CARBON —— BASED DESIGN

STEPS TO ZERO

RESEARCH ON LOW ENVIRONMENTAL IMPACT HOUSING CONSTRUCTION

Edition 1 | June 2022

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SPECIAL THANKS TO:

THE EXPERT PANEL

Arie Mooiman - KNB
David Anink – W/E adviseurs
John Mak – W/E adviseurs
Laetitia Nossek – DGBC
Roy Venhuizen - W/E adviseurs
Ruben Zonnevijlle - DGBC
Wouter ter Heijden – Witteveen+Bos

BPD, FAAM architects, Finch building, Shift a+u and Popma ter Steege Architects for making their projects available as case studies.

And W/E adviseurs for making the GPR building calculation software and accompanying advice available.

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FOREWORD

FACTS AND FIGURES FOR A NEW BUILDING CULTURE

Many sectors in society must deal with drastic changes: healthcare, the agricultural sector, the energy sector, the transport industry, the housing market. All these transitions now come together and determine for a significant amount how the Netherlands have to be planned. We will have to deal with space very differently, otherwise it simply wouldn't fit anymore.

The construction sector obviously has a big role in shaping space and is in itself a sector that has to undergo a transition. Our national ambition is after all to make the construction sector completely circular by the year 2050. This is a huge task, which needs a big change in the culture of the sector.

An important part of circular building is the material transition. We need that transition to be able to build with respect to nature and the living soil-water system. According to the College van Rijksadviseurs, in the use of biobased materials is key in this approach Biobased materials are natural, living materials, like wood, hemp, flax, cattail, bamboo, straw, and seaweed. These materials store Carbon and grow back during the lifetime of a building.

A handful of builders and clients are already working on circular, nature inclusive and biobased construction, however the temptation to build with the usual, but polluting building materials and processes remains big. Agreements with suppliers and certainty the cost play a large role in this. Furthermore, laws and regulations are not always set up for new construction methods.

To make these future building materials part of the regular building process, all parties must choose consciously for it. Not only designers but also clients, financiers, suppliers, contractors, and demolition contractors.

The choice becomes easier if we have a clear picture of what we want as a society. This begins with good bottom-up examples that show what is possible. Stories about successful cases create the desire for change.

Those stories and examples need facts and figures. If we can calculate and provide proof that biobased buildings deliver results, we can turn the desire to change into action. That's why I am very excited about this research. It lays a solid foundation for our vision of buildings without emissions and contributes to the much-needed new building culture. Because we need to move towards a building culture that is not just about an number of homes or profits, but also about a sustainable, healthy, nature-inclusive environment for everyone. Now and in the future!

Francesco Veenstra
Rijksbouwmeester

January 2023

PURPOSE OF THE PROJECT - SUMMARY

An emission-free construction industry - is it possible? In short: no. According to the latest IPCC report (April 2022), the sector does have a huge sustainability potential of 70%, but unavoidable emissions will still take place.

Therefore, it is all the more important to study in detail and properly prioritize each step after a more environmentally friendly building.

This publication is a continuation of the earlier publication 'Carbon-Based Design, research into the environmental impact of housing construction'. As part of that, six case studies were examined in more detail, some of which also form the basis for this research. There we tried to explain the system of Life Cycle Analysis in a simple way, mapped the impact of different building components and drew up 'rules of thumb' to reduce CO_2 emissions and increase capture.

In this report, we go one step further and quantify this untapped potential for reducing environmental impact in buildings. We aim to bring emissions as low as possible or even to zero. We do this on the basis of four concrete cases.

We make our calculation as far as possible on the basis of the current legal framework, the MPG, which portrays the total environmental impact of a building over its entire life cycle, but also translate this into emissions of CO_2 equivalents and test the results additionally according to the 'Paris Proof' methodology as drawn up by the Dutch Green Building Council (DGBC) and NIBE.

The results provide insight into the magnitude of certain measures and outlines what is needed to achieve a zero or positive impact on the environment. It also provides insight into where guidance from the Paris Proof and MPG method complements each other. In summary, three variants of increasing sustainability are studied more closely: reuse, renovation and biobased construction. These are brought to the lowest possible environmental impact by applying further measures. The results confirm those calculations of the IPCC report, that we will continue to cause emissions through building. It is therefore important every opportunity to consider the environmental burden and CO_2 savings within and outside the sector. Only when we consider CO_2 storage can we perhaps arrive at zero or up to positive-impact.

FINDINGS

The study is limited to residential construction. The calculation is made on the basis of four reference buildings. These stem in part from our research 'Carbon-Based Design' with an analysis of more than 24 recently completed buildings that we were provided with or actively sought out by a variety of parties. Of those cases studied here, the first half of the reference buildings are regular buildings without pronounced ambition on sustainability and the other half is characterized by a high ambition on sustainability in material use.

LIMITS OF THE STUDY

Previous research has shown that the quality of MPG calculations and their underlying data (also in the NMD) can vary greatly. We have therefore sought additional data within and outside the NMD for some issues. Where this is the case we have mentioned this.

The determination method for the MPG is constantly being developed and, in order to achieve the goal of the study, we had to make assumptions that are not applied in the official calculation method. One example is CO_2 storage in biobased materials. Research into this is underway, including by SGS Search .

The study is based on four case studies with a spread in urban and low urban development. The number is too small to depict a range of current housing production. The foundational MPG calculations have been reviewed for credibility by W/E Advisors (part of the expert panel involved). Nevertheless, it is beyond the scope of this study to determine whether the projects were built according to the drawings and calculations, and whether there may be architectural or technical objections to the materials chosen.

CHAPTER 1
BACKGROUND
DIFFERENT EMISSIONS IN THE CONSTRUCTION SECTOR

To reduce emissions from the construction industry, we must first understand, where these emissions actually originate and how they are calculated. This is explained in detail in “Carbon-Based Design ”. We only want to repeat here that the life cycle of buildings is divided into different phases and in each phase environmental damage occurs on different scopes (direct or indirect emissions). These emissions can be divided into two groups: operational and material-related emissions. In English, these are: operational & embodied emissions

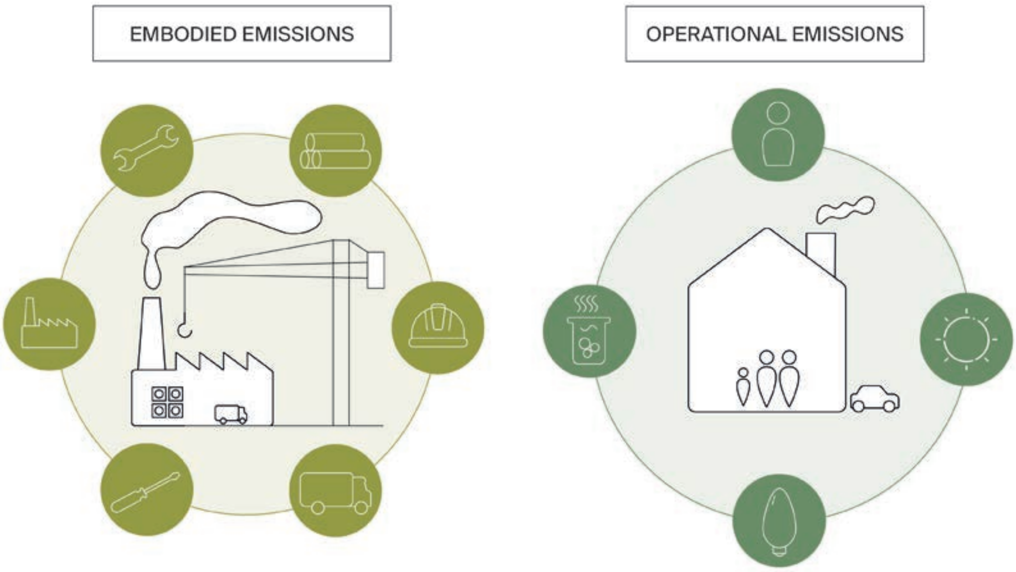


FIGURE 1
Difference between embodied and operational emissions

Operational emissions are caused during the use phase by: Electricity, Gas, Hot Water and Heating. The legal frameworks (EPC, BENG) around operational emissions have been tightened considerably in recent years and new buildings should hardly emit any operational emissions.

Material bound emissions are emitted at:

- Production of building elements;
- Transportation and assembly of building elements;
- Maintenance and renewals during use phase;
- Transportation and updating during discard phase;

By minimizing operational energy demand, material bound emissions have become proportionally more important anyway. But often a reduction in operational emissions is also accompanied by an increase in material-bound emissions in absolute terms.

Think thicker layers of insulation, heavier installations that minimize energy consumption, or installing solar panels to generate power.

FIGURE 2
construction emissions on a map - Derived from[1]

1 Le Den X, Steinmann J, Röck M, Birgisdottir H, Horup L H, Tozan B, Sørensen A. *Towards EU embodied carbon benchmarks for buildings - Summary report*, 2022,https://doi.org/10.5281/zenodo.6397514

APPROACH AND METHODOLOGY

This report is based on literature review and the analysis of four reference buildings. These were then improved step by step, creating hypothetical designs, as it were, that approximate an ideal building with a low environmental impact.
The cases are realized projects, which emerged from a longlist of 24 buildings, whose data was collected for the earlier Carbon-Based Design study. For this study, these were supplemented by two additional progressive buildings.

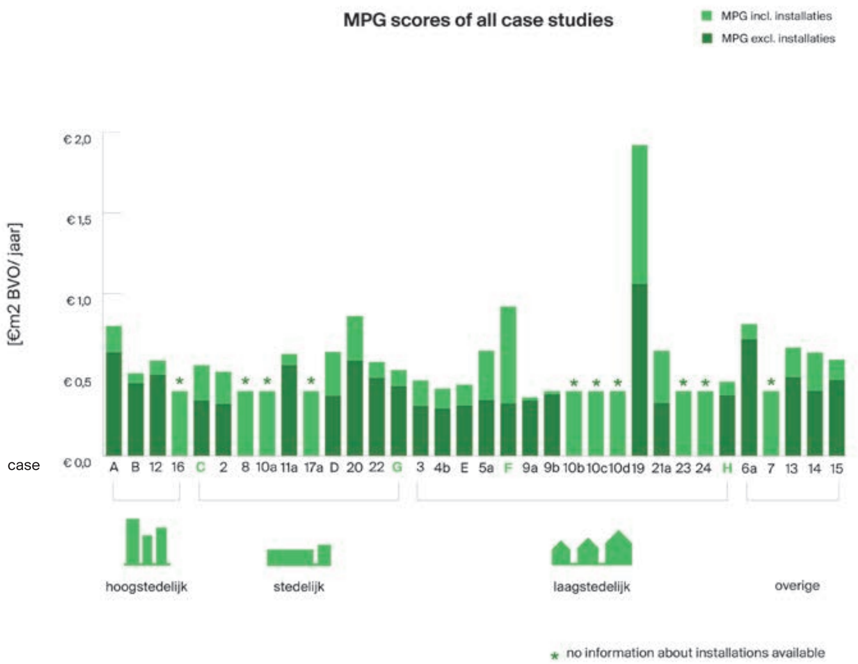


FIGURE 3
Summary of Compiled Case Studies

For all reference buildings, we requested the mandatory MPG calculation for the environmental permit, as well as additional explanatory material, such as the EPC or BENG calculation, floor plans and a description. The cases used here are:
Case C (1), Case G (2), Case F (3), Case H (4)

For the study, we reviewed four cases in detail. We selected for buildings with and without pronounced ambition on sustainability in two densities, urban and low urban. A new dataset of each project was created based on the official MPG calculations using the software GPR material. This provides insight into the underlying structure of the projects and allows for detailed analysis

The results were transferred to an Excel existing where we can also see the distributions the life cycle stages for each material and group the materials according to Brand's S-layers. [4]

FIGURE 4
S-Layers- categories to classify buildings

For this study, 4 of the layers are relevant. We have categorized the elements in the following way:

- Structure (horizontal, vertical support structure, foundation);
- Skin (Non-bearing roofs, closed facade, open facade)
- Services (PV, climate systems, water/light and pipes)
- Space plan (Fixed equipment, traffic space, non-load bearing interior walls incl. Doors etc., non-load bearing floors)

The starting point is the MPG calculation with the materialization as licensed. Subsequently, step by step, building elements have been replaced by alternatives with a lower MKI-/CO_2 value or other calculations have been made. These calculations are described in the chapter "Measures"

The Measures are quantified by the MPG score (€/m^2/year), our primary target value that expresses the total environmental impact using 11 indicators. In addition, a comparison is made based on the Paris Proof Score (CO_2e/m^2). This makes a statement whether a building falls within the maximum CO_2 budgets for the construction sector that must be observed in order to meet the agreements in the Paris Agreement. This is our secondary target value.

Some measures can be stacked, others are alternative choices. Where possible, we have created "Combinations" of a set of measures that are stackable. These combinations are our hypothetical alternative buildings for the case studies with the smallest possible environmental impact. Based on these combinations, further statements can be made about savings opportunities. All combinations were then applied to each case.

The average results of this serve to identify individual peculiarities and as conclusions for overall potential in reduction of MPG and saving of CO_2e/m^2.

In the "Measures" section, for further consideration, measures that are not part of the MPG's determination methodology are also included. For example, the possible effect of carbon storage for biobased measures is analyzed. Or, in another step, we calculate with innovative materials that have not yet been entered in the NMD in this way.

Embodied emissions have only recently become part of the public debate and the legal frameworks will be further developed, tightened and broadened in the coming years. Partly because of this, we often lack reliable data to draw well-founded conclusions. The methods and underlying assumptions, as well as further steps towards sustainability, are broadly explained in this report. For maximum transparency, all calculations can also be consulted in an online appendix.

