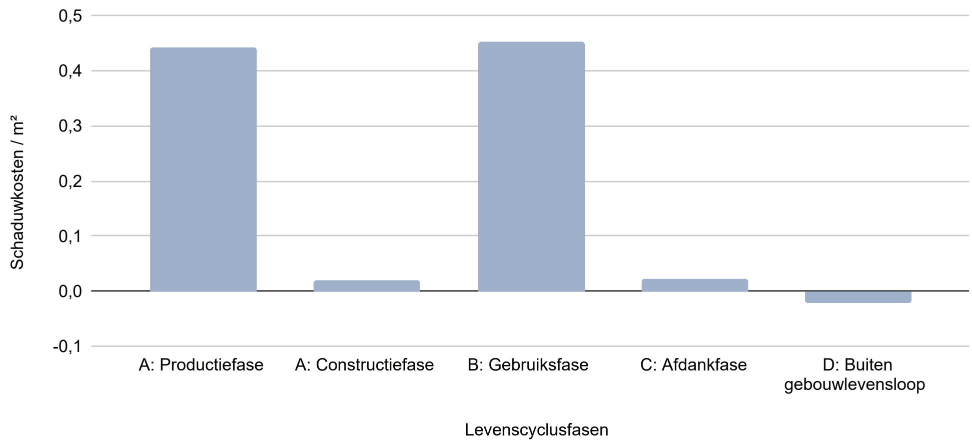
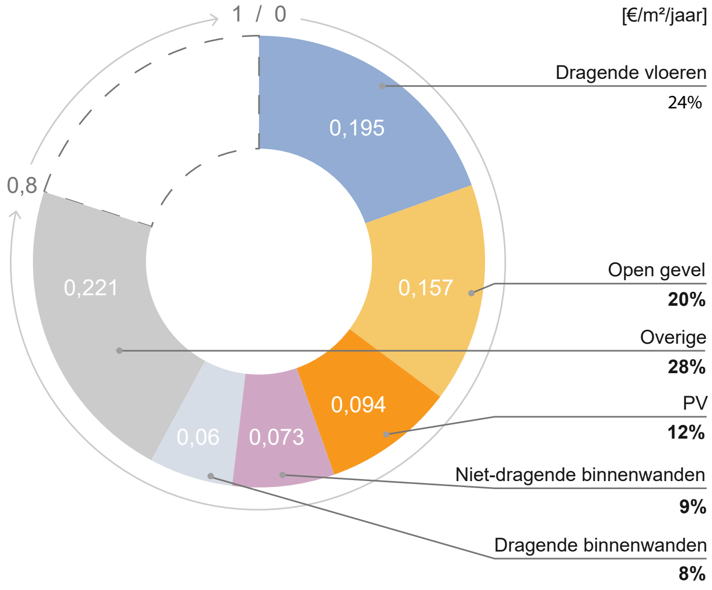


FIGURE 66.

MPG score of the five building parts that cause the highest emissions.



Non-load-bearing walls have a high CO_2 impact. The metal stud walls used in reference project A the CO_2 impact is about six percent of the total environmental impact. In reference project E, plaster blocks were used here and the proportion of CO_2 impact to the total environmental impact was two percent. The difference is in the material used, in addition to the fact that the ratio of walls to total floor area is slightly greater in project A.

According to Nibe's EPD database, the lifetime of a metal stud wall is approximately 25 years. This leads to a higher environmental impact given the relatively short lifespan. A positive aspect could be that a metal stud wall can be easily removed, compared to plaster block walls. The application of metal stud walls therefore has a positive impact on the flexibility of the floor plan. However, if the materials have to be removed after their lifespan and cannot be reused, new materials have to be applied. This means that there are still more CO_2 emissions.

CASESTUDY B – HIGHRISE BUILDING

This high-rise project is located on the outskirts of a city, connected to public transportation and near natural areas. It is part of a complex consisting of two buildings. An underground parking garage is also part of the design.

The size of the apartments ranges from 94 to 159 m^2, excluding the balconies (additional 41 m^2 of outdoor space). On average, the apartments have three potential bedrooms. In the example of a family (consisting of four people), an average apartment would provide approximately 38 m^2 of living space per person.

FIGURE 67.

Data overview of reference project B.

Materiaalgebonden energie	
MPG-score [€/m²/jaar]	0,52
MPG-score exclusief impact van PVs [€/m²/jaar]	0,50
Materiaalgebonden CO_2 [kg/m²]	308
Materiaalgebonden CO_2 exclusief impact van PVs [kg/m²/jaar]	3,5
% CO_2e van totale MPG-score	39
Levensduur van het gebouw toegepast in de MPG-berekening [jaar]	75

Energieprestatie	
EPC-score	0,2
Primair energieverbruik [kWh/m²/jaar]	14,1
Operationele emissies [kgCO_2e/m²/jaar]	7
PV / BVO	0,6
PV oppervlakte [m²]	42

Layout	
Gemiddeld oppervlakte appartement [m²]	99
Oppervlakte van het appartament [m²]	94-159
Oppervlakte van balkon [m²]	18-64
Geschatte aantal potentiële slaapkamers per appartement (gemiddeld)	3
Geschatte aantal potentiële inwoners per appartement (gemiddeld)	4
Oppervlakte per inwoner (gebaseerd op geschatte woonsituatie) [m²]	38
BVO gebruikt in MPG [m²]	6792

Gevel	
Raam U waarde [W/m²·K]	1,30
Dichte geveldelen Rc waarde [m²·K/W]	4,5
Open vs dicht *	
Glas type	HR+ dubbel + 5m² glazen deuren
Glas oppervlakte [m²]	1162
Type gevelbekleding	Baksteen
Oppervlakte gevelbekleding [m²]	1797
Totale oppervlakte glas + gevelbekleding [m²]	2959
Glas / (Totaal glas + gevelbekleding) [%]	39,3%

Draagstructuur	
Constructief materiaal	beton

Installaties	
Warmtepomp	
Warmtelevering extern	X
Warmtapwater levering extern	X
E-boiler	
Warmtedistributie leidingen	X
Vloerverwarming	
Wandverwarming	
Vloerkoeling	
WTW unit	X
Luchtdistributie toe- en afvoer	X
Ventilatie type D	
Ventilatie type C	
Balansventilatie kanalen	
Koelmachine	

Het meest toegepaste materiaal voor draagstructuren is beton. De constructiewanden zijn gesitueerd langs de gevel, als woningscheidende wanden en rondom de kern. Het toegepaste materiaal is beton. De gevels hebben relatief kleine openingen, die wel over de gehele verdiepingshoogte te vinden zijn. Buitenruimtes zijn op de hoeken van het gebouw boven elkaar geplaatst. Smalle balkons lopen om het gebouw heen.

FIGURE 68.

Floor plan of reference project B.

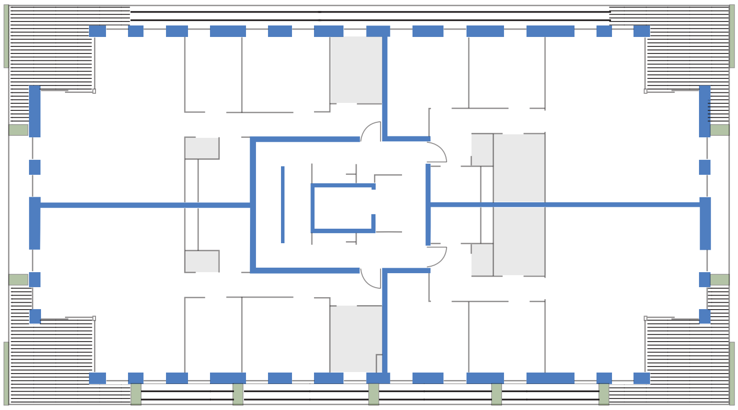


FIGURE 69.

Facade view of referen-ce project B.