Case	Layer	Original MPG 75 jaren levensduur							Original Paris Proof 30 jaren levensduur		
Case	Layer	MPG/Eenh.	Materiaal	Cat.	aantal/m2	Dikte	/m2/jaar MPG	totaal MKI	MKI	(kgCO2e/m2BVO) A1-3	A4-5
Case 1	Structure	1,56	Kelderwanden, kalkzandsteen lijmblokken VNK	2	162	300mm	0,00	760	760	3,06	0,27
		12,82	Vloeren constructief, Beton,in het werk gestort, C20/25; incl.wapening	3	69	280mm	0,00	886	886	2,10	0,04
		2,61	Vrijdragende Vloeren, Breedplaat, excl. druklaag, 60mm; prefab beton; AB-	2	733		0,01	1.909	1.909	5,89	0,40
		3,62	Vrijdragende Vloeren, Betonhuis; druklaag breedplaatvloer; betonmortel C2	2	733	220mm	0,01	3.075	3.075	8,02	0,29
		2,61	Vrijdragende Vloeren, Breedplaat, excl. druklaag, 60mm; prefab beton; AB-	2	2.962		0,03	7.717	7.717	23,83	1,61
		3,62	Vrijdragende Vloeren, Betonhuis; druklaag breedplaatvloer; betonmortel C2	2	2.962	220mm	0,05	12.428	12.428	32,31	1,18
		2,61	Vrijdragende Vloeren, Breedplaat, excl. druklaag, 60mm; prefab beton; AB-	2	740		0,01	1.928	1.929	5,97	0,40
		3,62	Vrijdragende Vloeren, Betonhuis; druklaag breedplaatvloer; betonmortel C2	2	740	190mm	0,01	2.683	2.683	6,98	0,26
		10,56	Balkon- en galerijvloeren, Beton, prefab; AB-FAB	2	411	250mm	0,02	4.337	4.337	12,67	0,97
		1,16	Systeemwanden dragend, Houten woningscheidende wand HSB prefab; inc	2	31		-	36	36	0,11	0,04
		0,09	Consoles, Staal; L-ongelijkzijdig 50x30, hoekstaal50x30	2	247		-	21	21	0,16	0,23
		0,09	Consoles, Staal; L-ongelijkzijdig 50x30, hoekstaal50x30	2	318		-	27	27	0,21	0,03
		1,66	Massieve wanden dragend, Kalkzandsteen elementen	2	1.619	300mm	0,03	8.056	8.056	15,06	3,40
			Subtotal				0,17	43.863	43.864	116,37	9,13
	Skin	6,15	Spouwmuren buitenblad, Baksteenmetselwerk	3	1.407	100mm	0,03	8.661	8.661	25,27	2,03
		1,56	Spouwmuren binnenblad, kalkzandsteen lijmblokken VNK	2	193	214mm	0,00	644	644	2,59	0,23
		1,48	Systeemwanden, HSB element; Europees naaldhouten multiplex en gipspla	3	1.158	160mm	0,01	1.712	1.712	4,82	0,26
		0,66	Isolatielagen, Glaswol MWA 2012; platen;	3	1.379	4,5m2k/w	0,01	1.179	1.179	2,09	0,03
		3,03	Buitenkozijnen, Aluminium vast en/of draaiend, geanodiseerd	3	218		0,00	658	658	2,48	0,11
		16,98	Buitenbeglazing, HR (dubbel) glas; coating, 4/12/4 mm	3	870		0,06	14.775	5.910	11,43	0,14
		0,26	Stelkozijnen, Onverduurzaamd hout; geverfd	3	84st		-	22	22	0,07	0,04
		6,34	Vensterbanken, Kunststeen; element	3	153	20mm	0,00	970	388	0,68	0,02
		0,61	Waterslagen, Aluminium; gemoffeld	3	153	100/2mm	-	94	50	0,24	0,00
		1,31	Isolatielagen, EPS	3	740	6m2k/w	0,01	1.657	1.657	4,62	0,20
		1,86	Plat dakbedekkingen, EPDM, sbs cachering; verkleefd	3	740		0,01	1.375	916	1,70	0,02
			Subtotal				0,12	31.746	21.797	55,98	3,07
	Spaceplan	1,78	Dekvloeren, Zandcement	3	733	70mm	0,01	2.282	2.282	5,74	0,24
		1,41	Afwerklagen, MOSA Keramische vloertegels; ongeglazuurd/geplaatst/gevc	1	354		0,00	499	499	1,02	0,13
		1,03	Isolatielagen, IsoBouw EPS 100 SE	1	733	4,5m2k/w	0,00	966	966	2,48	0,13
		2,01	Verlaagde plafonds, Akoestisch gipskartonplafond, enkel geperforeerde pla	2	95		0,00	192	77	0,34	0,00
		0,31	Afwerklagen, Spuitpleister	3	2.962	3mm	0,00	907	363	0,55	0,12
		1,45	Massieve wanden niet dragend, Gipsblokken, normale dichtheid (NBVG)	2	1.566	70mm	0,01	2.270	2.270	6,61	0,09
		0,56	Afwerklagen, MOSA Keramische wandtegels; geglazuurd/geplaatst/gevoe	1	826		0,00	466	466	1,71	0,27
		3,86	Binnenkozijnen, Staal; verzinkt+gemoffeld	3	423		0,01	1.631	1.631	5,65	0,02
		0,58	Binnendorpels, Gegoten Composietsteen binnendorpel	3	24		-	14	14	0,25	0,03
		10,75	Binnendeuren, Honingraat; geschilderd:alkyd	3	169st		0,01	1.816	726	2,02	0,04
		3,24	Binnendeuren, Houten vlakke binnendeur; honingraat, duurz. bosbeheer	2	24st		-	78	52	0,15	0,00
		62,65	Centrale trappen, Prefab beton; h:2.7.b:1.1m; incl. bordes	3	9st		0,00	564	564	1,74	0,24
		2,17	Balustrades, Staal; gepoedercoat; spijlen	3	43		-	94	75	0,69	0,01
		1,13	Leuningen, Aluminium	3	14		-	15	15	0,03	0,14
		131,56	Liftcabines, Staal; personenlift; gemoffeld	3	3		0,00	395	395	1,81	0,14
		117,53	Liftinstallaties, Staal; hefconstructie+contragewicht; 1 bouwlaag	3	3		0,00	353	353	1,54	0,11
		2,17	Balustrades, Staal; gepoedercoat; spijlen	3	169		0,00	368	294	2,69	0,02
			Subtotal				0,05	12.909	11.042	35,02	1,74
	Services	197,89	Warmteopwekkinginstallaties W-bouw, Warmtepomp lucht - water hybrid	3	24		0,02	4.749	1.900	4,70	0,03
		0,9	Warmtedistributiesystemen, Polyetheen/polybuteen; cv-leidingen; incl. kop	3	3.017		0,01	2.712	1.266	0,53	0,00
		1,22	Warmteafgiftesystemen, Vloerverwarming; leidingen:polybuteen+toebeho	3	3.017		0,01	3.691	1.477	1,47	0,01
		285,07	Warmtapwaterinstallaties, Elektrische boiler; CW:4-6, 120 liter	3	24		0,03	6.842	2.737	6,09	0,01
		0,54	Luchtdistributiesystemen, VLA Ventilatiesysteem, type C; W-bouw, individu	2	3.017		0,01	1.630	761	2,74	0,02
		0,27	Elektricteitsleidingen, Geisoleerde installatiedraad + mantelbuis:pvc	3	3.017		0,00	812	541	0,72	0,01
		140,18	Elektriciteitsopwekkingsystemen, PV,multi-Si; plat dak; incl. inverter+steun	3	264		0,14	37.008	14.803	29,72	0,02
		0,03	Waterleidingen, Polybuteen; leiding+mantelbuis	3	3.017		-	83	55	0,18	0,00
		0,06	Buitenrioleringen kavel, Pvc; gerecycled; leiding	3	3.017		0,00	187	87	0,29	0,00
		0,27	Hemelwaterafvoeren, Polyetheen; diameter:80mm; d:1.8mm	3	180		-	48	19	0,05	0,00
		0,12	Binnenrioleringen, Pvc; gerecycled; leiding	3	3.017		0,00	374	174	0,58	0,00
			Subtotal				0,22	58.136	23.820	47,06	0,10
			Total					146.654	100.523	881.852	48.687
				BVO	3.466	m2			per m2BVO	254	14
						MPG	0,56			268	embodied carbon in
				0	MPG -verbetering						

FIGURE 5
Example of the bill of materials with accompanying MPG and CO_2 values

EXPLANATION MPG (ENVIRONMENTAL PERFORMANCE OF BUILDINGS) CALCULATION-METHOD

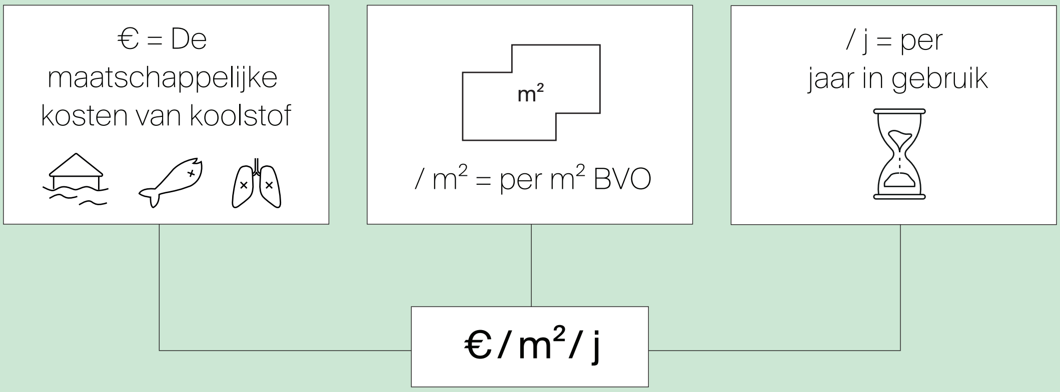


FIGURE 6
Schematic composition MPG

Since 2013, an MPG calculation must be submitted for every new building permit applied for in the Netherlands. Using calculation programs, the environmental impact of all building materials of a building can be calculated based on EPDs. The total environmental cost of the building (EIP) is divided by the gross floor area (GFA) and the estimated life span (standard 75 years) of even this, so that the so-called shadow costs of a building are determined in €/m^2/year.

The idea is that the MPG will be lowered step by step. Since July 1, 2021, the MPG value of new construction must be below 0.8 in order to apply for a building permit. At the moment it is established, that by 2030 this limit value must be at 0.5, even though there are discussions to bring it to 2025.

The MPG attempts to make a balanced statement about the environmental impact of buildings, therefore potential damages are included in a total of eleven categories - from climate change in CO_2, ozone layer depletion, human-toxicological effects to acidification. Through different weighting factors, these are brought to a number. This is to avoid waterbed effects, whereby optimization on one environmental aspect has a negative effect in another field. For these reasons, this value is also our main indicator.

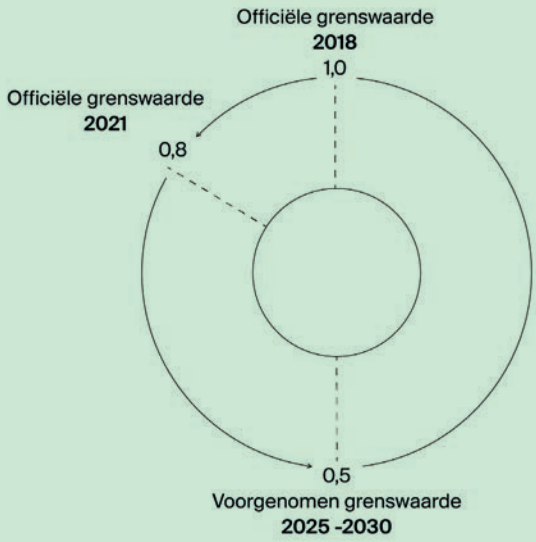


FIGURE 7
MPG avarage and limits

EXPLANATION PARIS-PROOF CALCULATION METHOD

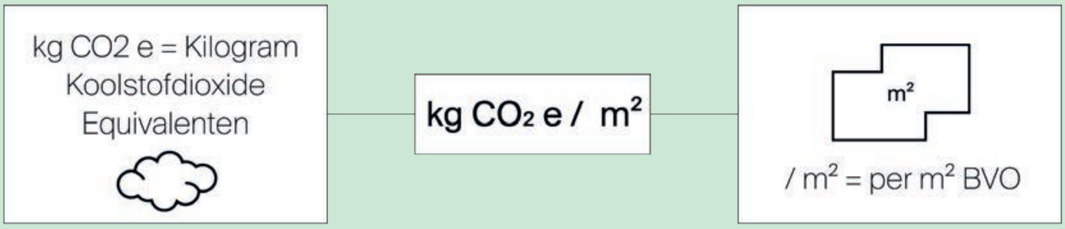


FIGURE 8
Diagram of Paris-Proof Calculation Methodology

To keep global warming between 1.5 and 2 degrees, the Netherlands is allowed to emit 909 million tons of residual CO_2 equivalents by 2050. Otherwise, tipping points may be exceeded and this will have serious consequences. Adaptation to climate change will then no longer be possible in parts of the world. This means that, apart from all long-term effects, the next 30 years are crucial to turn the tide. Therefore, as a secondary value, we have chosen to look at how many $kgCO_2e/m^2$ a building will emit in the next 30 years and whether that fits within the CO_2 budget for the Dutch Building sector. At the current share of 11% that would be approximately 100 million tons of residual budget to 2050 mean. In doing so, we follow The “Paris-Proof Embodied Carbon” calculation protocol, written by the Dutch Green Building Council (DGBC) and research firm NIBE.
To determine the Paris Proof Score, only Phases A1-5 are included and the life of the building is set to 30 years in the calculations. This means that for example PV panels with a lifetime of 25 years do not count three times, but 1.2 times.
If newer EPD are used in this calculation method, biogenic CO_2 storage also counts, because according to EN 15804 2A these values are explicitly expressed, while in old EPD biogenic CO_2 storage according to the principle +1-1=0 is completely disregarded.

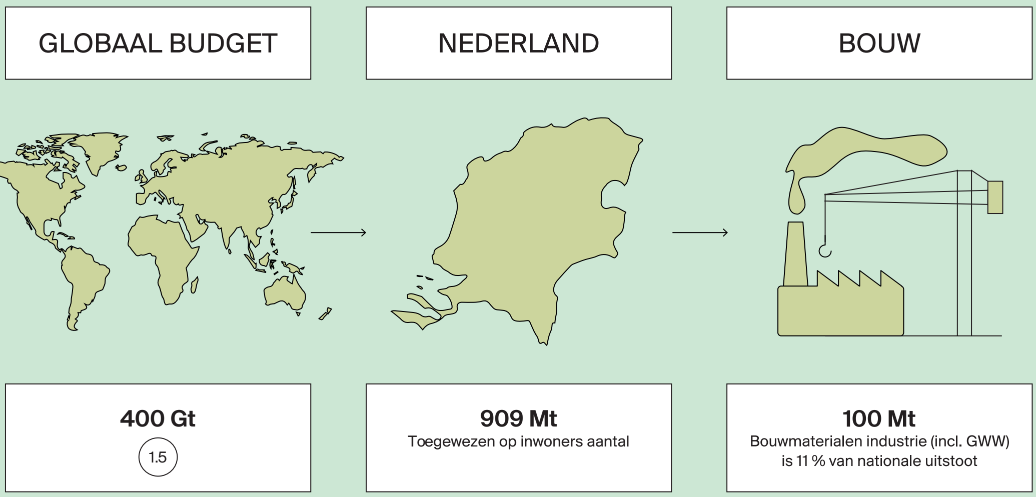


FIGURE 9
Derivation CO_2-Budget[1]

5 DGBC (2021): *Position Paper Whole Life Carbon*, versie 1.1: https://www.dgbc.nl/nieuws/rekenen-aan-paris-proof-materiaalgebonden-emissies-met-protocol-6244

If 70,000 new homes are built each year and between 2 and 16 million square meters are renovated each year (modeled on an S-curve), this results in a limit value in CO_2e/m^2 for each building. We use the resulting target values as our starting point to achieve “Paris Proof”. By the way, these are periodically tightened to simulate a realistic development.[1]

1 DGBC (2021): Paris Proof Embodied Carbon - Rekenprotocol

GRENSWAARDEN VOOR NIEUWBOUW

Tabel 1: Grenswaarden voor Paris Proof bouwwerken. Grenswaarde is gegevens in “embodied Carbon” per m^2 bouwwerk.

PARIS PROOF GRENSWAARDEN	EMBODIED CARBON KG CO_2-EQ. PER M^2			
	2021	2030	2040	2050
Woning (eengezinswoning)	200	126	75	45
Woning (meergezinswoning)	220	139	83	50
Kantoor	250	158	94	56
Retail vastgoed	260	164	98	59
Industrie	240	151	91	54

GRENSWAARDEN VOOR RENOVATIE

Tabel 2: Grenswaarden voor Paris Proof bouwwerken. Grenswaarde is gegevens in “embodied Carbon” per m^2 bouwwerk.

PARIS PROOF GRENSWAARDEN	EMBODIED CARBON KG CO_2-EQ. PER M^2			
	2021	2030	2040	2050
Woning (eengezinswoning)	100	63	38	23
Woning (meergezinswoning)	100	63	38	23
Kantoor	125	79	47	28
Retail vastgoed	125	79	47	28
Industrie	100	63	38	23

FIGURE 10

Limit values after Paris Proof [1]

1 DGBC (2021): Paris Proof Embodied Carbon - Rekenprotocol

	PRODUCTIE	BOUW	GEBRUIK	AFDANK	HERGEBRUIK	TIJDSFACTOR	MILIEU-IMPACT CATEGORIEN	DATABASE LCA PRODUCTKAARTEN
MPG	A1-3	A4-5	B1-5	C1-4	D	75 jaar	11 (incl. GWP)	NMD
PARIS-PROOF	A1-3	A4-5	-	-	-	30 jaar	GWP	NMD

TABLE 1

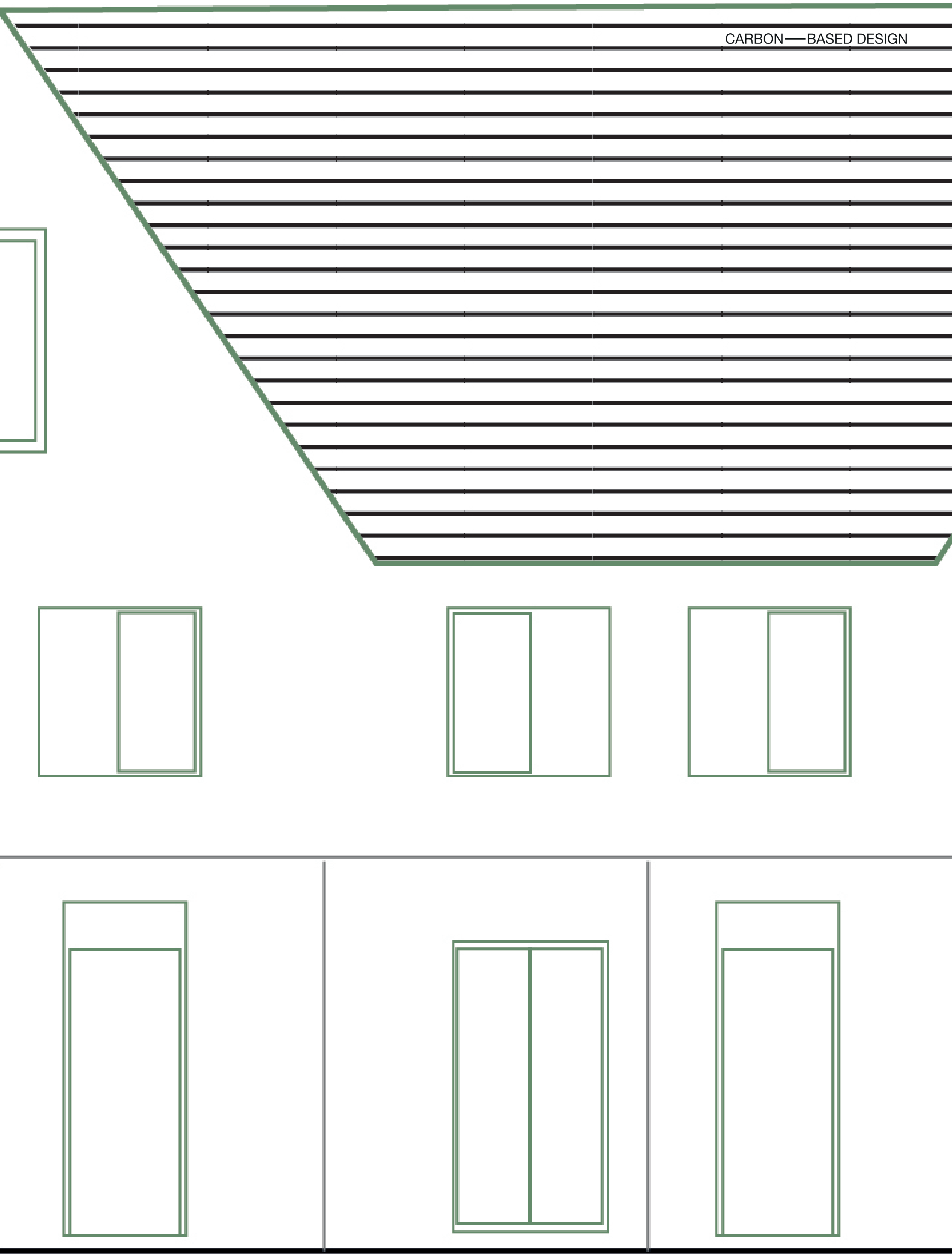
comparison of calculation method MPG and Paris Proof

CHAPTER 2
CASE STUDIES

Four cases were chosen for the study. Case 1 & 3 represent conventional buildings with already quite good MPG scores. In addition, Case 2 & 4 are our ambitious references with very good MPG scores. The reasons for this will be explained even later in the analysis. While Case 1 & 2 are stacked buildings, Case 3 & 4 compare two ground-up houses.

FIGURE 1
Facade views of four reference projects analyzed.

In making the comparisons, we have created as much of a level playing field as possible. The energy supply to a building also plays a major role in determining the embodied energy. Depending on the external energy supply, a building must also do its best in terms of material (systems, etc.) to meet the EPC/BENG requirements. Therefore, for example, we compared the MPG once without PVs and once with PVs. Still, it was difficult to sort out these aspects completely from the given data and make them truly comparable. In the chapter ‚Investment of CO_2 Over time‘ we will discuss this in more detail.



CASE 1

FIGURE 12
Facade view and floor plan
Case 1

MPG VALUE: 0.56 €/M²/YEAR; 0.42 €/M²/YEAR (WITHOUT PV)
PARIS-PROOF VALUE: 269 $KGCO_2E/M^2$

This apartment building in a medium-sized city is part of two similar buildings. The apartments range from 83 to 102 m². Several materials are used for the supporting structure: walls of sand-lime brick and wood-frame construction and concrete floors. 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.

FIGURE 13
MPG Score of Case 1 after S-layers (without PV)

The components of the floor plan have a relatively low environmental impact. The facade of the building has a medium environmental impact compared to the total impact. The windows are

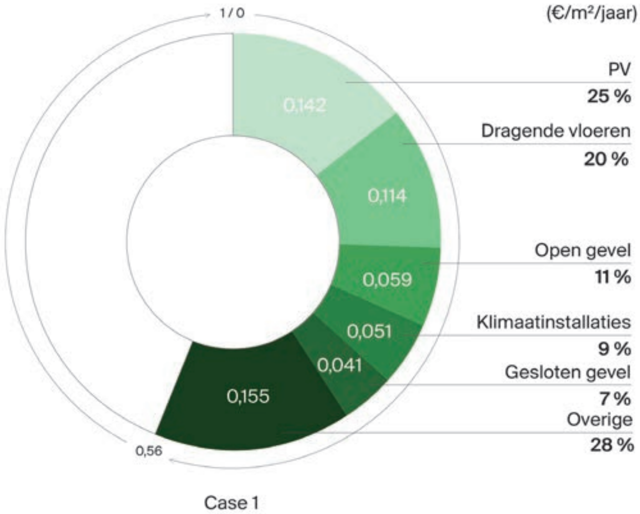


FIGURE 14
Top 5 emissions from Case 1

double glazed but with thinner panes (4 mm) than in case study D (6 mm). The indoor climate control uses natural ventilation as a supply.

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 more ambitious buildings.

Generally, the open façade has a large impact on the environmental impact, but in this case less than expected with an open façade percentage of 38 percent. As a result, the closed facade percentage is low and this is reflected in the low score for the closed facade, even though

FIGURE 12
MPG-value per life cycle fase
Case 1

category 3 masonry was chosen here, which is not representative of the Dutch brick industry. Overall, it is noteworthy that this building, which was built with fairly traditional materials, scored low in the MPG. The reason could be the very compact building volume and average height of 4 floors. Also, HSB with an exterior brick leaf has already been chosen for the exterior walls.

CASE 2

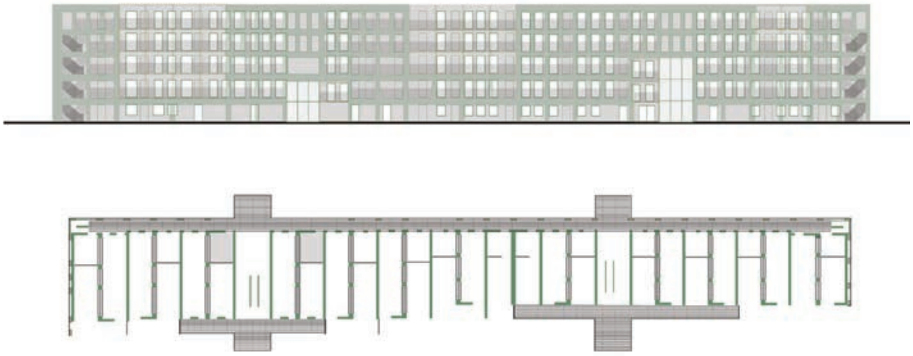


FIGURE 16
Facade and floorplan
Case 2

MPG VALUE: 0,49 €/M²/YEAR - 0,43 €/M²/YEAR (WITHOUT PV)
PARIS-PROOF VALUE: 271 KGCO$_2$E/M²

This apartment building in a medium-sized city is part of two similar buildings, which together share a courtyard. The apartments have two different sizes: 75 and 93.75 m^2.

The supporting structure consists of a concrete foundation with mostly wood above it. The main supporting structure consists of CLT (cross laminated timber) and further interior and exterior walls are realized with HSB (timber frame). A modular construction method is used here, which is not clearly reflected in a lower MPG. Though this method of construction is generally regarded as more sustainable

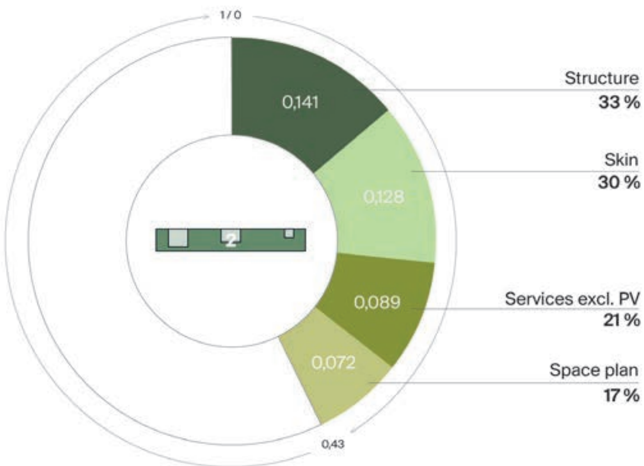


FIGURE 17
MPG-Score of Case 2 after S-layers (without PV)

In the MPG calculations, the supporting structure is still the largest component, but compared to Case 1, it becomes clear that wood provides a lower environmental impact. This does not include the CO_2 storage. The most polluting building components (besides the PV panels) are the climate control systems, the open facade and the supporting floors (first floor of concrete, but mainly of CLT).

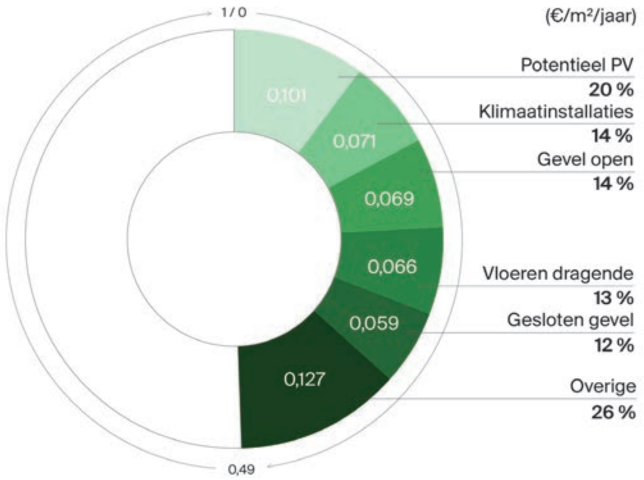


FIGURE 18
Top 5 emissions from Case 2

The building obtains its energy from the regional grid. According to the description, this is almost entirely renewable energy, which means that to meet BENG requirements, fewer PV panels are necessary.

FIGURE 19
MPG value per life cycle stage Case 2

CASE 3

FIGURE 20
Facade and floorplan of Referen-
ce project Case 3

MPG VALUE: 0,92 €/M²/YEAR; 0,40 €/M²/YEAR (WITHOUT PV)
PARIS-PROOF VALUE: 379 KGCO$_2$E/M²

This semi-detached house of 160 m² to accommodate five people. The main structural materials are sand-lime brick (walls) and concrete (floors).

The shadow costs of building materials are not very high for this case study. The PV panels have the largest embodied energy (per square meter GFA) of all the case studies. They increase the MPG score from 0.32 (without PV) to 0.92 (with PV). Compared to Case 4, no electricity from the grid is used here. Thus, this zero-to-the-meter house has an MPG score that is very high, but it also achieves an excellent EPC score.

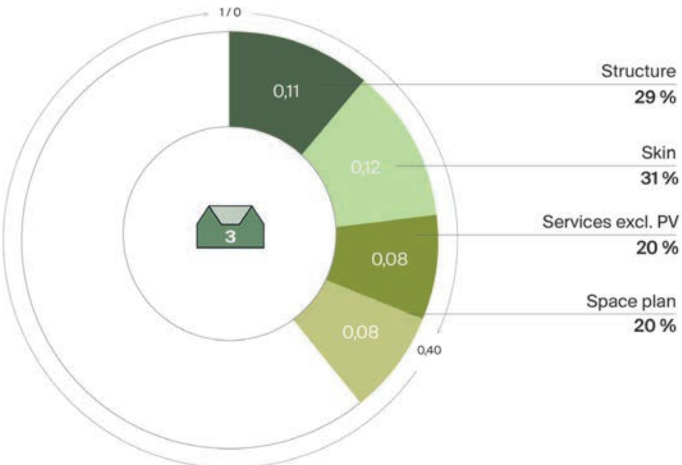


FIGURE 21
MPG-Score of Case 3
after S-laag (without pv)

The closed façade surface has a relatively large impact. It is brick and wood cladding applied to a substructure of sand-lime brick. In shadow cost, the wooden facade has only a small advantage over the brick facade. (3,09 €/m² vs. 3,42 €/m²).

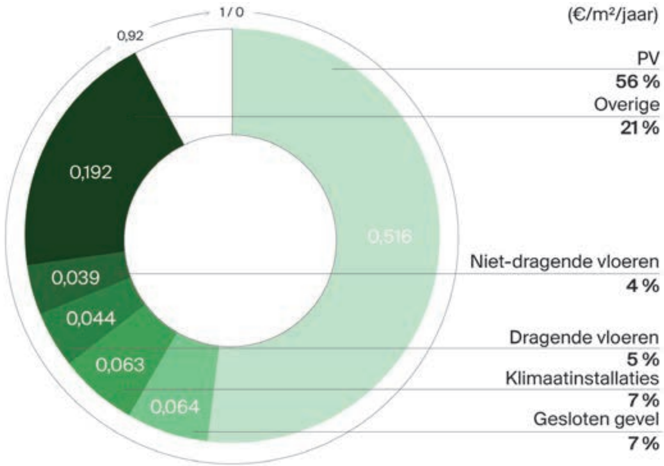


FIGURE 22
MPG score of the five building sections that cause the largest emissions from Reference Project Case 3

The climate control systems have a visible effect on the MPG. The environmental impact of the load-bearing floors is reasonably small. An interesting observation is that the load-bearing floors have a reasonably low environmental impact and thus have a similar environmental impact to non-load-bearing floors (cement screeds).

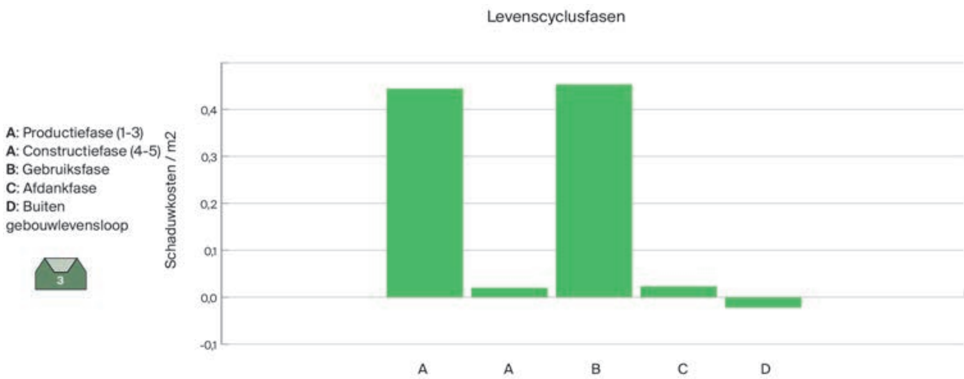


FIGURE 23
MPG value per life cycle stage
Case 3

CASE 4

FIGURE 24
Façade and floorplan
Case 4

MPG VALUE: 0,46 €/M²/YEAR, 0,37 €/M²/YEAR (WITHOUT PV)
PARIS-PROOF VALUE: 222 KGCO$_2$E/M²

Ground-up housing is a poor description for the building, yet the entire complex is a combination of several apartments and houses put together. The housing sizes range from 83 to 243 m^2. Together they form a small village on the outskirts of the city. For our calculations we use a medium sized apartment that is 173.6 m^2. Note that the MPG score is expressed per square meter. Even though the apartment has a low MPG score, the house skin does have a high environmental impact. In part, the low MPG score would also be explained by the size of the house.

The MPG score without solar panels is very small with 0,37 €/m^2/yr.
Again, the foundation is made of concrete, but the above supporting structure is built of wood (HSB). As a result, the structure is responsible for less environmental impact than the facade. On closer inspection this can be explained by the high environmental impact of the open facade.

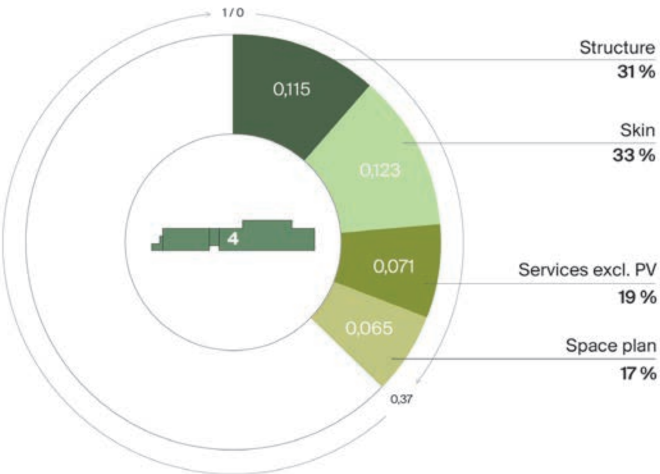


FIGURE 25
MPG-Score from Case 4 after
S-laag (without pv)

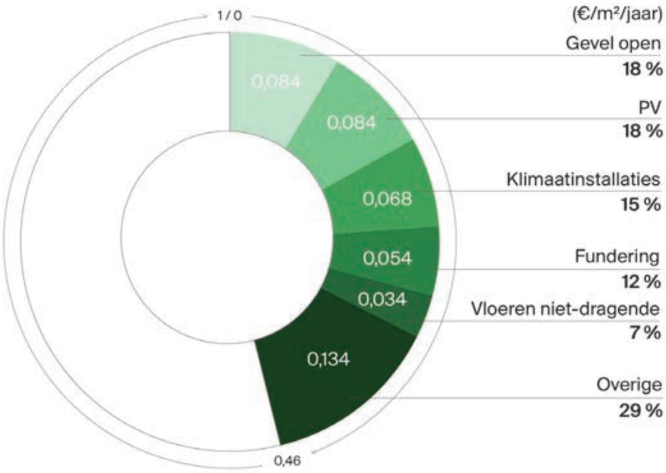


FIGURE 26
Top 5 emissions from Case 4

The surrounding energy grid is as sustainable as in Case 2 and provides a low operational energy requirement for the building. In the comparison of operational and embodied emissions, this building even came up with a negative operational emission, which means that the building is energy efficient. The embodied emissions could be cancelled out by this if you look at operational and material-related independently.

It is striking that in phase D ‚reuse' a relatively high negative value emerges. This is probably because it is assumed that all the wood in the building will be burned at the end of the lifecycle and will then replace fossil fuels. However, the question is whether this would still be the case in 75 years.