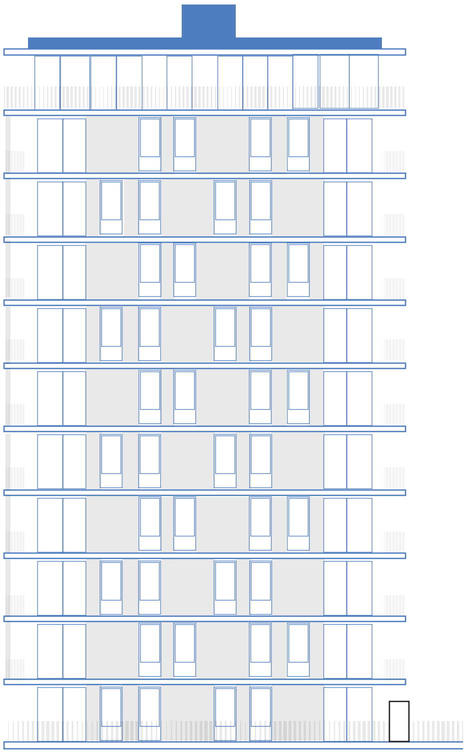
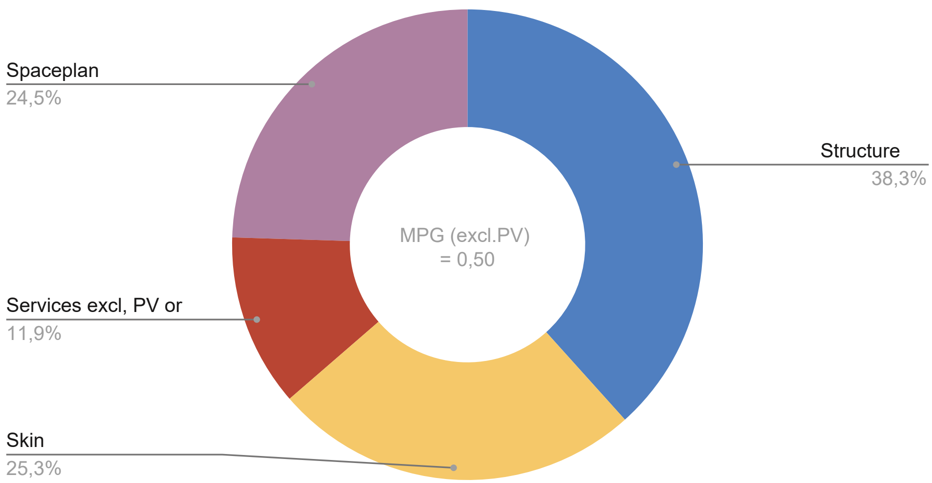


FIGURE 70.

MPG score broken down into Stewart Brand's S-layers.



The facade and the spatial plan are both responsible for a quarter of the total environmental impact. Compared to the other reference projects, the components of the floor plan stand out emphatically. This is particularly due to the material choices, such as a cement screed and plaster blocks for non-load bearing walls.

When looking at the environmental impact of the life cycle phases, the production and usage phases have a lot of impact in different projects. However, the construction phase also shows a significant environmental impact. The reason for this is probably that the structure is built from concrete poured into the structure. In comparison, prefabricated concrete would come out slightly lower and a wooden supporting structure significantly lower (in relation to the total environmental impact).

The floors have a thickness of 280 mm, with a span of about 8 meters. This amount of concrete has a large impact on the proportion of embodied carbon. On top of the structural floor, a cement screed was applied to level the floor and to meet the acoustic requirements between two floors. A cement screed has many practical properties and is often used. However, the environmental impact of the material is significant. Together with the concrete floor, the total environmental impact is high.

FIGURE 71.

MPG score by lifecycle stage.

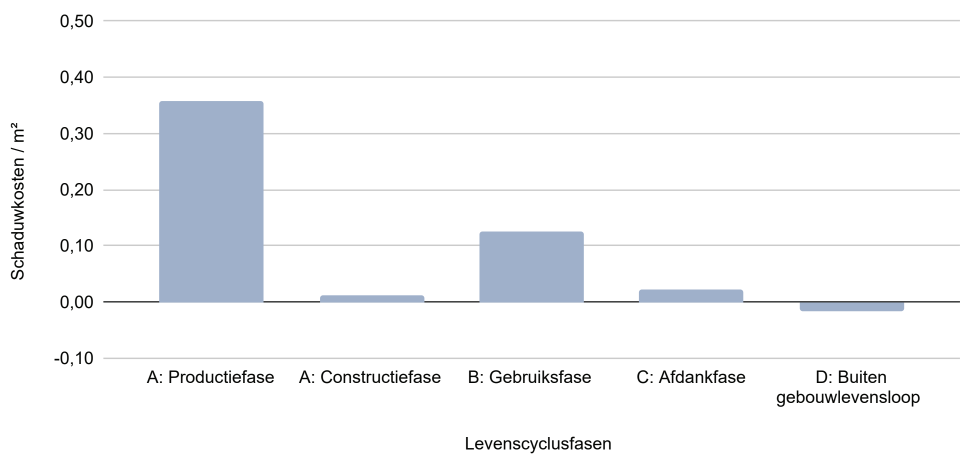
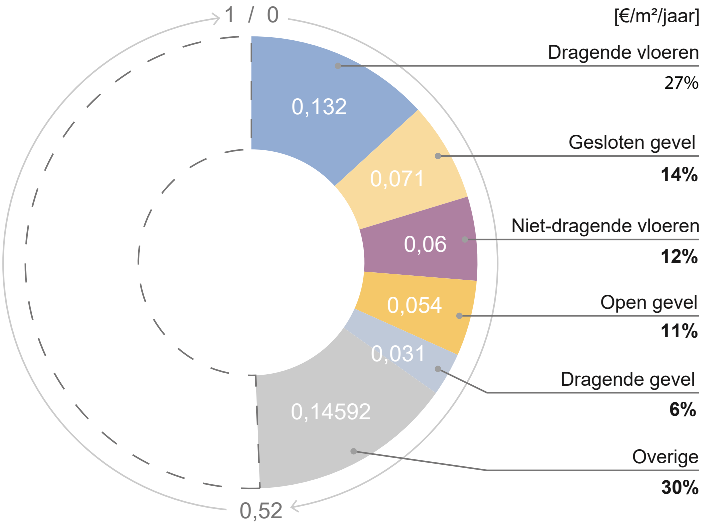


FIGURE 72.

MPG score of the five building parts that cause the highest emissions.



The building has an underground parking garage. At eight percent of the total MPG score, this has a consequential impact and is probably why a structural grid of 8 meters span was applied.

The closed portions of the masonry facade have the second greatest impact. More information can be found in the design guidelines section.

The impact of glazing is substantial. Tall windows and glass doors result in a large area of glass, despite the possibility for smaller window openings. Using a daylighting analysis, the glass area would be optimized. However, a reduction in the number of openings will only have a significant impact if the closed façade sections are made of a different material. The bricks have similar CO_2 emissions to the windows: so, one culprit would be replaced by another. However, when shifting from glass to a wooden façade, for example, the effect is significant. This already considers the shorter life span of the wooden façade but not the possible CO_2 capture performance.

The non-load-bearing walls are made of gypsum blocks. These have high embodied carbon emissions. It would be better to choose a type of wall with less embodied carbon that is also demountable. Buildings like this one, where large floor spans are used, have a high potential for flexible floor plan adaptation or even for major transformations such as change of function. When flexible and demountable walls are applied, this potential can be well exploited.

What can be further observed is that very few PV panels have been applied. The total impact of the installations is relatively low compared to the other reference projects.

CASESTUDY C - MID-RISE BUILDING

This apartment building in a medium-sized city is part of two similar buildings. The apartments range from 83 to 102 m^2 and have an average of one to two bedrooms. For example, a small family with one child would live on 35 m^2 per person. In addition, they would have access to their 10 m^2 balcony.

FIGURE 73.

Data overview of reference project C.

Materiaalgebonden energie	
MPG-score [€/m²/jaar]	0,56
MPG-score exclusief impact van PVs [€/m²/jaar]	0,42
Materiaalgebonden CO_2 [kg/m²]	345
Materiaalgebonden CO_2 exclusief impact van PVs [kg/m²/jaar]	2,6
% CO_2e van totale MPG-score	41
Levensduur van het gebouw toegepast in de MPG-berekening [jaar]	75

Energieprestatie	
EPC-score	0,4
Primair energieverbruik [kWh/m²/jaar]	63
Operationele emissies [kgCO_2e/m²/jaar]	13
PV / BVO	7,62%
PV oppervlakte [m²]	264

Layout	
Gemiddeld oppervlakte appartement [m²]	87
Oppervlakte van het appartament [m²]	83-102
Oppervlakte van balkon [m²]	9-11
Geschatte aantal potentiële slaapkamers per appartement (gemiddeld)	1
Geschatte aantal potentiële inwoners per appartement (gemiddeld)	3
Oppervlakte per inwoner (gebaseerd op geschatte woonsituatie) [m²]	35
BVO gebruikt in MPG [m²]	3466

Gevel	
Raam U waarde [W/m²·K]	1,1
Dichte geveldelen Rc waarde [m²·K/W]	4,5
Open vs dicht *	
Glas type	HR dubbel
Glas oppervlakte [m²]	870
Type gevelbekleding	Baksteen
Oppervlakte gevelbekleding [m²]	1,407.00
Totale oppervlakte glas + gevelbekleding [m²]	2277
Glas / (Totaal glas + gevelbekleding) [%]	38,2%

Draagstructuur	
Constructief materiaal	kalkzandsteen + HSB + beton

Installaties	
Warmtepomp	X
Warmtelevering extern	
Warmtapwater levering extern	
E-boiler	X
Warmtedistributie leidingen	X
Vloerverwarming	X
Wandverwarming	
Vloerkoeling	
WTW unit	
Luchtdistributie toe- en afvoer	
Ventilatie type D	
Ventilatie type C	X
Balansventilatie kanalen	
Koelmachine	

FIGURE 74.

Floor plan reference project C.

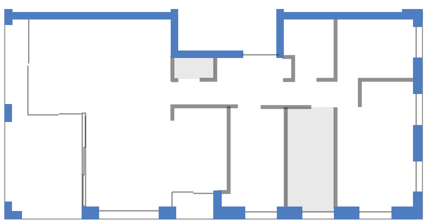


FIGURE 75.

Facade reference project C.

Several materials are used for the supporting structure: walls of sand-lime brick and wood frame construction and floors of concrete. The roof floor is also made of concrete.

The supporting structure is made of concrete. The concrete floor slabs have a span of 8 meters. These supporting floors are constructed of 60 mm precast concrete slabs (wide slab floor) and a compression layer of 220 mm concrete mortar. The resulting shadow costs are reasonably high.

The components of the floor plan have a relatively low environmental impact. The kitchens and washrooms are not included in the MPG calculation. The apartments are not be equipped with these amenities before they are sold. The residents are able to choose their preferred type of kitchen and bathroom components.

The building facade has an average environmental impact relative to the overall impact. The windows are double-glazed but with thinner panes (4 mm) than, for example, in case study D (6 mm). The indoor climate concept uses natural ventilation as a supply (in case study B a fully mechanical system is used).

For this case study, most of the emissions come from PV panels. If the PV panels were not included in the MPG calculation, the MPG score would be quite low - similar to the two smaller mid-rise buildings.

The load-bearing floors are again in the top 5. Here wide slab (prefabricated) floors have also been chosen and the impact in absolute terms is relatively low.

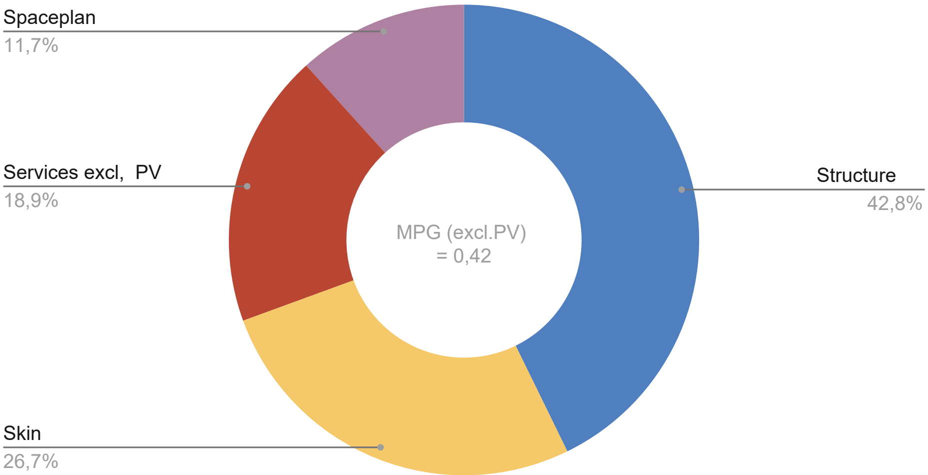


FIGURE 76.

MPG score broken down by Brand's S-layers, excluding PV panels.

The open façade also has a large impact on the environmental impact, but less than expected with a proportion of 38 percent. The absolute contribution is also lower than in cases A and D, which have a similar amount of façade openings. The reason is that the total amount of material is lower, because case C uses double glazing (2 x 4 mm) instead of 12 mm and 16 mm in cases D and A.

This is also reflected in the low score for the closed façade, even though it is made of masonry, which normally has a high impact.

Overall, it is noteworthy that this building, constructed in a fairly traditional way, scores low in the MPG, without probably having had this as a goal in the design phase.

FIGURE 77.

MPG score by lifecycle stage.

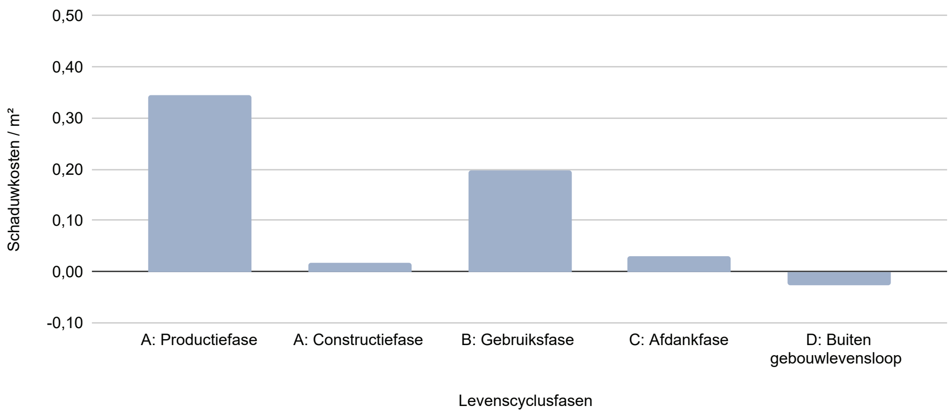
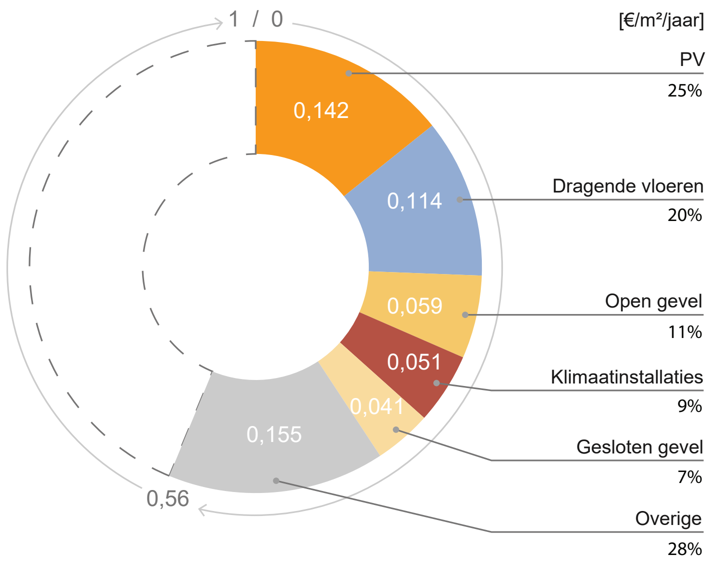


FIGURE 78.

MPG score of the five building parts that cause the highest emissions.



CASESTUDY D – MID-RISE BUILDING

This reference project concerns a mid-rise building of which several copies have been built in the vicinity. The building provides one-room apartments with a floor area between 34 and 48 m^2. In addition, the apartments contain an outdoor area of approximately 4 m^2. The surface area per square meter of living space per person amounts to 21 m^2, assuming two residents per apartment.

Of the six building projects highlighted, this building uses the most wood. The lower floors form a concrete base, while the upper floors use mostly wood.

FIGURE 79.

Data overview of reference project D.

Materiaalgebonden energie	
MPG-score [€/m²/jaar]	0,64
MPG-score exclusief impact van PVs [€/m²/jaar]	0,34
Materiaalgebonden CO_2 [kg/m²]	469
Materiaalgebonden CO_2 exclusief impact van PVs [kg/m²/jaar]	3,0
% CO_2e van totale MPG-score	38
Levensduur van het gebouw toegepast in de MPG-berekening [jaar]	92

Energieprestatie	
EPC-score	9,75
Primair energieverbruik [kWh/m²/jaar]	50 *
Operationele emissies [kgCO_2e/m²/jaar]	4-5
PV / BVO	12,68%
PV oppervlakte [m²]	350

Layout	
Gemiddeld oppervlakte appartement [m²]	41
Oppervlakte van het appartament [m²]	34-48
Oppervlakte van balkon [m²]	0-8
Geschatte aantal potentiële slaapkamers per appartement (gemiddeld)	1
Geschatte aantal potentiële inwoners per appartement (gemiddeld)	2
Oppervlakte per inwoner (gebaseerd op geschatte woonsituatie) [m²]	21
BVO gebruikt in MPG [m²]	2761

Gevel	
Raam U waarde [W/m²·K]	ca, 1,1
Dichte geveldelen Rc waarde [m²·K/W]	5,5
Open vs dicht *	
Glas type	HR++ dubbel
Glas oppervlakte [m²]	482
Type gevelbekleding	Hout
Oppervlakte gevelbekleding [m²]	800
Totale oppervlakte glas + gevelbekleding [m²]	1282
Glas / (Totaal glas + gevelbekleding) [%]	27,6%

Draagstructuur	
Constructief materiaal	CLT (meestal) + beton

Installaties	
Warmtepomp	X
Warmtelevering extern	
Warmtapwater levering extern	
E-boiler	
Warmtedistributie leidingen	X
Vloerverwarming	X
Wandverwarming	
Vloerkoeling	X
WTW unit	
Luchtdistributie toe- en afvoer	
Ventilatie type D	X
Ventilatie type C	
Balansventilatie kanalen	
Koelmachine	

FIGURE 80.

Facade reference project D.