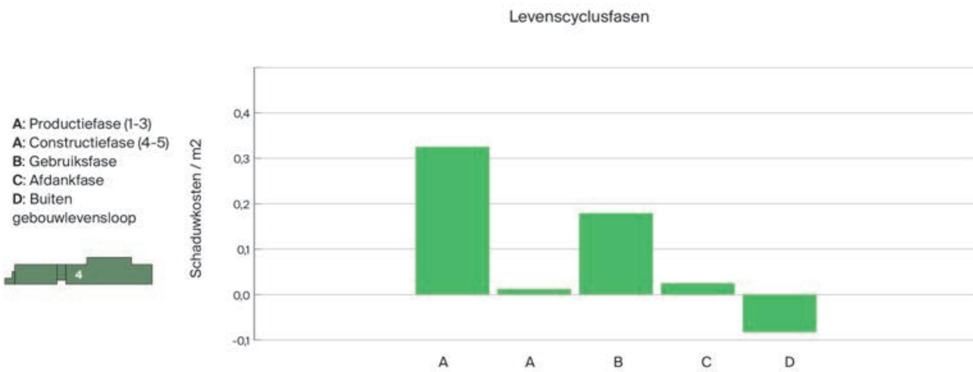


FIGURE 27
MPG value per life cycle phase
of Case 4

COMPARISON VALUES

FIGURE 28
MPG scores after S-layers per case (without PV)

When comparing all MPGs, the shares of each layer appear to be about the same. Case 1 has a larger share in the support structure, this is mainly due to the amount of concrete used. We show this comparison without PV panels, because these have a very heavy impact, the need for them is strongly dependent on the external energy supply and this aspect is location bound and less influenceable for a designer. Without PV, the shares for services are also similar.

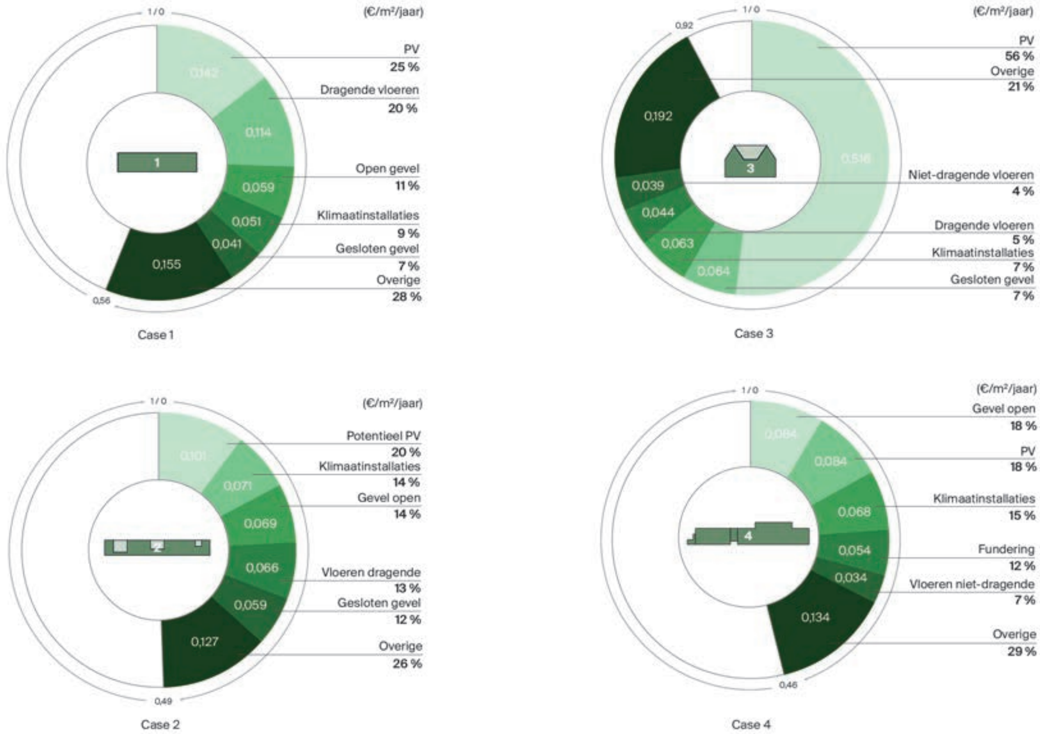


FIGURE 29
Building components with largest emissions per case (with PV)

If we do calculate with PV panels, one can see clearly here, that for Case 3 this makes a huge difference, however, this building is then also energy autonomous and thus does not receive external supplies of energy.

In a comparison of emissions by life cycle phase, Phase C „discard“ of Case 2 stands out. While most products place gains through recycling or fossil fuel avoidance in phase D, the CLT floor in Case 2 is assigned all potential gains already in phase C. Case 3 also has greater consumption in phase B “use” due to the large amount of PV panels, because the replacement of the PV elements falls into it. Over 75 years of age, that is two replacements. The cases with wooden structures show a larger gain in phase D, because fossil fuel avoidance is credited here.

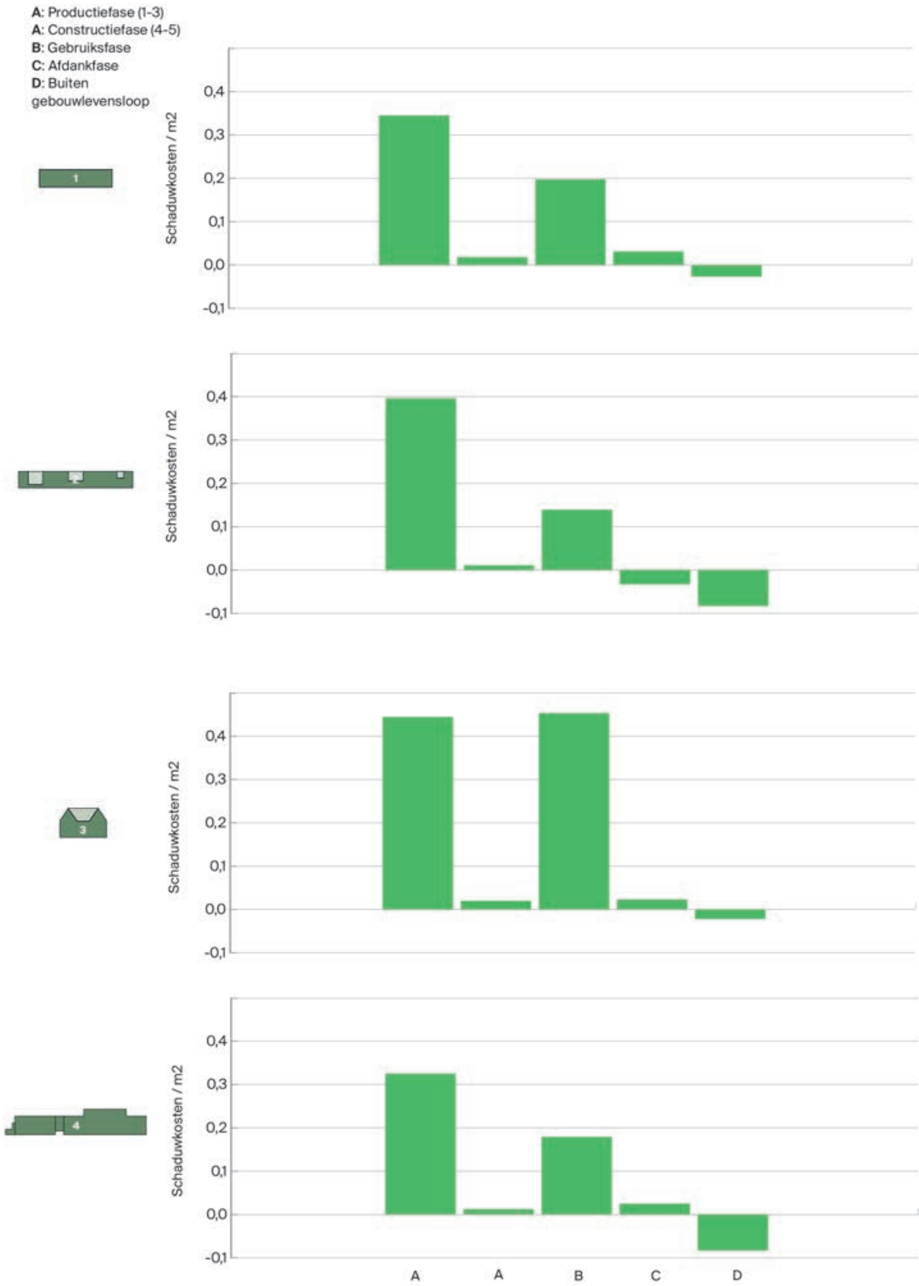


FIGURE 30
Distribution of Impact over Life Cycle

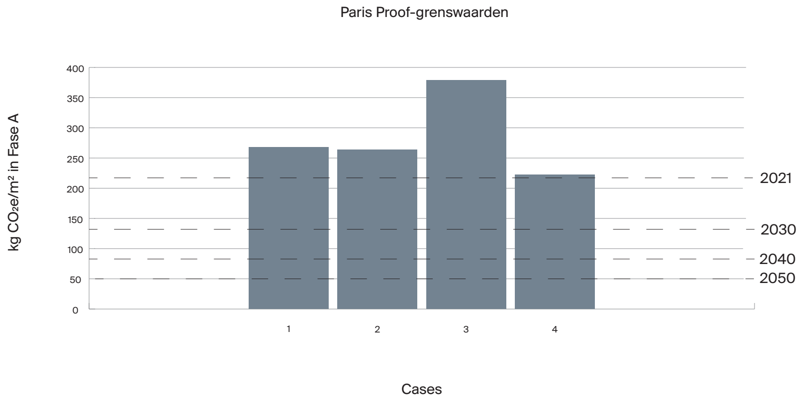


FIGURE 31
Paris Proof-limits and values of all Cases;

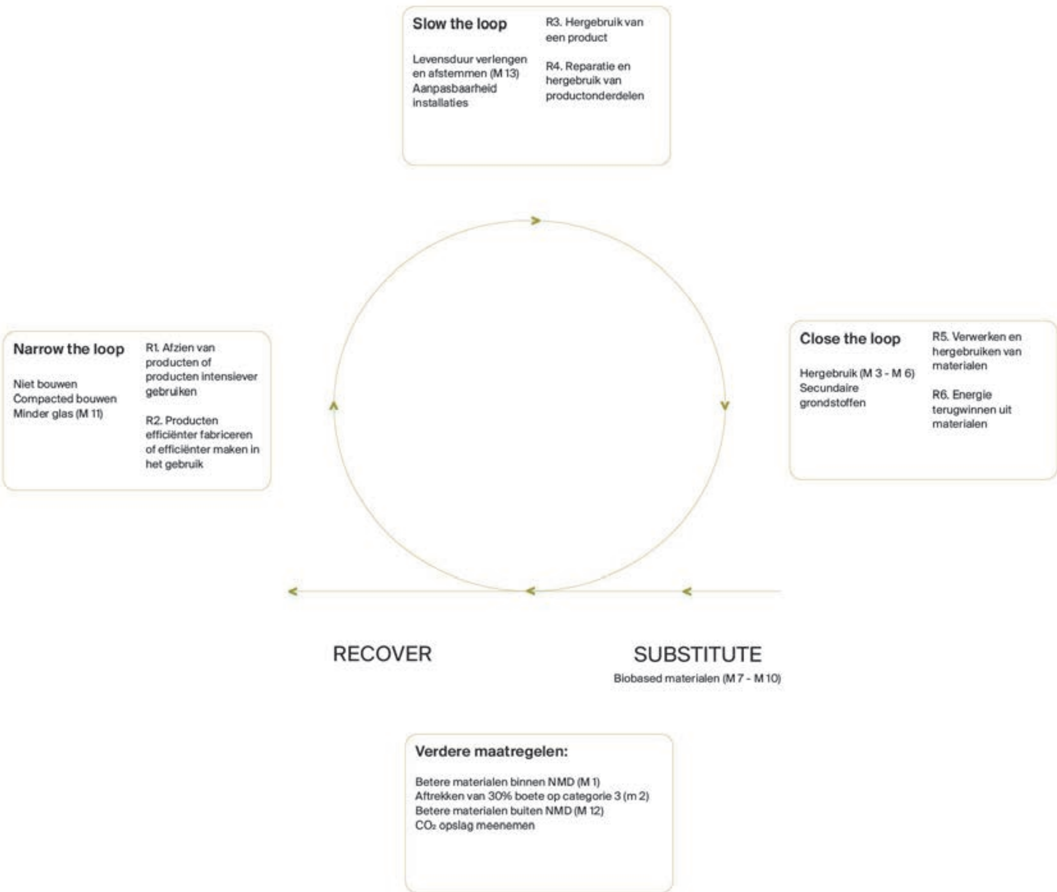
* For Case 3 & 4, those limits (for single-family homes) would be even slightly lower .

In a comparison according to the Paris Proof protocol, it is striking how poorly Case 3 scores here, which in turn is due to the quantity of PV panels used. This should be placed in context; PV panels are of course a good investment in terms of sustainability. More on this in the chapter “Compare CO_2 over time”. Furthermore, it is nice to see that Case 4 almost reaches the Paris Proof threshold.

CHAPTER 3
STEPS TO ZERO
MEASURES

Our steps to zero are linked to the CB23 Design Strategies. These are oriented to the principles of the so-called R-ladder:

The R-Ladder creates a hierarchy of principles for sustainable use of materials and energy, with the end goal of 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 positive impact and the last principle being the least desirable. Further, these principles are grouped by “Narrow the Loop” - prevention, “Slow the Loop” - life extension and “Close the Loop” - reuse.



REDRAW FIGURE 32
R-ladder linked to our measures

We use this structure to search for measures, which are applicable within the existing calculation methods. In addition, we looked for further measures outside the legal system. A total of 20 measures were applied:

PREVENTION (NARROW THE LOOP)

M 0: DO NOT BUILD - (UP TO 100% SAVINGS)

The greatest potential for CO_2 savings, within Western Europe, is simply to build less. This seems banal and contradictory to reports of housing shortages and build, build, build but there is a lot to be said for this. The average living area grew by about 200 percent between 1950 and 2020. One of the biggest suspected drivers of this increase is the increase in one- or two-person households, for example, empty-nesters whose children are out of the house and who do not find attractive offers that encourage them to leave their (overly large) homes. Only demographic shifts will cause this to diminish over time. Research by KAW and others shows that the so-called necessary 1,000,000 homes can largely be solved within the existing city and partly also within the existing stock of buildings. Furthermore, office buildings, for example, appear to be used much less than was thought and there is much potential for more living space here. Here is also a comment on the MPG method. It expresses the environmental impact per m^2 GFA and makes no statement, for example, the environmental impact per user. As a result, the MPG score of a large house with a two-person household is better than a Tiny House with a three-person household.

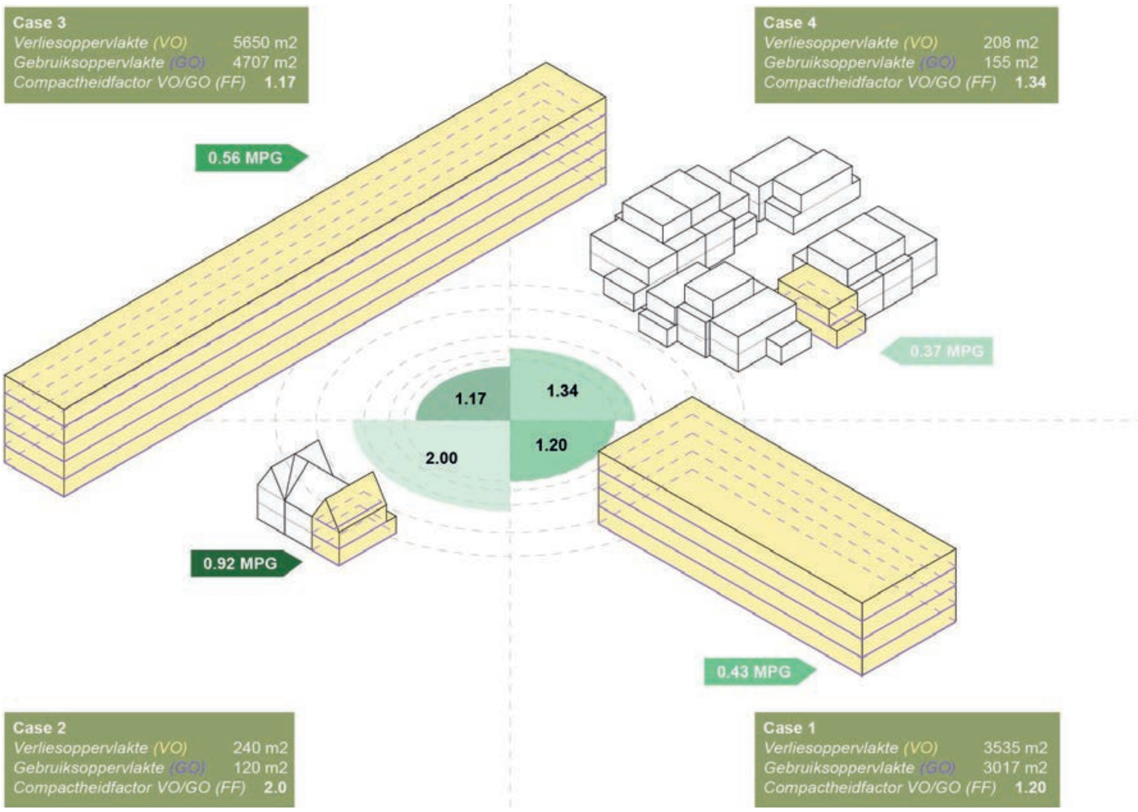


FIGURE 33
comparison cases on compactness and MPG

M 1: BUILD MORE COMPACTLY

The compactness of a building describes the ratio of a building‘s envelope (façade, roof, and bottom floor) to its area of use. The more compact a building, the less envelope is needed per square meter of usable area. This means that the material-related emissions of a more compact building are also lower.