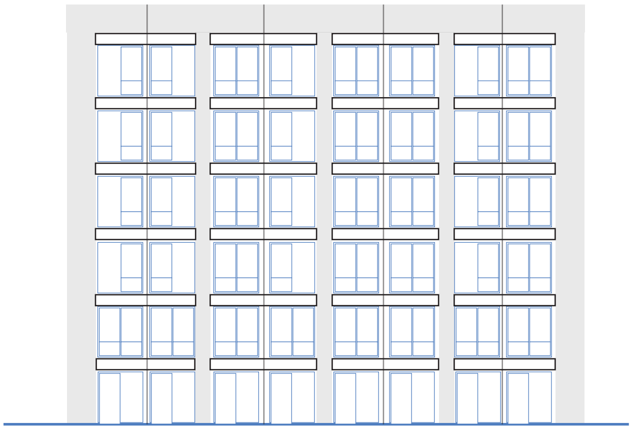
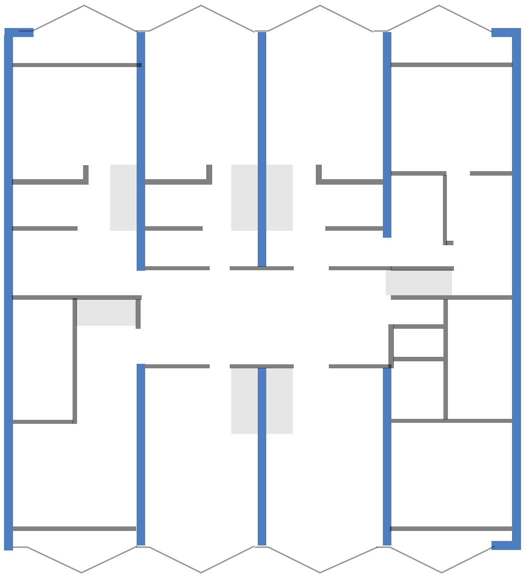


FIGURE 81.

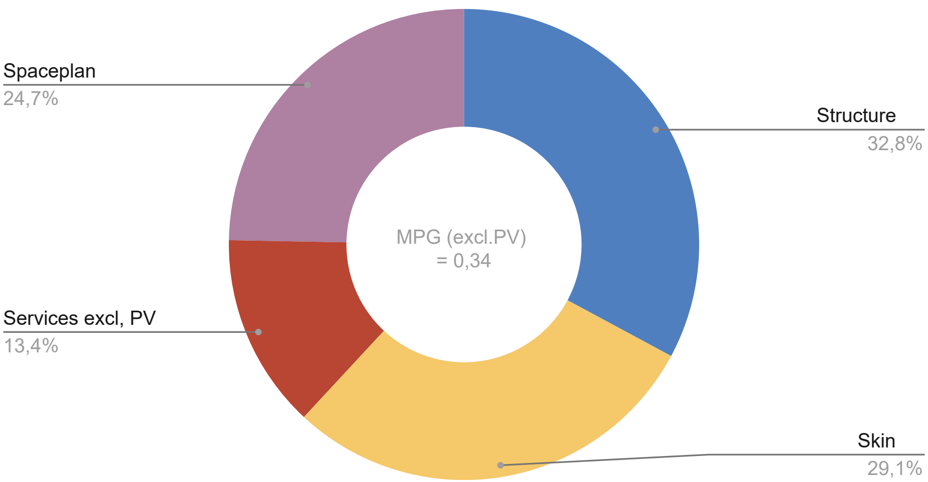
Floor plan reference project D.



The main supporting structure of the building consists of CLT elements, with a thickness of 240 mm and a span of 5.4 m. The CLT floor is finished with a cement screed. The floors are supported by concrete walls. Some parts of the facade are also load bearing, the material used here is also CLT.

FIGURE 82.

MPG score broken down to the S-layers excluding PV panels.



This project has a negative EPC score and uses all available space on the roof for the application of PV panels. In the usage phase of this building, the initial environmental impact will be compensated by the local production of renewable energy.

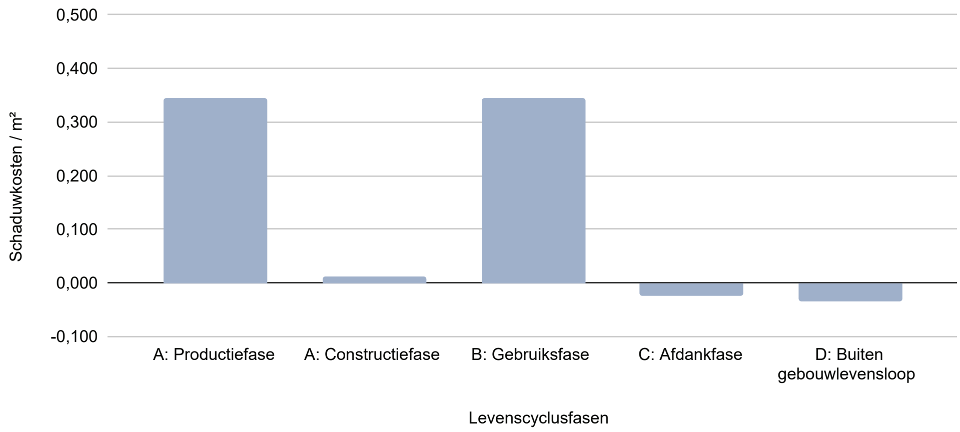
Attention: In this project, the EPC standard has been replaced by the BENG standard. The BENG 2 score (fossil energy consumption per m2) was compared with the 'primary energy consumption' of the EPC standard in this analysis.

The construction phase does not contribute significantly to the MPG score compared to the other cases. Therefore, the fact that case D has particularly low emissions here does not make a big difference. In the usage phase the elements with a shorter lifespan have an influence, because it is assumed that they will have to be replaced several times. This probably concerns the solar panels and parts of the facade.

The building component with the second highest environmental impact is the open façade. The relatively large areas of glass have a large impact on the total shadow cost. This raises the question of why the designer chose this. Given that the apartments are relatively small per capita, it could be that the designer wanted to create a certain spatial quality and tries to compensate a relatively small surface with generous views.

FIGURE 83.

MPG score by lifecycle stage.



If we calculate the MPG score not per square meter but per resident, it is striking that this project scores remarkably well. In that sense, a good balance has been made.

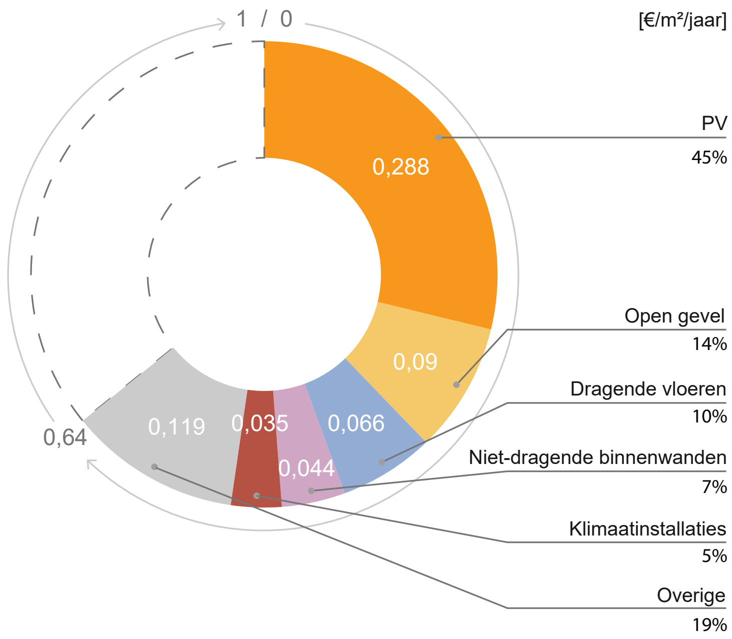
The MPG score only shows the shadow cost per square meter, but has no direct relationship with housing density. Realizing small homes with a lot of spatial quality could be an efficient solution to solve the housing shortage and also reduce the environmental impact of the construction industry.

The use of transparent sections in the facade has a significant environmental impact. Not all transparent sections are functional. The part where the parapet would be situated is probably a design choice not based on functionality, but rather on aesthetic principles. As a designer, it is important to critically consider where to apply transparent sections and where not to, in order to reduce CO_2 impact.

Parts of the structural elements are made of wood. This should have a positive effect on the overall environmental impact. However, this is not reflected in the MPG score. The structural CLT floors have a similar impact per square meter compared to the structural concrete floors. More information on this in the 'design guidelines' section.

FIGURE 84.

MPG score of the five building parts that cause the highest emissions



CASESTUDY E – LOW RISE ROW HOUSE

This terraced house has a floor area of 151 square meters. The layout allows for two bedrooms on the second floor and another potential space for a bedroom on the top floor. For four residents, this would amount to 38 square meters of floor space per person. The main structural materials used are sand-lime walls, HSB elements for walls and concrete floors. The roof structure is wood.

Overall, the embodied emissions of this case study are the lowest of the six case studies. It scores relatively low in the categories of façade, floor plan and installations.