Moreover, more compact construction not only saves materials, but is also better for the buildings energy needs. Compactness is also considered the basis for an energy-efficient (passive) house because heat is lost through the building envelope. It is therefore often referred to as “loss area”. A more compact volume means less loss area, so less energy demand.

The graph below shows the required U-value versus compactness factor. The smaller the form factor, the more compact the building. It is worth noting that small changes in the form factor make little difference if it is already high (3+). Once the form factor is below 2.0, further improvements have an exponential effect on the required insulation

It is quite difficult to achieve a form factor of less than 2.0 for a detached residential building. As shown in the illustration below, a three-story semi-detached building with a use area (GO) of 120m^2, (Case 3) still has a form factor of 2.0. The same building as a detached house with a flat roof would have a form factor of 2.94 and thus require almost 1.5 times as much loss area and cladding material. For larger and stacked buildings, a better form factor and thus a lower MPG score is possible. If the living area of the semi-detached house from case 2 were built in a compact residential block of 8 apartments with a form factor of 1.17, a higher heat transfer coefficient

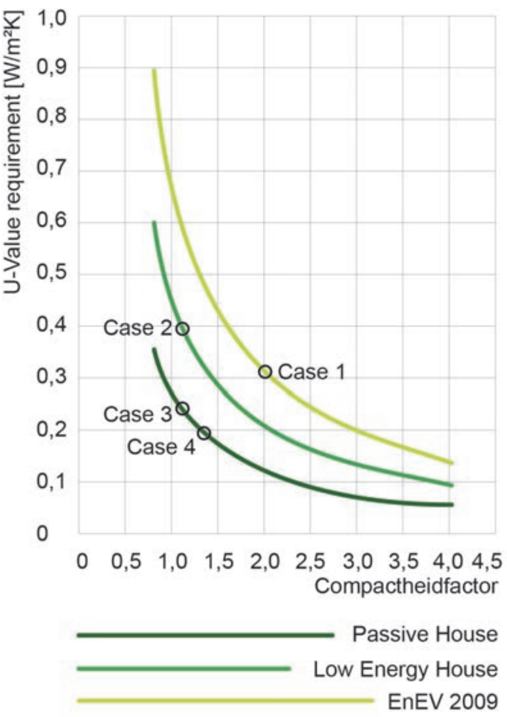


FIGURE 34
Ratio of required U-factor to form factor[8]

(less insulation) would be allowed and the MPG would drop to 0.84 (9% reduction). If the living area is situated in a middle high-rise building of 36 apartments, the MPG would drop to 0.81 (an additional 3% reduction, 12% from the original MPG score of 0.92).
Here it can be seen, that in the worst case, in terms of form factor, of a detached loft following a high-rise urban building, the MPG can drop to 17% and the Paris Proof Score to 20%. A more realistic scenario will be the real building of a semi-detached house with a mid-urban building, where that still leads to a 7% reduction in MPG.

M 2: GLASS AREA AFTER 20% OF FACADE

Glass (in solar panels, windows or elsewhere) has a major impact on the environmental performance of a building, especially since it has to be melted at high temperatures, . Also, the recycling rate is surprisingly low, presumably to ensure the purity of the glass. Glass also has a

8 source: https://elrondburrell.com/blog/passivhaus-heatloss-formfactor/

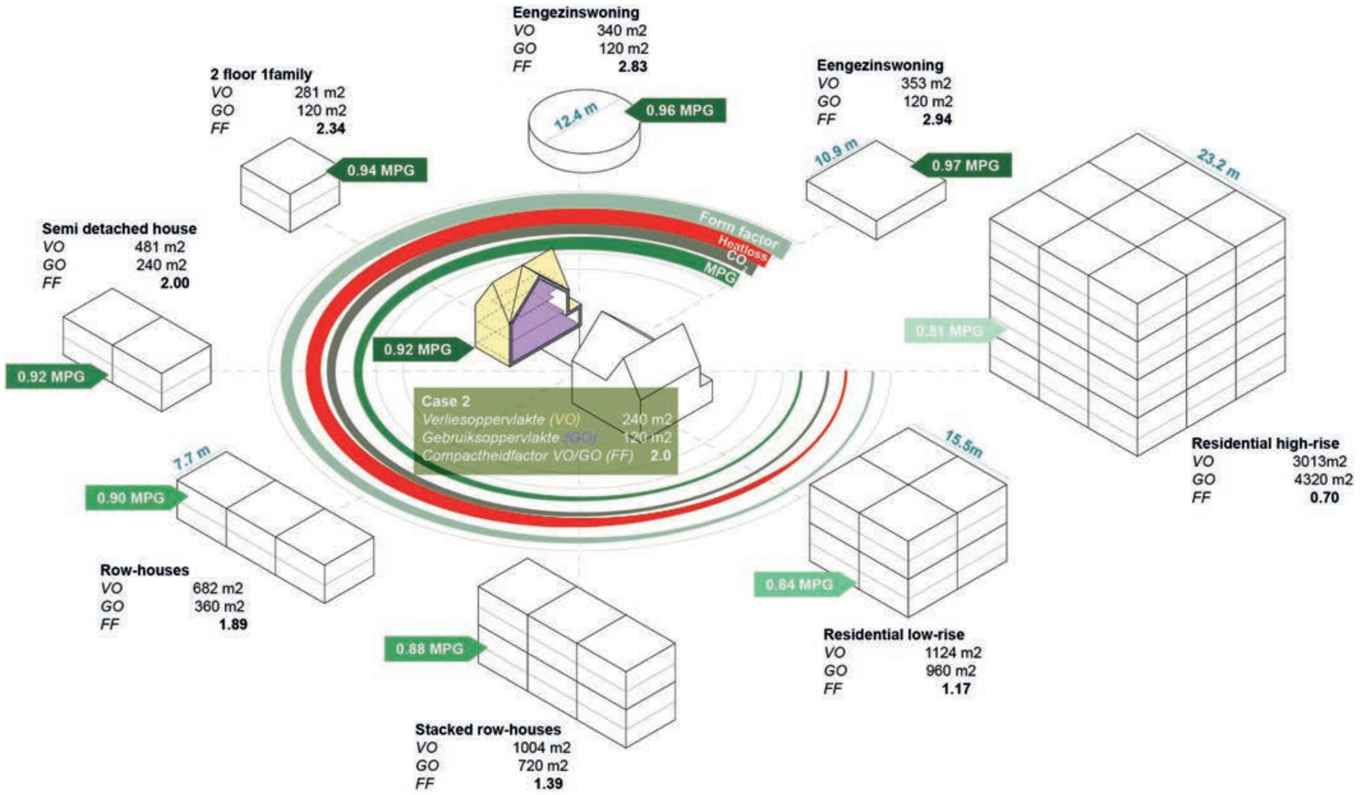


FIGURE 26
Ratio form factor and MPG-value

major effect on a number of other environmental performances of a building. Even triple glazing is still a weak link in a well-insulated facade I.[1,2]

Good daylighting, on the other hand, can reduce electricity consumption, and in winter, solar gains can be achieved through good positioning of openings. We leave these trade-offs aside for this calculation and have reduced the glass area of each building to a maximum of 20% of the total. According to some studies, it could even be less, but that depends very much on the sizes and positioning of the openings. Moreover, the same applies to glass as to electrical installations, that only category 3 products are available. More category 1 and 2 dates will lead to improvement in environmental impact.

The replacement closed façade is then filled with the original façade elements. The steps are:

1. Determine proportion of open and closed facade.
2. Determine factor for reduction glass and factor for increase closed façade to come after a 20/80 ratio.
3. Apply factors to all elements respectively.

This measure is only used on the mid-urban Cases, because for the low urban Cases the ratio is already at 20% or less. We did not adjust the thickness of the glass (2 or 3x 4mm, 6mm or 8mm), also it will probably be possible for small facade openings because the glass has to absorb less stress.

Just adjusting the opening percentage yielded an average 5% improvement for the MPG value. For the Paris-Proof score the effect was negligible. This measure only becomes important if the transparent parts of the facade are also replaced with more environmentally friendly materials. We explain this later in “steps to zero”, under the strategies “biobased” and “renovation”

1 CBD p24 f.
2 Passivehouselecture, https://www.arup.com/perspectives/publications/research/section/re-thinking-the-life-cycle-of-architectural-glass

SLOW THE LOOP

M 3: EXTENDING REPLACEMENT INTERVALS

For building elements, which have a shorter life span than the building itself, the MPG calculations multiply the building element by an associated factor. For example:

- Lifespan of PV panels: 25 years.
- Life span most buildings: 75 years
- MPG for PV panels in buildings: MPG of one PV panel x 3

We took case 1 to measure the effect of extending plant life by 5 years. For example:

- Assumed life span of PV Panels: 30 years
- Service life of building: 75 years.
- MPG for PV panels in buildings: MPG of one PV panel x 3.

The following elements were found to be most relevant for life extension in the study:

- pv-panelen from 25 to 35 years.
- boiler: from 15 to 25 years.
- heatpump : from 15 to 25 years.
- glazing: from 30 to 75 years.

At the material level, these changes mean an MPG reduction of:

- pv-panels x factor 0,7.
- boiler x factor 0,6.
- heat pump x factor 0,6.
- glazing x factor 0,4.

These factors were then applied to each case. The results below show that extending the life of PVs has the most impact. Extending the life of PV, boiler and heat pump to even 10 years would result in an MPG Improvement of 0.06 (10%) for Case 1. However, longevity is often unfavorable for plants in a holistic approach because they improve rapidly on efficiency (see refrigerators or solar panels).

Looking only at extending the life of solar panels, the MPG decreases by 4.3% with a 5 year extension, with another 5 years the MPG decreases another 3%. Extending the lifetime to 40 years (an additional 15 years) would reduce the MPG by another 2.2%, bringing it to a total of 9%. Thus, the effect of the extension decreases with time.

It is not only the building systems where a longer life span could reduce the MPG. Another example could be the exterior glazing which has a 25 year life span while the exterior frames in which they are installed have a 75 year life span. In the case of Building 1, extending the life of the glazing to 75 years would reduce the MPG by another 0.034 (6%).

In total, the MPG drops by 13% due to this measure. Of which PV panels alone make up to 7% and glazing up to 6%. For CO_2, savings of 8% are achieved, 5% through all building systems and 3% through glazing

Note: Extending the life span of elements can lower the environmental impact over the entire life cycle of the structure, but this does not happen without modification of the element and a potentially higher initial environmental burden. This calculation makes it clear that especially for elements with a short life cycle it is interesting to look at life cycle extension to reduce the environmental burden over the total life cycle. The Circular Manufacturing Industry Implementation Program (UPCM) for air conditioning systems formulates it as follows::

By 2030, the environmental impact of climate installations in the built environment will have been reduced by 25% compared to 2016 as a result of life cycle extension (60%) and more sustainable concepts and production.

M 4: MATCH THE TECHNICAL SERVICE LIFE TO THE EXPECTED SERVICE LIFE

Another interesting aspect is the skewed relationship between life spans. Within the installation section for case 1 are elements with varying life spans of 15, 20, 25, 30, 35 and 50 years. Since the heat pump is replaced every 15 years, the distribution system every 35 years and the underfloor heating every 30 years, and assuming that with each replacement other components are also modified, which just don‘t fit the new system, then a lot of resources are wasted in the process.

Perhaps a more optimized approach would be better, where, for example, the rain water drains [gutters] (life span 20 years) are coordinated with the replacement of the sewers (life span 35 years) and the water pipes (life span 50 years) and a shift in water management can take place, where rainwater is stored locally and used for flushing toilets, laundry, etc. It is likely that the impact of this step will be less than extending maintenance intervals. However, this requires

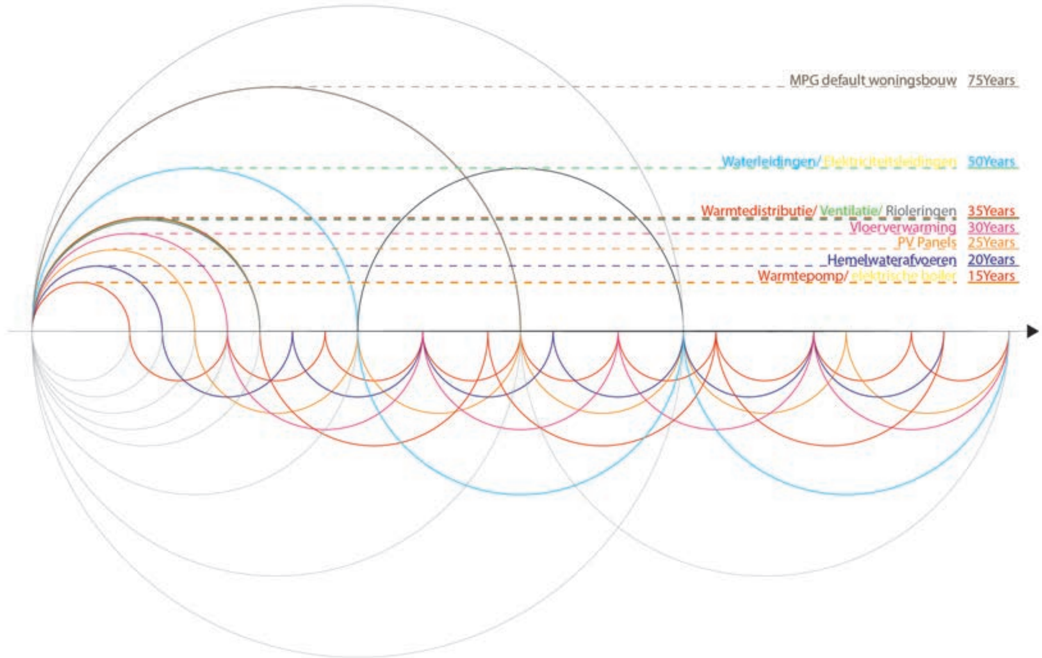


FIGURE 36
Ratio of replacement intervals of Case 1

further research, as this is where outside NMD methods need to be calculated.
Another approach is to ensure detachability of elements with unequal life spans:

M 5: DETACHABILITY: PLAN ADAPTABLE INSTALLATIONS

As discussed in “Carbon-Based Design”, bundling and compressing plants into central shafts will reduce both production emissions and emissions during replacement/repair. Finishing installations takes a lot of material that is often only decorative. In addition, compared to the whole building, installations have a short lifespan and often need to be adapted, repaired or replaced. It is then a great advantage if this can be done without greater interventions.
If detachability and adaptability are designed in from the start, it would be nice to see that reflected in the MPG. For example, it would be valued with a positive effect on phase D. Because these calculation rules are not available in the determination method, we have not been able to quantify this measure. The CB‘23 guidance mentions the following key indicators for measuring circularity[3]:

- Functional quality, technical quality, degradation and adaptive capacity.
- Future-proof building.

3 https://platformcb23.nl/images/downloads/2020/meten-van-circulariteit/20200702_Platform_CB23_Leidraad_Meten_van_circulariteit_versie_2.pdf

- Anticipate multiple life cycles.
- Spatially-functionally adaptive.
- Technical adaptive

CLOSE THE LOOP

M 6: REUSE OF SUPPORTING STRUCTURE (STRUCTURE)

Reuse of building components or entire buildings is obviously an important measure. According to the NMD determination method of July 2020, a flat rate factor of 0.2 is used for this purpose for A1-3, C3, C4 and D for each reused material. A factor of 0.2 is used because in practice adjustments are made to the element and the work itself also causes emissions.

If a building component has not yet fulfilled its theoretical life span, you can also speak of a "residual debt" due to the environmental impact of this building component. However, this would be difficult to implement and for the time being it is considered more important to encourage the reuse of materials.

Within the MPG calculations, it was technically complicated to make this calculation at the element level. We have therefore chosen to make a statement about each S-Layers.

The savings potential for reusing the supporting structure varies depending on the impact of the structure on the entire project. For example, Case 1 saves a total of 21% on MPG and 35% on Paris-Proof score, while the same measure for Case 3 saves only 7% on MPG and 15% on CO_2. On average these values are at 13% MPG and 26% CO_2 savings.

M 7: REUSE OF FACADE ELEMENTS (SKIN)

The same calculation method was used for the other S-Layers. Again, the results differ in correlation with the proportion, which each layer makes up in each project. The bandwidth in difference is slightly less, because the facade makes up about the same proportion in all cases.