FIGURE 85.

Data overview of reference project E.

Materiaalgebonden energie	
MPG-score [€/m²/jaar]	0,44
MPG-score exclusief impact van PVs [€/m²/jaar]	0,31
Materiaalgebonden CO_2 [kg/m²]	263
Materiaalgebonden CO_2 exclusief impact van PVs [kg/m²/jaar]	2,5
% CO_2e van totale MPG-score	39
Levensduur van het gebouw toegepast in de MPG-berekening [jaar]	75

Energieprestatie	
EPC-score	0,4
Primair energieverbruik [kWh/m²/jaar]	54
Operationele emissies [kgCO_2e/m²/jaar]	14
PV / BVO	0,00%
PV oppervlakte [m²]	0

Layout	
Gemiddeld oppervlakte appartement [m²]	151
Oppervlakte van het appartament [m²]	151
Oppervlakte van balkon [m²]	0
Geschatte aantal potentiële slaapkamers per appartement (gemiddeld)	3-4
Geschatte aantal potentiële inwoners per appartement (gemiddeld)	4
Oppervlakte per inwoner (gebaseerd op geschatte woonsituatie) [m²]	38
BVO gebruikt in MPG [m²]	170

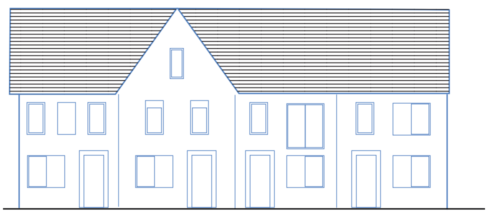
Gevel	
Raam U waarde [W/m²·K]	1,6
Dichte geveldelen Rc waarde [m²·K/W]	4,5
Open vs dicht *	
Glas type	HR++ dubbel
Glas oppervlakte [m²]	14
Type gevelbekleding	60,5% baksteen+ 39,5% hout
Oppervlakte gevelbekleding [m²]	115
Totale oppervlakte glas + gevelbekleding [m²]	129
Glas / (Totaal glas + gevelbekleding) [%]	10,9%

Draagstructuur	
Constructief materiaal	kalkzandsteen + HSB + beton

Installaties	
Warmtepomp	X
Warmtelevering extern	
Warmtapwater levering extern	
E-boiler	X
Warmtedistributie leidingen	X
Vloerverwarming	X
Wandverwarming	
Vloerkoeling	
WTW unit	
Luchtdistributie toe- en afvoer	
Ventilatie type D	
Ventilatie type C	X
Balansventilatie kanalen	
Koelmandel	

FIGURE 86.

Facade reference project E.



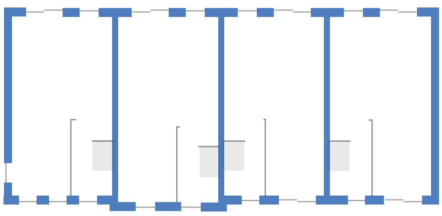
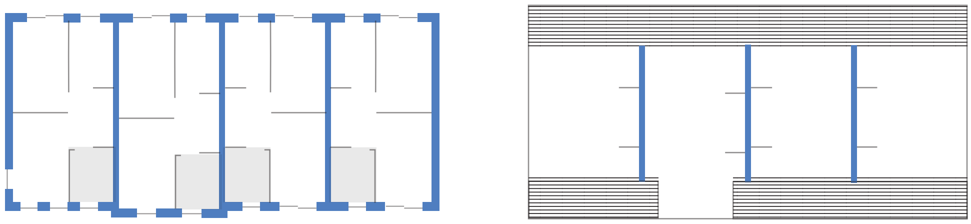


FIGURE 87.

Floor plan reference project E.



The operational emissions are on the high side compared to the other case studies. It is insightful to compare these case studies with case study F: same housing typology, but different installation concept. Case study E has no PV panels and uses energy from the local electricity grid. While case study F generates all energy sustainably with PV panels. The embodied carbon of the PV panels are reflected in the MPG score of case study F, while the non-renewable energy consumption is reflected in the EPC score of case study E.

Regarding the installation concept, there are similarities between case study E and case study C. In both projects, the following installations are used: a heat pump, electric water heater, floor heating and ventilation type C (mechanical exhaust and natural supply). (See case study C for a further explanation).

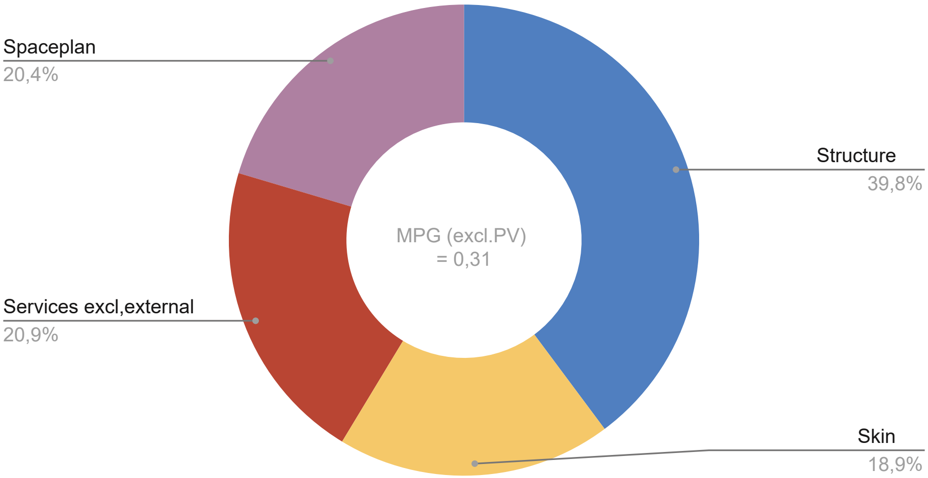
As mentioned, the facade has a relatively low environmental impact. The building has relatively small facade openings and sixty percent of the cladding material is wood. This reduces the environmental impact of the façade.

When looking at the five largest sources of emissions, it is noticeable that structural floors are at the top. An interesting observation is that in case study F the same amount of concrete is used in the floor slabs. The difference is in the category of the EPD: E uses category 3 (generic data) while F has inputs from category 2. The effect on the score is visible in the comparative graphs earlier in this chapter.

Another observation is that the climate installations have quite a lot of environmental impact. Multiple installations contribute to this, so it is difficult to conclude where the impact can be reduced. In this study, no clear correlation emerged between building typology and installations.

FIGURE 88.

MPG score broken down to the S-layers excluding PV panels.



The environmental impact of non-load bearing floors is among the largest emitters in this project. These score slightly lower than in case study B, where the same amount of cement is used (the largest emitter in that category). However, B also uses EPS (presumably as acoustic insulation) in floors between apartments. A house like case study E needs less acoustic insulation, which may be a reason why this acoustic layer was not applied.

This case study is the only one that assumes "Central electrical facilities; energy, generation" (external electricity from the grid). The project assumes that it will obtain electricity from the grid (instead of, for example, gas or district heating) for its energy facilities. Therefore, the environmental costs of the external infrastructure are included in the MPG. In GPR Material, this is described. The product concerns the material use for electricity production based on NL-mix. The material use has been calculated back to 1 kWh. In comparison with case F the MPG is much less influenced by the external energy source than it is in case F, because of the large number of solar panels.

FIGURE 89.

MPG score by lifecycle stage.

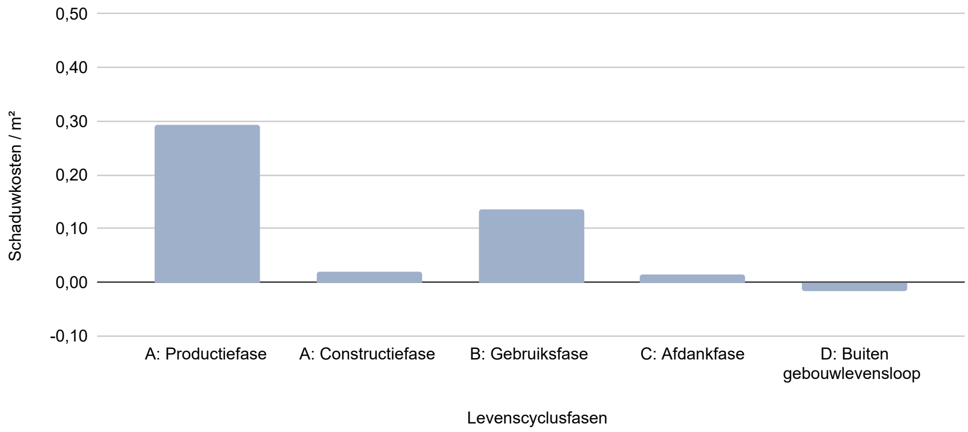
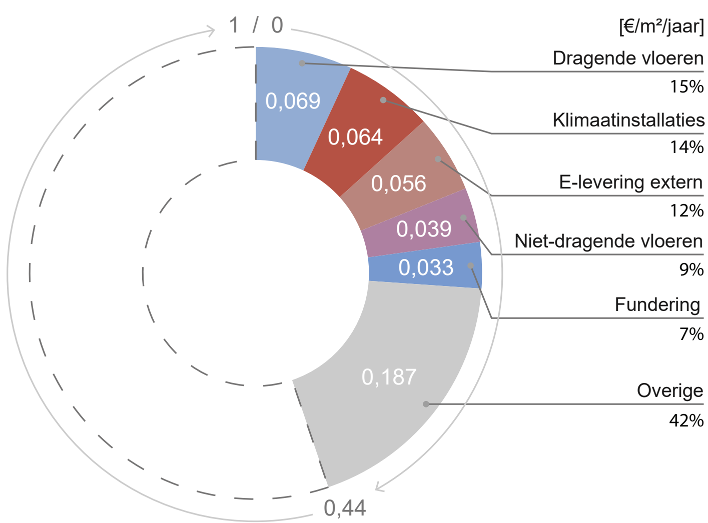


FIGURE 90.