The reuse of facade elements provides an average improvement of 12% on MPG and 15% on Paris-Proof score.

M 8: REUSE INTERIOR BUILDING (SPACEPLAN)

For interior construction, it was noticeable that in Case 2, the interior construction has a larger share of the total. Subsequently, the savings for Case 2 was 25% on MPG and 35% on Paris Proof. On average, this measure achieved MPG savings of 12% and 19% on Paris Proof and thus would be more effective than reusing the façade elements and almost as effective at the MPG level as reusing the supporting structure.

M 9: REUSE BUILDING SYSTEMS (SERVICES)

The reuse of building services is a complicated discussion. Especially in large projects, it is for various reasons not usual to reuse the full set of cables, pipes and equipment in a new situation. Especially with equipment, technological progress is also great and a new installation quickly pays for itself financially, but also in terms of environmental impact. Nevertheless, cable trays, ventilation ducts and other products, for example, are highly standardized and are elements that are already widely available in the second-hand building materials trade. Especially in smaller projects, it should not be difficult to work with second-hand material here, as the security of supply is high. For equipment, a stronger focus could be on adaptability. Often it is only small parts (e.g. a water pump in a central heating boiler) that are responsible for the efficiency gains. If these parts could be replaced separately, it would not be necessary to replace the entire boiler.

During the life of a building, building systems are regularly replaced. For example, the lifetime of a PV panel is 25 years, of power lines 50 years. In the LCA calculation of a building with 75 years, the PV panels are then counted 3 times and the power lines 1.5 times. In our calculation we assume for convenience that each time recycled material is used.

The reuse of building systems is not considered in the combinations, as this does not seem realistic in practice at the moment. Yet we mention the possible effect here because we see potential in making installation products circular. Assuming the reuse of the entire installation system, we then achieve an average savings of about 12% on MPG and 15% on Paris-Proof score.

COMPARE INVESTMENT OF CO_2 OVER TIME

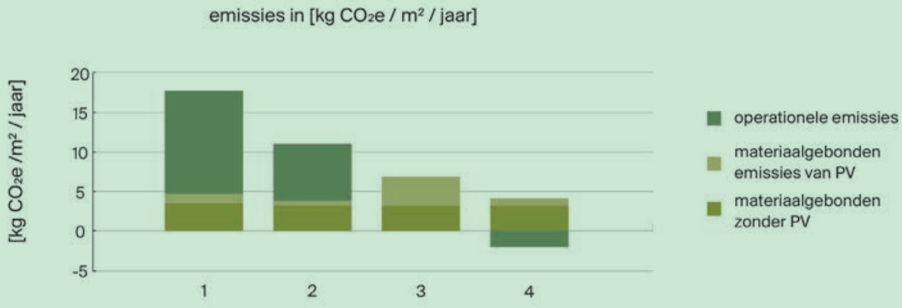


FIGURE 37
Ratio of operational to embodied emissions per Case

Our calculation of operational and embodied energy per year is a simplification of reality. Actually, these emissions will look more like this:

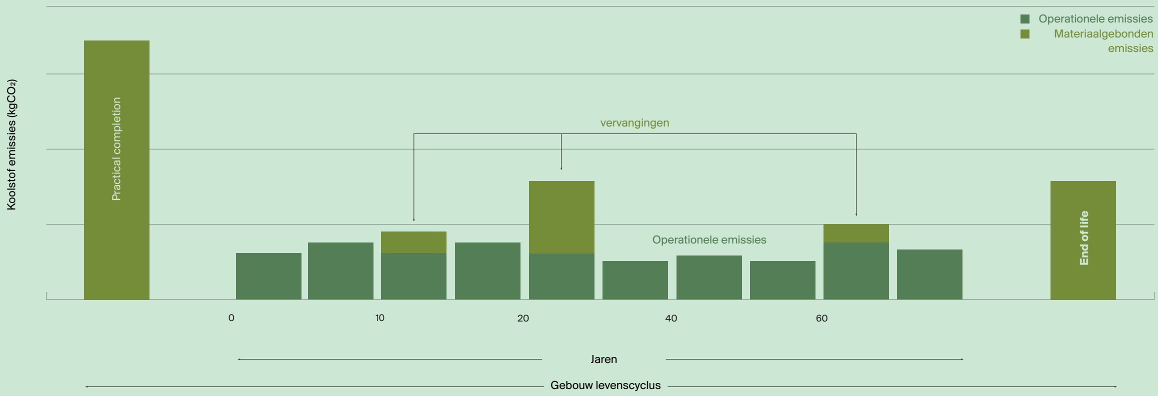


FIGURE 37
Chart: Emissions over time

In the comparison of operational emissions with embodied emissions, it is important to know in advance how much CO_2 emission, for example, the production of a PV panel causes and when it will produce enough green energy to pay for itself.

The same applies to building systems and insulations, while they initially increase emissions, within the next few years they will keep operational energy low and on balance save energy. The same applies to triple glazing, which initially causes greater emissions only to have a lower environmental impact later through operational energy savings. In addition, it is also important to keep in mind, that an energy-autonomous building needs a lot of emissions „investment“ at the beginning of its life. So it is important to know the payback periods and make a conscious decision, which investment, for example, will only pay for itself within the next eight years, to 2030 or even later

SUBSTITUTE

M 10: LOAD-BEARING STRUCTURE IN CLT

Instead of not building or reusing existing elements, we also investigated alternative construction methods, and especially with biobased materials. The first measure investigated is the replacement of the supporting structure with a CLT (cross-laminated timber). For comparability, we rely on a TNO report from 2021: here a concrete wall or floor of 200 mm is equated with a CLT wall or floor of also 200 mm. In addition, an insulation layer for sound attenuation and plasterboard cladding for fire protection are added. In this way we have replaced the entire supporting structures. Usually this is concrete, in some cases supporting structures made of sand-lime brick or HSB are replaced. Structural timber with the same volume of CLT equated, for example in Case 2.

Foundations are disregarded for alternative construction methods due to lack of alternatives.

The results vary by case. For example, for Case 1, a CLT supporting structure improves the MPG by 21% and Paris-Proof score by 27%. It was also noticed that replacing the supporting structure with CLT is especially relevant for the conventional cases. For the other cases, the improvement on the MPG was minimal because they already use a wooden supporting structure. Subsequently, the average improvement in MPG is at 8% and for Paris-Proof score at 12%.

It appears that the chosen CLT in phase A is even CO_2-negative, because here temporary CO_2 storage is already taken into consideration. For this specific product, the temporary CO_2 storage is already included in the product sheet according to the new EN 1508 - A2. For the calculation of our secondary target value, however, we chose an equivalent product, without CO_2 storage in phase A, because otherwise CO_2 in production etc. would be mixed with CO_2 that has been biogenically sequestered.

For the MPG calculations, by the way, all life phases were considered and also for the material according to EN 1508-A2 the stored CO_2 is released again in phase C (discard).

M 11: LOAD-BEARING STRUCTURE IN HSB

An alternative to building with CLT is Timber Frame Construction (HSB). Especially with relatively conventional low-rise buildings, CLT will be structurally over-dimensioned and a lighter structure may also suffice. Based on the above-mentioned TNO report, we have, for example, replaced a house dividing wall of 200mm concrete with 238 mm HSB and additional insulation and cladding. Steel parts with similar spans as 200mm concrete floor we replace with a similar structure.

For the older Cases 1 and 3, replacing the concrete structure with HSB makes a big difference. In the newer cases, a large part of the structure already consists of renewable raw materials. Based on this, an improvement in the MPG of 17% is achievable in Case 1. However, depending on the chosen HSB product, this can also be worse than the original MPG of Case 2 for example.

We investigated two variants, one in which a loose HSB product with a low MKI and additional insulation materials was chosen and one in which a complete product with all components is used. The first variant scored significantly worse, even though there is a risk that connecting elements such as screws, for example, are not considered. This is difficult to understand, however, because the description of the products and materials in the NMD is fairly brief.

In terms of Paris-Proof score, HSB in any case ensures less CO_2 emissions than concrete, in our cases up to 24% less.

M 12: BIOBASED FACADE

The biggest difference in alternatives façade elements makes is replacing brick with wood cladding. While this has a shorter lifespan, depending on the product between 15 and 75 years. For our replacements, we chose the best possible wood, which can last 75 years. This is a category 2 product, limited in availability and is called „Siding Dutch Wood“.

Replacing aluminum frames with wood frames further contributes to a better score of about two-thirds less. The replacements have significantly more effect on the Paris Proof score that looks at GWP than on the MPG because wood generally needs to be treated and varnished and impregnation often contain toxic substances that also cause environmental damage other than just GWP.

Replacing EPS insulation with lightweight wood fiber insulation (at 55kg/m3), where it is not pressure resistant for example, scores better than EPS. Should dense wood fiber insulation (at 115kg/m3) be chosen, it scores worse than EPS. Comparatively, for example, a plant-based roof membrane does not seem to have a better EIP than an EPDM membrane.

By consistently applying biobased materials, on average only a 3% improvement on MPG is achieved. On Paris-Proof score the picture is clearly different. Here, on average, almost 10% CO_2 reduction is achieved. Logically, the improvement was greater if the original facade consisted mainly of brick - up to 13% MPG in Case 3.

Incidentally, none of the cases studied is higher than five stories, so fire safety and the possible treatment of the wood for this purpose with often environmentally harmful agents was not considered.

M 13: INDOOR BIOBASED CONSTRUCTION

Replacing interior building elements in an MPG calculation is quite complicated, as few alternatives are known here. We therefore applied similar steps as in M9 (Facade biobased) and also chose alternative products of wood for example for stairs, doors and claddings. Spray plaster has been replaced with clay plaster, which is not biobased in a strict sense, but corresponds better to a circular approach. The Carbon-Based Design study revealed sand cement screeds with disproportionate environmental impact. We replaced these with a drying system based on gypsum fiberboard, which alone lead to a two-thirds reduction over sand cement.

Overall, the impact of this measure was quite small, also because the interior construction in our cases does not have a large share to the total MPG. Moreover, for some elements such as elevator installations or cabins, there are no biobased alternatives. On average, M 13 scores 4% better in MPG and 8% better on Paris-Proof score.

ALTERNATIVE MEASURES

Not all measures are relevant to designers or easy to apply to existing building designs or in combination with other measures. For the sake of completeness, we would like to mention them, also because they often have a greater impact than the measures that can be calculated fairly precisely with the existing tools. Below are a number of measures with accompanying calculations that go beyond the determination method of the MPG

M X1: SEARCH FOR BETTER MATERIALS WITHIN THE NMD (NATIONAL ENVIRONMENTAL DATABASE)

In this step, we replaced some building elements with similar, more environmentally friendly materials. The challenge here is to determine whether two materials are truly interchangeable and therefore provide the same performance. The replacement is therefore limited to a few better performing doors, different sand or cement. The biggest difference can be achieved simply by using better data. For example, replacing category 3 PV panels (generic data including 30% ‚penalty') with category 1 solar panels (product specific) reduces the impact on this specific component by half. Also, the choice in bricks makes a big difference. Case 1 applies category 3 data for the masonry that may indicate foreign brick. Just choosing Dutch Brick with category 2 data halves the MPG for this building section. The same is true for Case 3, where choosing a different type of solar panel similarly halves and in total reduces the MPG by 25%.

On average, the savings in MPG come down to 13%. For the Paris-Proof score savings, the observations were the same, with an average CO_2 savings of also 13%.

M X2: DEDUCT THE 30% STORAGE FACTOR ON CATEGORY 3 MATERIALS

Within the NMD, several products are only available with category 3 data. This means that no product- or sector-specific LCA calculations have been made. A 30% ‚mark-up' is then applied to these elements, because of the great uncertainty of the data and also to prevent this category being misused for specific products that in fact perform worse (categories 1 or 2). For the vast majority of cases, however, a lower EIP is achieved through more specific data. It can therefore be assumed that more product-specific data will also result in products in the NMD that score at least 30% better than the present cat3 products in the NMD.

We wanted to know how big the difference would be, if specific data were available for all products and if at least the storage factor would be dropped. We subtracted the 30% storage factor from all category 3 products.

In particular, it is striking that electrical systems are almost never present in categories 1 or 2 and therefore category 3 products often have to be used. A better data pool will also stimulate industry to improve their environmental performance. The same goes for glass and specific building components like elevator cabins or stairs.

Depending on how many materials were commonly used in each case, the difference was also different. On average, the MPG improvement was 14% and the Paris Proof score improved by 11%.
Note that this is only a bureaucratic improvement. In fact, of course, the same material with the same environmental impact is still being used, only it would have been calculated specifically for a product. Only through better availability of data could the MPG be improved by 14%.

M X3: SEARCHING FOR POTENTIALLY BETTER MATERIALS OUTSIDE THE NMD

One of the criticisms of national LCA databases in general is that they protect their own market, that little data is available and that innovative materials in particular are poorly represented. We started looking for reliable data outside the NMD, but unfortunately that is more difficult than we thought, on the one hand because data from other databases are not directly comparable with NMD data, and on the other because many new products do not yet have an EPD at all, which would provide insight into this data.

Therefore, as a calculation example, we have worked with flat rates based on research or press releases for some of the major pollutants in our projects. For example, we replaced concrete with a geopolymer concrete, which according to manufacturer data emits a quarter in phase A. For the facade, we calculated with brick strips, which according to the manufacturers have an EQI of 1.26 €/m^2, With these two main elements, we achieve on average an MPG improvement of 5% and about 9% CO_2 savings on the Paris-Proof score. Remarkably, innovation of only two materials has a significant impact on entire MPG of a building.

M X4: CO_2 SEQUESTRATION

The inclusion of fixed carbon within our building elements and thus within our calculation methods, is a discussion, which has a lot of attention at the moment. We have already explained the idea behind this in “Carbon-Based Design”. On the one hand, it is true that biogenic building elements and especially CLT can sequester a lot of carbon temporarily, which will eventually be released at the end of the lifecycle, or hopefully after a successful cascade. On the other hand, the use of wood does not mean an immediate gain for the environment, because the wood is taken from forests, sawn, dried, glued to be used in buildings. Here also additional CO_2 is released and the forest will temporarily be able to absorb less CO_2. Only when enough trees regrow (preferably in the same forest) is this potentially sequestered carbon a gain to the atmosphere. This assumes that forest management is conducted sustainably and the forests do not take irreversible damage. This real gain, which is immediately credited in most CO_2 calculations, will only really happen after a few years.

At the same time, it also offers a great opportunity, to sequester carbon within the built environment for the long term, at least for the next, critical decades. European hardwood from mixed forests or, for example, poplar wood from Dutch soil could be an interesting alternative to spruce wood that is grown and harvested on an industrial scale before being transported over long

distances.
Because many factors influence this, there is no European consensus on how this should be calculated, which is why it is not (yet) included in the NMD. We have therefore estimated the stored CO_2 in biogenic products based on a study and also used this to calculate the ‚Paris Proof' values.

To get a sense of how this relates to the overall environmental impact of a building, we have again translated this into an MPG value, by quantifying the stored CO_2 in phase A, knowing that it will be released again at the end of the lifecycle. Our calculation method is as follows:

First, the amount of biogenic material grown is examined. This is multiplied by a CO_2 factor/m^3 depending on the type of wood, insulation material or other product. For the MKI value of this captured CO_2, the weighting factor 0.05 according to the NMD is taken. Later, this MKI can be subtracted from the original MKI. With this value, an MPG can be calculated again - the MPG value with CO_2 sequestration. The steps are thus as follows:

1. Original MPG value (€/m^2/year) after MKI bring (€).
2. Calculate the amount of wood within the building (m^3).
3. Calculating CO_2 within wood.
4. Bring captured CO_2 with weighting factor (0.05) after MKI.
5. Original EQI minus EQI (of CO_2) divided by m^2 and 75 years = MPG value with CO_2 storage

The MPG is thus (temporarily) compensated between 16% and 62%, depending on the case. Looking at the Paris-Proof score, it is striking that the results in terms of CO_2 savings mostly offset the entire building. It results in between 96% to 192% savings. The average CO_2 savings is 143%, so the building including CO_2 storage becomes net CO_2 positive in the Paris-Proof score. More than 80% of the CO_2 is in the construction.

1. MKI en MPG			**$kgCO_2$ in het gebouw**	**MKI 142.193€**	**MPG 0,55 €/m²/jaar**
2. + 3. CO_2 binnen het gebouw	m³	x $kgCO_2$	Total		
	CLT 1.306,66 m³	x 759 (CLT) =	992.013 $kgCO_2$		
	Gevel 25 m³	x 824 (Douglas) =	20.869 $kgCO_2$		
	Isolatie 221 m³	x 85 (Steico) =	18.757 $kgCO_2$		
	Buitenkozijnen 3,36 m³	x 1.167 (Robinia) =	3.921 $kgCO_2$		
	Isolatie 163 m³	x 170 (Steico) =	27.691 $kgCO_2$		
		∑ $kgCO_2$	**1.063.251 $kgCO_2$**		
4. Nieuwe MKI	MKI CO_2 opslag, Wegingsfactor 0,05 €/$kgCO_2$	x 1.063.251 =		-53.163 €	
	nieuwe MKI		Δ €	89.030 €	
5. Nieuwe MPG	**MPG met CO_2 opslag**			89.030 / 3466 m² / 75 jaar =	**0,34 €/m²/jaar**
	MPG verbetering			**Δ €/m²/jaar**	**0,21 €/m²/jaar**

FIGURE 39
Example CO_2 storage calculation

M X5: CO_2 NEUTRAL ENERGY GRID

In principle, the building sector will become CO_2 neutral if the energy grid is as well. Cases 2 and 4 show that the energy network also has a large influence on the material bound emissions of a building. For example, fewer solar panels would have to be installed, or an analysis that integrally approaches building-bound and operational energy might conclude that operational consumption is more acceptable than the energy consumption and environmental damage of better insulation.