MPG score of the five building parts that cause the highest emissions.



CASESTUDY F – LOW-RISE ROW HOUSE

This 160 m² row house can accommodate up to five people, given three bedrooms on the second floor and one more on the top floor. Each of the five occupants would have 32 square meters of floor space.

The main structural materials are sand-lime brick (walls) and concrete (floors).

FIGURE 91.

Data overview of reference project F.

Materiaalgebonden energie	
MPG-score [€/m²/jaar]	0,92
MPG-score exclusief impact van PVs [€/m²/jaar]	0,32
Materiaalgebonden CO_2 [kg/m²]	555
Materiaalgebonden CO_2 exclusief impact van PVs [kg/m²/jaar]	2,6
% CO_2e van totale MPG-score	37
Levensduur van het gebouw toegepast in de MPG-berekening [jaar]	75

Energieprestatie	
EPC-score	0
Primair energieverbruik [kWh/m²/jaar]	30
Operationele emissies [kgCO_2e/m²/jaar]	0
PV / BVO	29,49%
PV oppervlakte [m²]	46

Apartment layout and oppervlakte	
Gemiddeld oppervlakte appartement [m²]	159
Oppervlakte van het appartament [m²]	159
Oppervlakte van balkon [m²]	0
Geschatte aantal potentiële slaapkamers per appartement (gemiddeld)	3
Geschatte aantal potentiële inwoners per appartement (gemiddeld)	5
Oppervlakte per inwoner (gebaseerd op geschatte woonsituatie) [m²]	32
BVO gebruikt in MPG [m²]	156

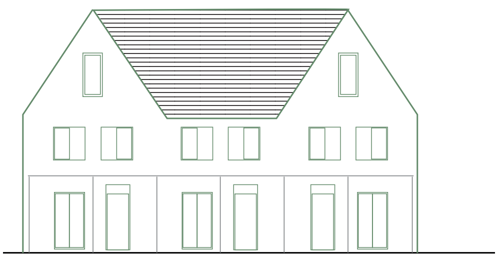
Thermal values van facade, as in EPC	
Raam U waarde [W/m²·K]	1,6
Dichte geveldelen Rc waarde [m²·K/W]	4,5
Open vs dicht *	
Glas type	HR++ dubbel
Glas oppervlakte [m²]	17,4
Type gevelbekleding	70,1% Baksteen+ 29,9% Hout
Oppervlakte gevelbekleding [m²]	165
Totale oppervlakte glas + gevelbekleding [m²]	183
Glas / (Totaal glas + gevelbekleding) [%]	9,5

Draagstructuur	
Constructief materiaal	kalkzandsteen + beton

Klimaatinstallaties	
Warmtepomp	X
Warmtelevering extern	
Warmtapwater levering extern	
E-boiler	X
Warmtedistributie leidingen	X
Vloerverwarming	X
Wandverwarming	
Vloerkoeling	
WTW unit	
Luchtdistributie toe- en afvoer	
Ventilatie type D	
Ventilatie type C	
Balansventilatie kanalen	
Koelmachine	

FIGURE 92.

Facade of reference project F.



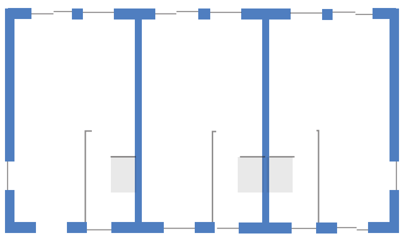
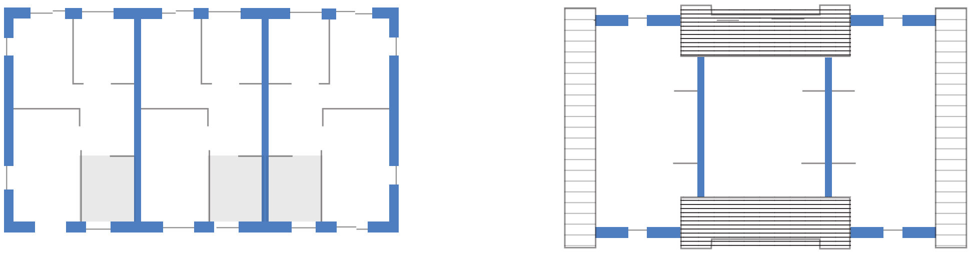


FIGURE 93.

Floor plans of reference project F.



The shadow costs of building materials are not very high for this case study. The PV panels have the highest embodied carbon (per square meter GFA) of all the case studies. As shown in the graph on the previous page, they increase the MPG score from 0.32 (without PV) to 0.92 (with PV). Compared to Case E, no electricity from the grid is used here.

This zero-to-the-meter home has an MPG score that is very high, but has an excellent EPC score.

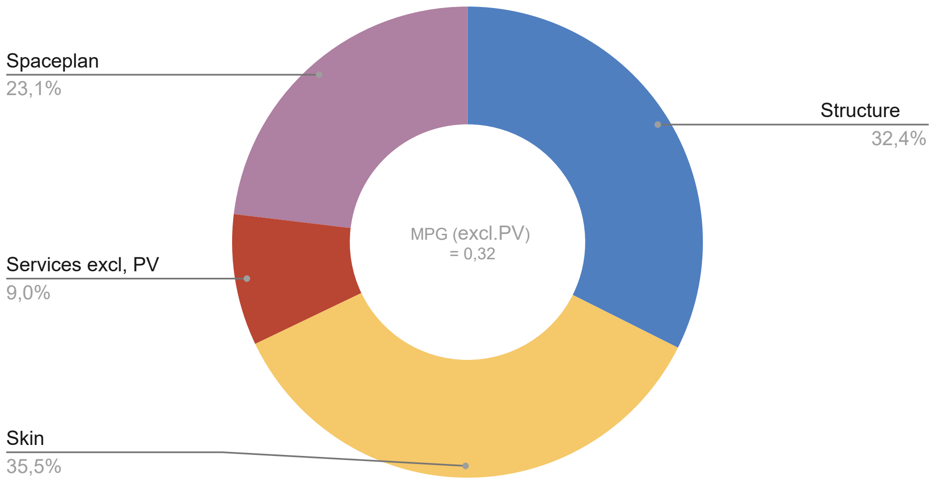
The closed façade surface has a relatively large impact. Both case studies E and F used brick and wood cladding. F uses more brick relative to wood. The climate installations have a visible impact, as mentioned earlier in case study E, where a similar installation concept was used.

The environmental impact of the load-bearing floors is smaller than in case study E, although they both use a concrete ribbed floor of similar volume. The difference there is in the choice of a Category 2 product that is labeled as more environmentally friendly, compared to a Category 3 counterpart. In fact, the environmental impact is half that of the concrete floors of case study E.

An interesting observation is that load-bearing floors and non-load-bearing floors have a similar environmental impact. Replacing concrete floors with wood floors can realize the same change in CO_2 emissions as choosing a different leveling layer to replace a sand-cement screed, such as plaster leveling granules.

FIGURE 94.

MPG score broken down by the S-layers, excluding PV panels.



For buildings in low-city environments such as case study F, we should include the environmental impact of the external infrastructure. As mentioned in the previous chapter, a house in a remote location needs up to 9 times as much infrastructure and correspondingly 7.5 times the social costs compared to a house in a metropolitan area. To quantify CO_2 emissions, a comparison between buildings and infrastructure should be made so that the ratio of impact becomes clear.

FIGURE 95.

MPG score by lifecycle stage.

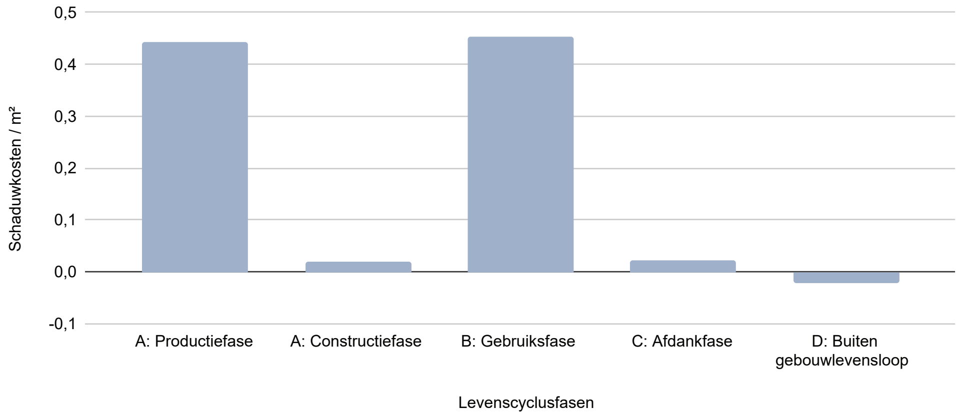
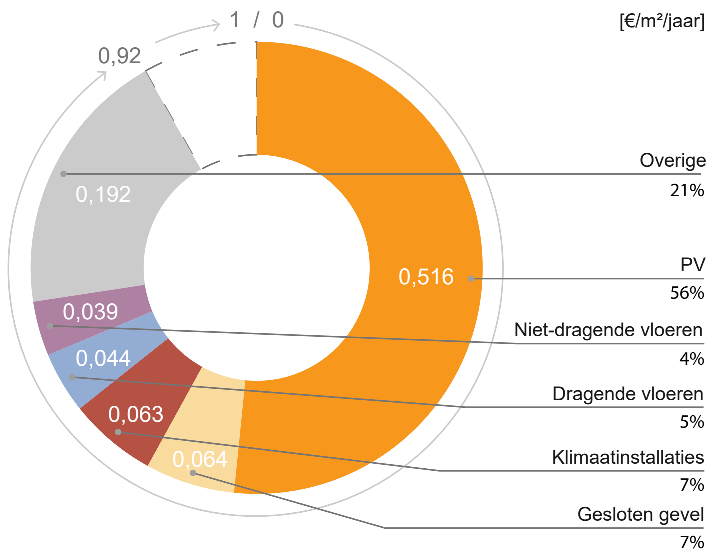


FIGURE 96.

MPG score of the five building parts that cause the highest emissions.



V. POLICY RECOMMENDATIONS

INCLUDE INFRASTRUCTURE COSTS

As the six case studies show, it is relatively easy to build a two- or three-story single-family or intermediate house that is energy-neutral, particularly because of the large roof areas that can be used for solar panels and parking solutions at the door. However, an MPG calculation only looks at the building and does not consider the urban infrastructure (roads, pipes, pavement and natural consumption).

Research by the Flemish Government Architect clearly shows that the social costs of dispersed (low) development are many times higher than in easily accessible, compacted urban areas. Different forms of housing must remain possible, and living in the city is not for everyone. However, when we talk about the environmental performance of buildings, these external costs should be examined.

A farmhouse of three hundred square meters, with two Tesla's in front of the door and a swimming pool in the garden is not sustainable. Emissions from scope 2 and 3, i.e. the emissions that were needed to build the PV panels and the Tesla's, as well as the additional costs, such as roads and other infrastructure, must be weighed.

BRING SHADOW COSTS INTO PLAY

Environmental impact is expressed as the MPG which is euros per square meter per year. So, it is always about impact or emissions per square meter as an objective unit of measurement to compare different materials and construction methods. As designers, however, we see many opportunities to not build or to build less and, for example, to come up with smarter floor plans. For residential construction, we should think about an environmental impact per home or per occupant. That would allow a fairer comparison, for example between a small studio in the city with large glass surfaces (bad for the MPG) and the villa of three hundred square meters in the countryside.

It could be simple: If we actually had to pay that 0.60 euros per square meter per year (MPG score = 0.60) (72 euros for a 120 square meter house), you at least have an incentive to live smaller and the social costs are possibly covered. This then creates a good steering instrument, similar to the WOZ tax.

TEST MPG SCORES AT DELIVERY

As MPG requirements become more stringent, it is to be expected that more and more suppliers will make detailed EPDs available. This will make it increasingly interesting and important to make precise choices in the design phase, and a supplier who, for example, knows how to manufacture his bricks with fewer CO_2 emissions will have an advantage over a competitor who does not.

However, the MPG calculations are made at the time of the application for a building permit, when the final product choices have not yet been made. There is then a good chance that, based on price difference, a product with a larger carbon footprint will ultimately be chosen. So, there should be a test at a later date that measures the actual built footprint. Developments such as Madaster, which maintains a database of materials used in a building, can easily make such calculations.

ENSURE MORE EPD'S IN THE NMD

The National Environmental Database (NMD) consists largely of so-called generic (category 3) product information. These are based on many assumptions. Therefore, a 'penalty' of thirty percent is calculated on them. The calculated MPG value and the actual impact of the product used can therefore differ quite a bit. Because the requirements in the MPG are still very low, this is not yet a problem in practice. It does, however, make it very difficult to compare the MPG values of buildings.

Today, only a fraction of all materials in the NMD is based on a Class 1 EPD, but many more EPDs exist and can be used by software such as One Click LCA. A more detailed footprint calculation is therefore possible outside the MPG. The reason so few Class 1 EPDs are included in the NMD appears to be because they must be prepared by an NMD-certified expert and it costs money to be included in the database.

INCLUDE CO_2 STORAGE IN THE MPG

The discussion about including CO_2 sequestration in the MPG is currently wide-ranging. How can it be that wood and other biobased materials, which in fact sequester CO_2 for the duration of their use, do not score much better in the MPG, if at all, than clearly polluting materials like concrete and glass? As described in the chapter 'The CO_2 cycle', the life cycle analysis also looks at the end-of-life phase of a material. Generally speaking, wood is assumed to be incinerated. Energy is then extracted from it, but that is low-grade reuse. The reason for this end-of-life scenario is that this is how wood waste is often processed nowadays. In the process, the previously captured CO_2 is released again.

However, it makes sense to also look at the timing of emissions. First, in the case of wood and other biobased materials, emissions only occur at the end of the life cycle. That is in principle in 75 years, realistically in maybe 30 or 40 years. This means that the 'time-value' of this carbon is many times lower than the emissions that are occurring now and will have an impact on the climate in the next 75 years. Secondly, it is unlikely, given the climate crisis we are in, that the CO_2 released during combustion in 75 years' time will not be captured. Third, a whole cascade of reuse can be imagined, from sawing CLT panels into beams, smaller structures, and making wood wool to reusing the cellulose in the form of paper.

Companies such as Dierix and Bloc are working on contracts that regulate the take-back of the construction wood, and probably with this they can argue the end-of-life scenario differently in their EPDs. Commissioned by DGBC, TNO has published a paper 'Valuing CO_2 performance of biobased construction' with possible options for such a valuation, also outside the MPG.

IMPLEMENT CARBON ACCOUNTING

The expected life span of a building largely determines the environmental impact of a building (expressed in €/m^2/year). This assumes an average life span of a building of 75 years. What happens to a building in 50 or 100 years is difficult to predict. In practice, however, we often see a shorter life span, particularly in non-residential construction, and a longer one, particularly in privately owned housing.

In order to be able to deal fairly with a shorter or longer life span of a building, a method of carbon accounting is conceivable, whereby the embodied carbon are written off over a certain life span, as it were. If demolition takes place prematurely, a carbon debt remains; if the life span is longer, it contributes to the value of the building. Examples of this are RECAP (Real Estate Carbon Accounting Framework), developed by the investor Alstria, or ideas for a Whole Life Carbon approach, as formulated by DGBC.

25 Fraanje, P. en Nijman, R., DGBC, TNO, (2021). ***Waarderen van CO_2 prestaties van biobased bouwen.***

COMPREHENSIVE ASSESSMENT OF EMISSIONS

Operational and material emissions are communicating vessels, so to speak. A higher investment in the construction phase can yield large savings in operational emissions over the lifetime of a building. Conversely, the reuse of an existing building, for example, can result in a sub-optimal energy performance. Given the urgency to reduce CO_2 emissions now, the unpredictability of the building's lifecycle and many other factors, it is desirable to determine the best solution on a case-by-case basis. Instead of setting hard requirements for operational and material emissions, which in special situations can lead to undesirable conflicts, it is advisable to draw up the requirements integrally and leave the choice to the designer/owner. It then becomes important to monitor and keep track of this by means of a form of carbon accounting.

VI. REFERCES

Alba Concepts, (2019). *Rapport Meetmethodiek Losmaakbaarheid voor GPR Gebouw en BREEAM-NL.*

Alliander and Spectral. (2021). *Jouliette @ De Ceuvel.* Jouliette. https://www.jouliette.net/

Asrani, K., (2019). *Investing in Circular Transformation. A shift in the role of investors in the circular construction industry.*

Azcarate-Aguerre, J. (n.d.). *Façade Leasing pilot project at. TU Delft.* https://www.tudelft.nl/bk/onderzoek/projecten/green-building-innovation/facade-leasing/facade-leasing-pilot-project-at-tu-delft

Bayera, P. en Aklin, M. (2019). *The European Union Emissions Trading System reduced* CO_2 *emissions despite low prices.*

Bergsma G. et al., (2020). *Top 10 milieubelasting gemiddelde Nederlandse consument.* CE Delft, Delft.