However, on the one hand, this is a very limited perspective on the sustainability of the future - a CO_2 tunnel vision. The product may be able to be CO_2 neutral, but there is already local scarcity on the energy grid and, for example, the use of space for solar panels, wind turbines etc. is very large and again has many effects on the environment. So, it remains relevant to build a building energy efficiently and to minimize energy consumption in the production of building materials.

OUTCOMES COMPARED BY MEASURE:

While always a combination of measures will be applied, it is worth taking a look at each measure in isolation. These are the average results, sorted after largest outcome:

- Don't build (100% savings in MPG & Paris-Proof).
- Build more compactly (up to 17% MPG savings & up to 20% Paris-Proof).
- Extend replacement intervals (up to 16% MPG savings & up to 8% Paris-Proof).
- More product data and innovations (14% MPG savings & 11% Paris-Proof)
- Reuse (12% MPG savings & up to 25% Paris-Proof per reused layer)
- Biobased construction (4-8% MPG-savings & 8-22% Paris-Proof depending on the layer)
- Less glass surface (5% MPG-savings & hardly Paris-Proof)

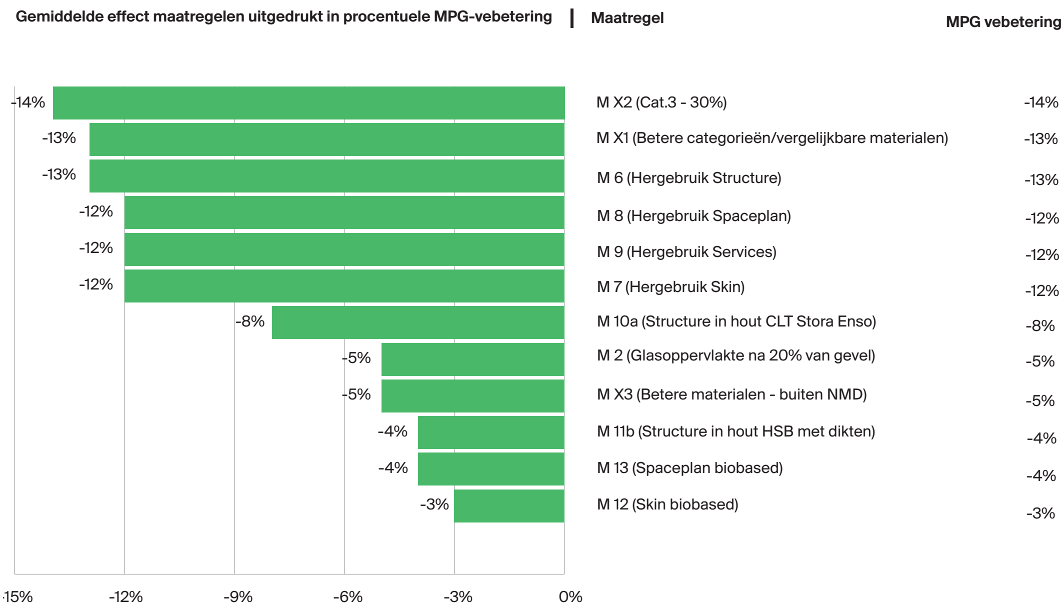
Specific to the Paris-Proof score:
• Factor in CO_2 storage (145% Paris-Proof)

It cannot be mentioned often enough and makes sense, but not building is the most sustainable measure. Next, renovation is better than new construction and so on. In addition, the share of CO_2 storage is huge, as previously explained, but we may be counting ourselves rich when it is released at the end of the life cycle. Building more compactly is a good optimization especially for detached single-family houses in outlying areas and a strong case for building in high densities, as it also has many other positive effects on energy consumption for mobility, infrastructure, etc..

Extending replacement intervals makes a big difference mainly for building systems: mainly by using PV panels longer, followed by heat pump and boilers. Furthermore, using glass longer is an untapped potential. Surprising is how much improvement theoretically more available data makes. As indicated, this is a paper profit but it is important to be able to tighten the MPG more quickly and thus also give the real alternatives a fair and ambitious playing field.

In terms of designer influence, the effect of building longevity, reuse, compactness and detailing (and therefore the extension of component life) is unquestionable. Wherever possible, emphasis should be placed on the reuse of existing resources. The application of biobased materials has surprisingly little effect on the MPG and scores particularly well on the Paris-Proof score. Biobased materials in the façade have hardly any impact, while this is very visible and thus eagerly done for marketing purposes. The impact is greater when a building of CLT construction is provided with a brick façade than a concrete supporting structure with a wooden façade.

FIGURE 41
average effect of measures expressed as percentage MPG-improvement



Important note: In the study, the measures were simplified. In practice, a building is integrally designed with the right materials in the right place. The simple replacement of materials will often be accompanied by additional measures, with additional environmental impact, to achieve a quality building.

STEPS TO ZERO

From the measures, we developed the following basic strategies that construct different scenarios.

STRATEGY 1: REUSE (M 6+ M 7+ M 8)

This combination approximates a material-minimal repair of a building, minimal renovation. It combines M 6 (reuse of supporting structure), M 7 (reuse of facade) and M 8 (reuse of interior construction). Basically, only the electrical and sanitary systems are renewed (services). When calculating this combination, the effects of the measures listed are listed.

This results in a large gain of about 45% MPG savings in almost all Cases, except Case 3, where the large share of installations reduces the effect of reuse. On average, the improvement is 37%.

Note that for simplicity we assume that also elements that need to be replaced during the life of the building are reused materials. Normally, Module B should always calculate with new elements. A more precise approach would therefore also have to define the term reuse more precisely. In fact, these are often products that are written off for reasons other than reaching the end of their useful life. Thus, the elements are not actually "used", they are just rejected elsewhere.

Furthermore, we have added all applicable measures: M X2 (deducting 30% penalty from category 3 products), M 3 (extending replacement intervals) and also looked at temporary CO_2 storage.

STRATEGY 2: RENOVATION (M 6+M 12+ M 13)

This combination simulates construction, where the supporting structure is reused (M 6). Relative to Strategy 1 all other building parts are built new and biobased material are used where possible. This means that the facade and interior construction are biobased (M 12 + M 13) and building systems are new. We achieve an improvement in MPG of 23% for Case 1 and 2. For Case 3 and 4 this improvement is lower, because the buildings already, for the large part, consist of wood. In terms of Paris-Proof score, the average improvement is at 39%. Further details can be found on the last pages of this report. Note: CO_2 storage is not included in this.
In addition, the following measures have been applied: M X2 (deducting 30% penalty of category 3 products), M X1 (better materials within NMD), M 2 (open façade share after 20%), M 3 (extending replacement intervals) and CO_2 storage. On average, the environmental burden is reduced by a total of 71%! Even without CO_2 storage, the MPG decreases by 49%.

STRATEGY 3: BIOBASED (M 10+ M 13+ M 2)

The complete replacement of all conventional building elements with renewably produced products will not be possible in practice at this time due to lack of alternatives for all products. Think here of glass and the like. However, by applying M10 (supporting structure in CLT), M13 (facade elements in as much biobased as possible) and M² (interior construction in biobased where possible) we have created a hypothetical biobased new building, where only the foundation and other non-replaceable parts such as elevator installations or services are not biobased. So, a combination from supporting structure, facade and interior construction with renewable raw materials. The results are just like the results of some measures depending on the original building, case 4 for example scores even 4% worse. The largest effect is in case 1 with a 22% better MPG value.

In addition, we have applied the following measures in order to achieve the lowest possible MPG and CO_2: M X2 (deduction of 30% penalty of category 3 products), M X1 (better materials within NMD), M 2 (open façade share after 20%), M 3 (extending replacement intervals) and CO_2 storage. On average, this results in 45% MPG savings.

RESULTS BY CASE

Although it is valuable to know the average outcomes per measure and to get a sense of what are sensible measures, the outcomes vary greatly depending on the Case under consideration. For this reason, we depict our “steps to zero” split up per case, also to make clear, that each case must be examined for which measures are applicable and useful!

The results for MPG (€/m^2/year) are shown in green, while dark green represents the remaining MPG value. Temporary CO_2 storage is indicated by shading.

For the Paris-Proof score (kgCO_2/m^2) the same applies in gray. The areas completely filled with gray represent the final result. The shaded areas indicate the CO_2 storage value, which sometimes goes deep into the negative.

To repeat, the limits for the single values:

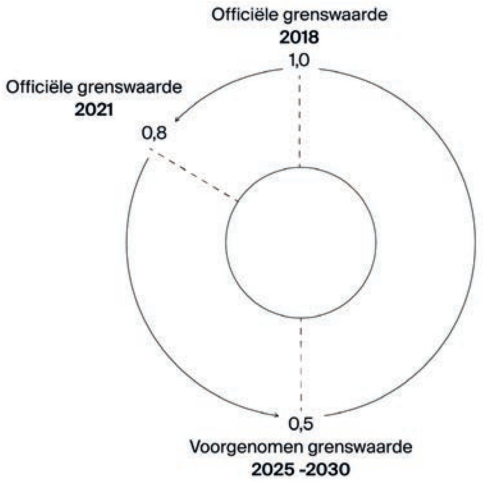


FIGURE 41

MPG average and limits

GRENSWAARDEN VOOR NIEUWBOUW

Tabel 1: Grenswaarden voor Paris Proof bouwwerken. Grenswaarde is gegevens in "embodied Carbon" per m^2 bouwwerk.

PARIS PROOF GRENSWAARDEN	EMBODIED CARBON KG CO_2-EQ. PER M^2			
	2021	2030	2040	2050
Woning (eengezinswoning)	200	126	75	45
Woning (meergezinswoning)	220	139	83	50
Kantoor	250	158	94	56
Retail vastgoed	260	164	98	59
Industrie	240	151	91	54

GRENSWAARDEN VOOR RENOVATIE

Tabel 2: Grenswaarden voor Paris Proof bouwwerken. Grenswaarde is gegevens in "embodied Carbon" per m^2 bouwwerk.

PARIS PROOF GRENSWAARDEN	EMBODIED CARBON KG CO_2-EQ. PER M^2			
	2021	2030	2040	2050
Woning (eengezinswoning)	100	63	38	23
Woning (meergezinswoning)	100	63	38	23
Kantoor	125	79	47	28
Retail vastgoed	125	79	47	28
Industrie	100	63	38	23