Blok, R., Habraken, A. P. H. W., Pronk, A. D. C., & Teuffel, P. M. (2018). *Resource-efficient structural design.* In C. Mueller, & S. Adriaenssens (Eds.), Proceedings of the IASS Symposium 2018: Creativity in Structural Design (pp. 1-10).

Brand, S. (1994). *How Buildings Learn. What Happens After They're Built.*

Chagas, T., (2017). *What is the future of the CDM?*

Churkina, G., (2020). *Buildings as a global carbon sink.*

Cortés Vargas, T.C., (2019). *Circular Façade Systems and Construction. Design for Remanufacturing Window Systems.*

DeBrincat, G. en Babic, E. (n.d.) *Re-thinking the Life-Cycle of Architectural Glass.* Arup, Glasgow. https://www.arup.com/perspectives/publications/research/section/re-thinking-the-life-cycle-of-architectural-glass

Diederen, P. (2021, September 30). *The Lee Towers - Transformatieproject.* diederendirrix. https://www.diederendirrix.nl/nl/projecten/the-lee-towers/

Drouilles, J. (2019). *Environmental impact assessment of Swiss residential archetypes: a comparison of construction and mobility scenarios.*

Era Contour, TBI. (2020, November 9). *LOFT. Houtbaar.* https://www.houtbaar.nl/loft/

Feenstra, J. en Veulemans, W., (2018). *Geld verdienen aan* CO_2*-opslag in grasbodems.*

Nagler, F., (2012). Voordracht *"Einfach Bauen"*, 29. Sep. 2012.

Fraanje, P. en Nijman, R., DGBC, TNO, (2021). *Valuation of Carbon Performance of Biobased Construction.*

Frianta, M.C., (2020). *A typology of circular economy discourses: Navigating the diverse visions of a contested paradigm.*

Haagen B. en. Klijn A.R., (2013), CO_2*-emissiehandel als impuls voor de bouw- en vastgoedsector?*

Habraken, N. J. (n.d.). *Open Building Legacy.* Open Building. https://www.openbuilding.co/legacy

Hildebrand L., (2014). *Strategische investering van belichaamde energie tijdens het architectonische planningsproces.*

Hoxha, E., et al. (2020). *Biogenic carbon in buildings: a critical overview of LCA methods.* Buildings and Cities, 1(1), pp. 504–524. DOI: https://doi.org/10.5334/bc.46

Habraken, J., (1961). *De Dragers en de Mensen: Het Einde van de Massawoningbouw.*

Kader, bureau voor kwaliteitszorg, (n.d.). CO_2 *prestatieladder en* CO_2 *footprint.*

Keijzer, E. et al. (2021). *Een verkenning van het potentieel van tijdelijke* CO_2*-opslag bij houtbouw.* TNO, Utrecht.

King, B. (2017) *The New Carbon Architecture: Building to cool the climate.*

Kriegh, J., et al. (2021). Carbon-Storing Materials: Summary Report.

Kurvers et al. (2013). *Robust Climate Design Combines Energy Efficiency with Occupant Health and Comfort.* ASHRAE IAQ 2013 Proceedings: Environmental Health in Low Energy Buildings.

Lee, A. et al., (2018). *Study on the Analysis of* CO_2 *Emissions of Apartment Housing in the Construction Process.*

Liski, J., et al. (2001). *Which rotation length is favourable to carbon sequestration?*

Lokin, V. en Boeschoten, H., (2020). *Laat woningbouw en nieuw bos hand in hand gaan, dat levert geld op.*

Milieucentraal (2021). *Tests en Advies op maat*. https://www.milieucentraal.nl/over-milieu-centraal/tests-en-advies-op-maat/

Ministerie van VROM, (2020). *Bouwen met Tijd. Een praktische verkenning naar de samenhang tussen levensduur, kenmerken en milieubelasting van woningen.*

Mooij, M. (2021, Nov. 23). *Congres Paris Proof Embodied Carbon Dutch Green Building Council*. https://www.dgbc.nl/agenda/congres-paris-proof-embodied-carbon-334

Pit, M. et al., (2021). *Lessen in Circulariteit.* De Architekten Cie, Amsterdam.

Platformcb23. (2021). *Circulair ontwerpen: Werkafspraken voor een circulaire bouw.* https://platformcb23.nl (benaderd 30/6/2021)

Renger, B.C. et al., (2014). *Net-positive building carbon sequestration.*

Rijksdienst Voor Ondernemend Nederland. (2021, April 28). *R-ladder - strategieën van circulariteit.* https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/circulaire-economie/r-ladder

Sadler, P. en Robson, D., (2013). *Carbon Sequestration By Buildings.*

Salat, S., (2007). *Energy and bioclimatic efficiency of urban morphologies: towards a comparative analysis of Asian and European cities.*

Stichting Nationale Milieudatabase, (2020). *Bepalingsmethode Milieuprestatie Bouwwerken, Versie 1.0.*

Stoffberg, G.H., (2016). *Carbon trading for Landscape Architects.*

Strain, L., (2017). *University of Washington, Time Value of Carbon.*

Strengers, B. et al. (2018). *Negatieve emissies: Technisch Potentieel, Realistisch Potentieel en Kosten voor Nederland*

United Nations (2020). *United Nations Environment Programme Emissions Gap Report 2020,* Nairobi.

Van Dam, J. en Van der Oever M., (2019). *Catalogus biobased bouwmaterialen 2019.*

Van Leeuwen, M. en Van der Velde, O., NIBE, (2019). *Potentie van Biobased materialen in de bouw.*

Vos, G., (2020). *Rijksdienst voor Ondernemend Nederland. Circulaire gebouwen. Strategieën en praktijkvoorbeelden.*

VII. FIGURES

Baumann, H., Tillman, A. (2004). *Hitch Hiker's Guide to LCA. An Orientation in Life Cycle Assessment Methodology & Applications.*

Brand, S., (1994). *How Buildings Learn. What Happens After They're Built.*

CE Delft (2019), *Uitstoot broeikasgassen in Nederland. Een analyse van de sectoren en bedrijven met de meeste uitstoot.*

Churkina, G. et al. (2020). *Decarbonizing construction. Buildings as a global carbon sink.*

Climate Action Tracker (May 2021). Based on national policies and pledges as of May 2021.

Danish Transport and Construction Agency, (2016). *Introduction to LifeCycle of Buildings. Trafik-Og Byggestyrelsen.*

DeBrincat, G. en Babic, E. (n.d.) *Re-thinking the Life-Cycle of Architectural Glass.* Arup, Glasgow. https://www.arup.com/perspectives/publications/research/section/re-thinking-the-life-cycle-of-architectural-glass

EN 15804, Environmental Product Declaration Ecomatters.

Gemeente Rotterdam, (2020), *Rotterdamse Mobiliteitsaanpak februari 2020.*

Habraken, J., (1961). *De Dragers en de Mensen: Het Einde van de Massawoningbouw.*

King, B. (2017) *The New Carbon Architecture: Building to cool the climate.*

Kriegh, J., et al. (2021). *Carbon-Storing Materials: Summary Report.*

Milieucentraal (2021). *Tests en Advies op maat.* https://www.milieucentraal.nl/over-milieu-centraal/tests-en-advies-op-maat/

Nationale Milieudatabase, https://milieudatabase.nl/

Rood, T. et al., (2019). *Circulaire economie in kaart, Planbureau voor de Leefomgeving.*

Van Broeck, L. (2019, April 2). *Maatschappelijke kosten van verspreide bebouwing voor het eerst becijferd* . Vlaams Bouwmeester. https://www.vlaamsbouwmeester.be/nl/nieuws-opinie/maatschappelijke-kosten-van-verspreide-bebouwing-voor-het-eerst-becijferd.

W/E adviseurs (2013). *Richtsnoer 'Specifieke gebouwlevensduur'. Aanvulling op de Bepalingsmethode Milieuprestatie Gebouwen en GWW-werken (MPG).*

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How can we ensure that the 1,000,000 new homes needed in the Netherlands by 2030 put as little pressure as possible on the climate goals that are already difficult to achieve? Even if all future homes are built according to current agreements (Nearly Energy Neutral Building BENG, and 4% emission reduction in industry), the CO_2 budget for construction (for a 1.5 degree warming scenario) will run out in 2026.

The publication Carbon-Based Design provides insight into the CO_2 cycle and the role the construction sector and the circular construction economy have in it. The focus is on the embodied carbon (or the material-related emissions during the production and construction process) in residential construction. By gaining insight into the construction process and which parts of it have the most impact on total emissions, we can adjust our design and development strategy accordingly. The aim is clear: to design and realize buildings with the lowest possible CO_2 emissions, or ideally even CO_2 storage.

CARBON —— BASED DESIGN