FIGURE 42
Limits after Paris Proof

CASE 1

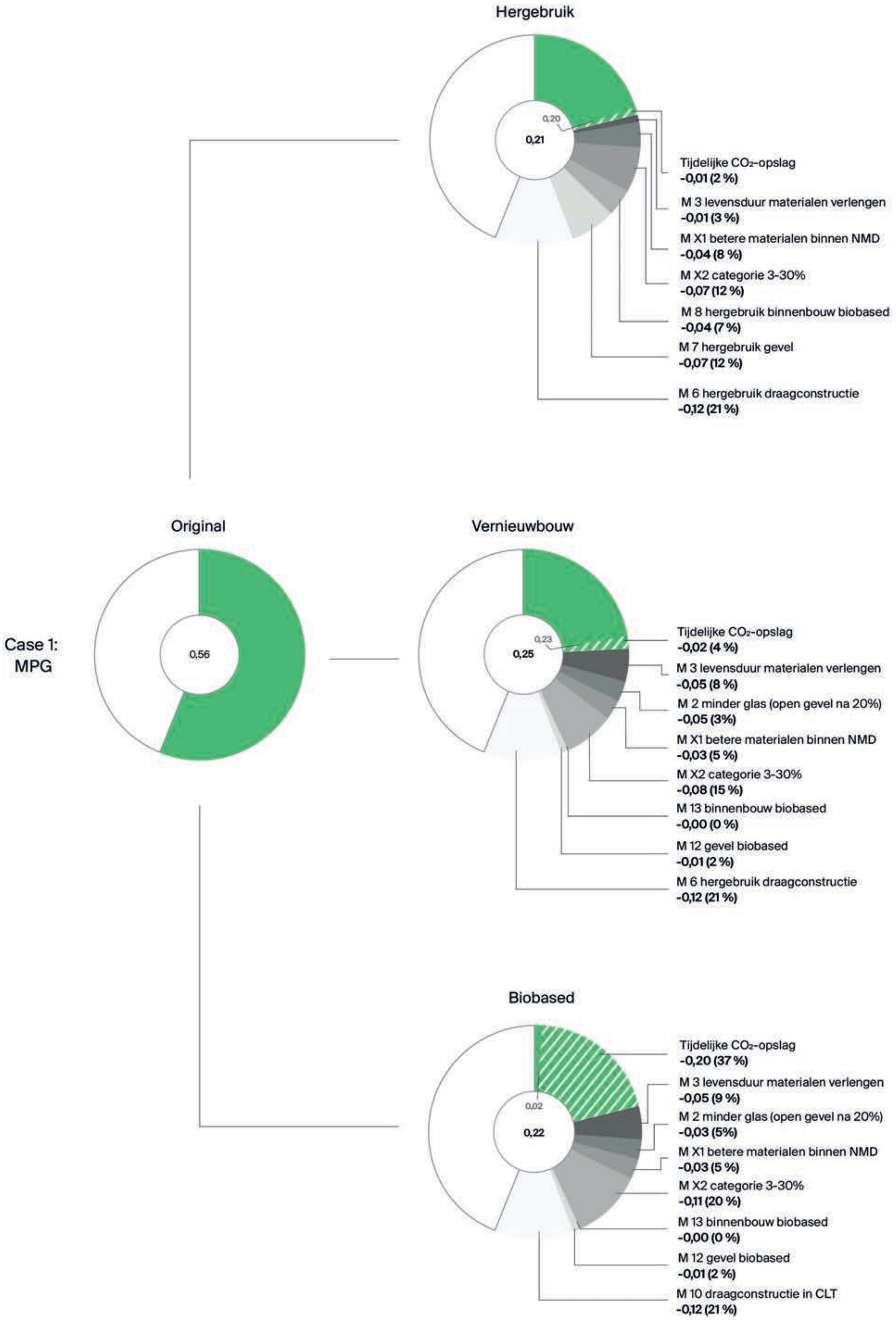


FIGURE 43

MPG Steps to Zero Case 1

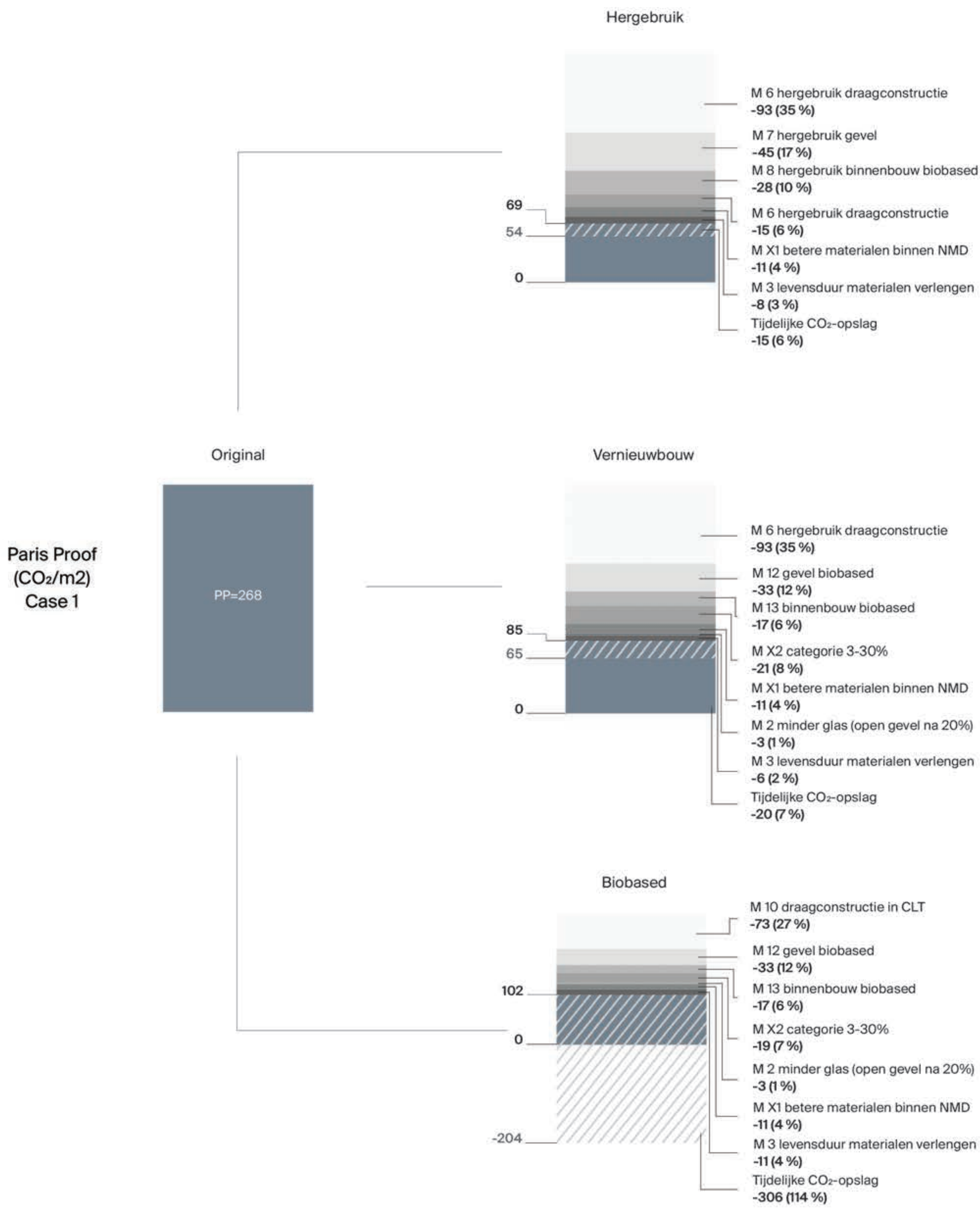


FIGURE 44

Paris Proof Steps to Zero Case 1

CASE 2

FIGURE 45

MPG Steps to Zero Case 2

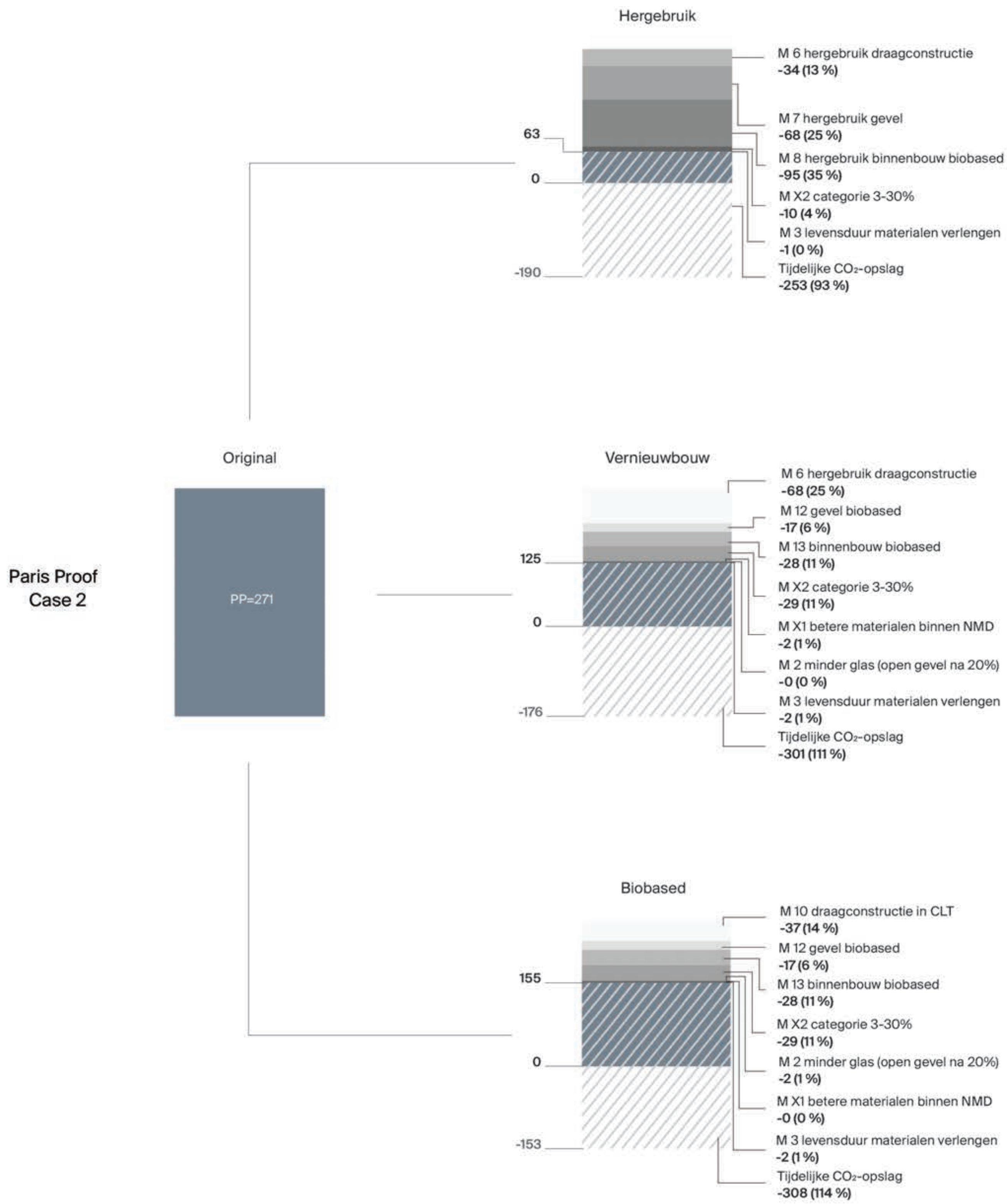


FIGURE 46

Paris Proof Steps to Zero Case 2

CASE 3

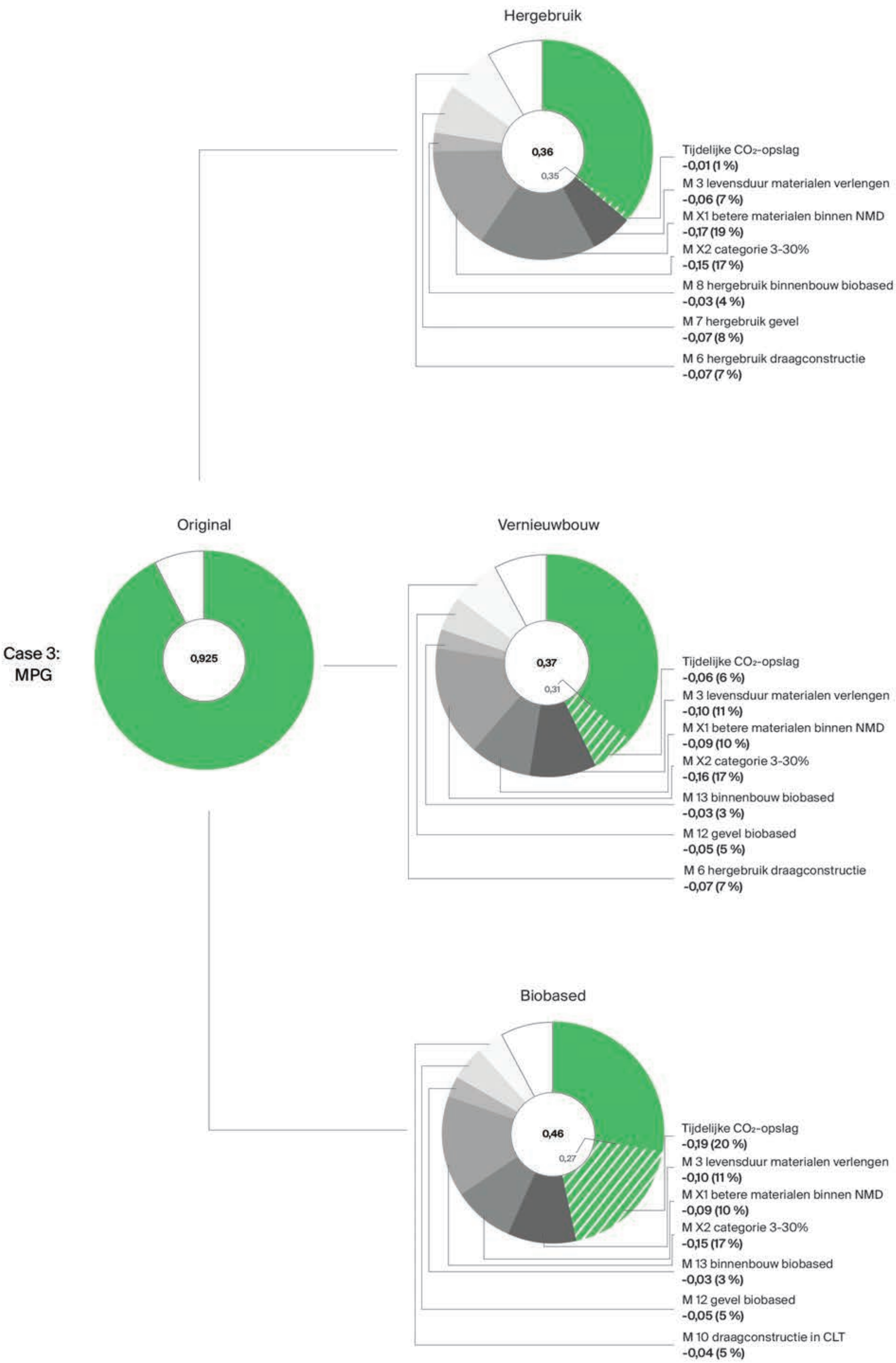


FIGURE 47

MPG Steps to Zero Case 3

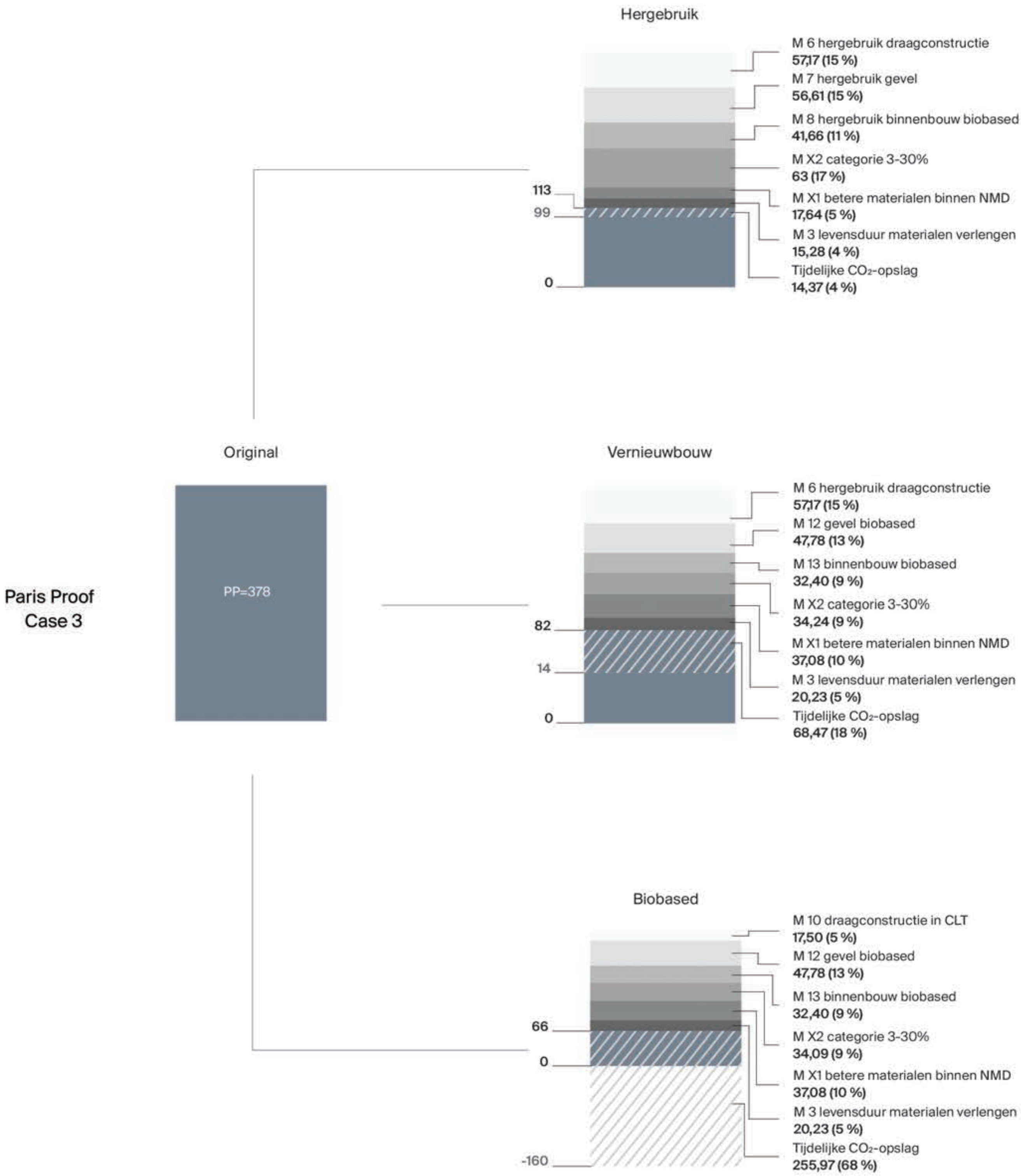


FIGURE 48

Paris Proof Steps to Zero Case 3

CASE 4

FIGURE 49
MPG Steps to Zero Case 3

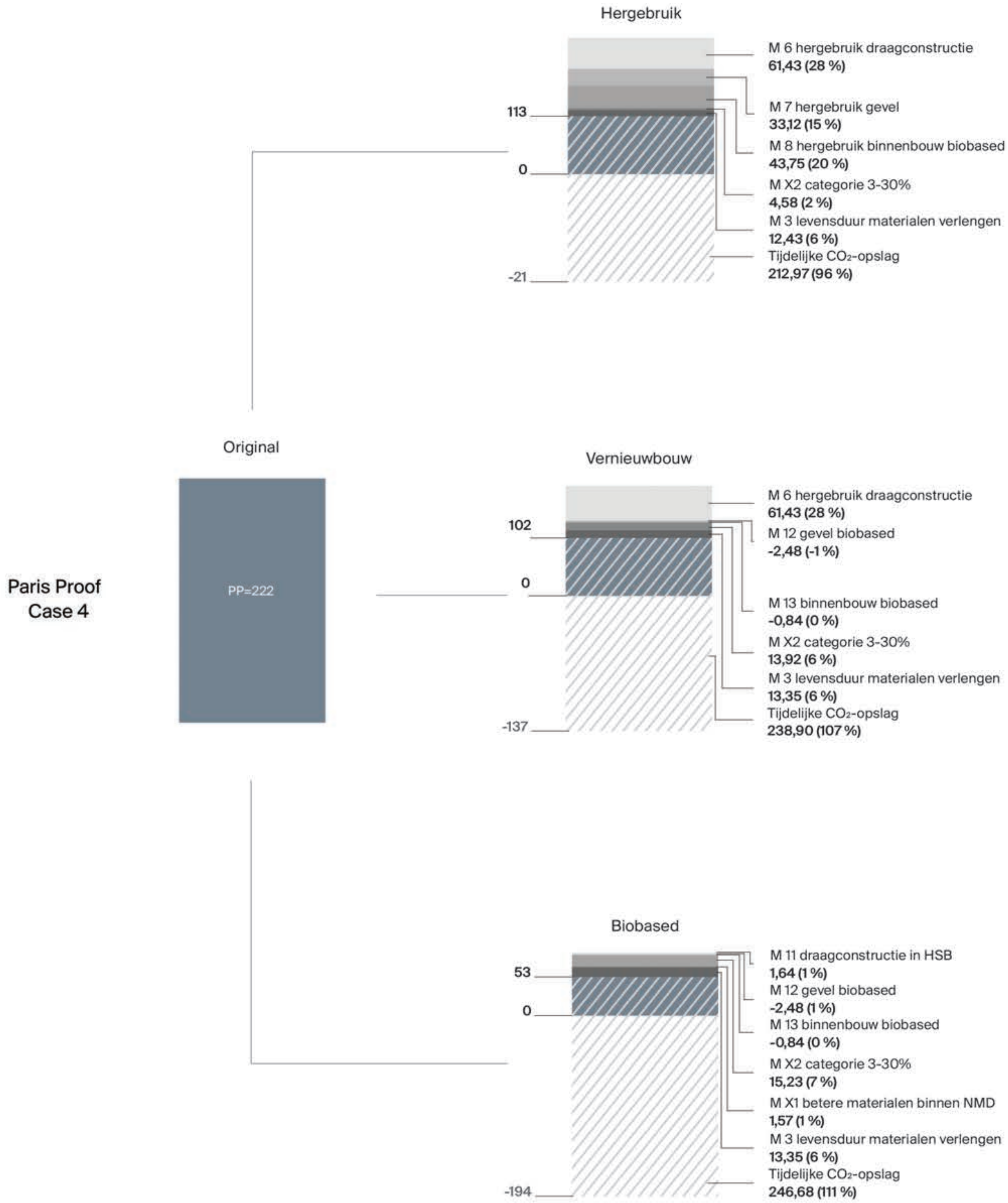


FIGURE 50
Paris Proof Steps to Zero Case 4

GEMIDDELD

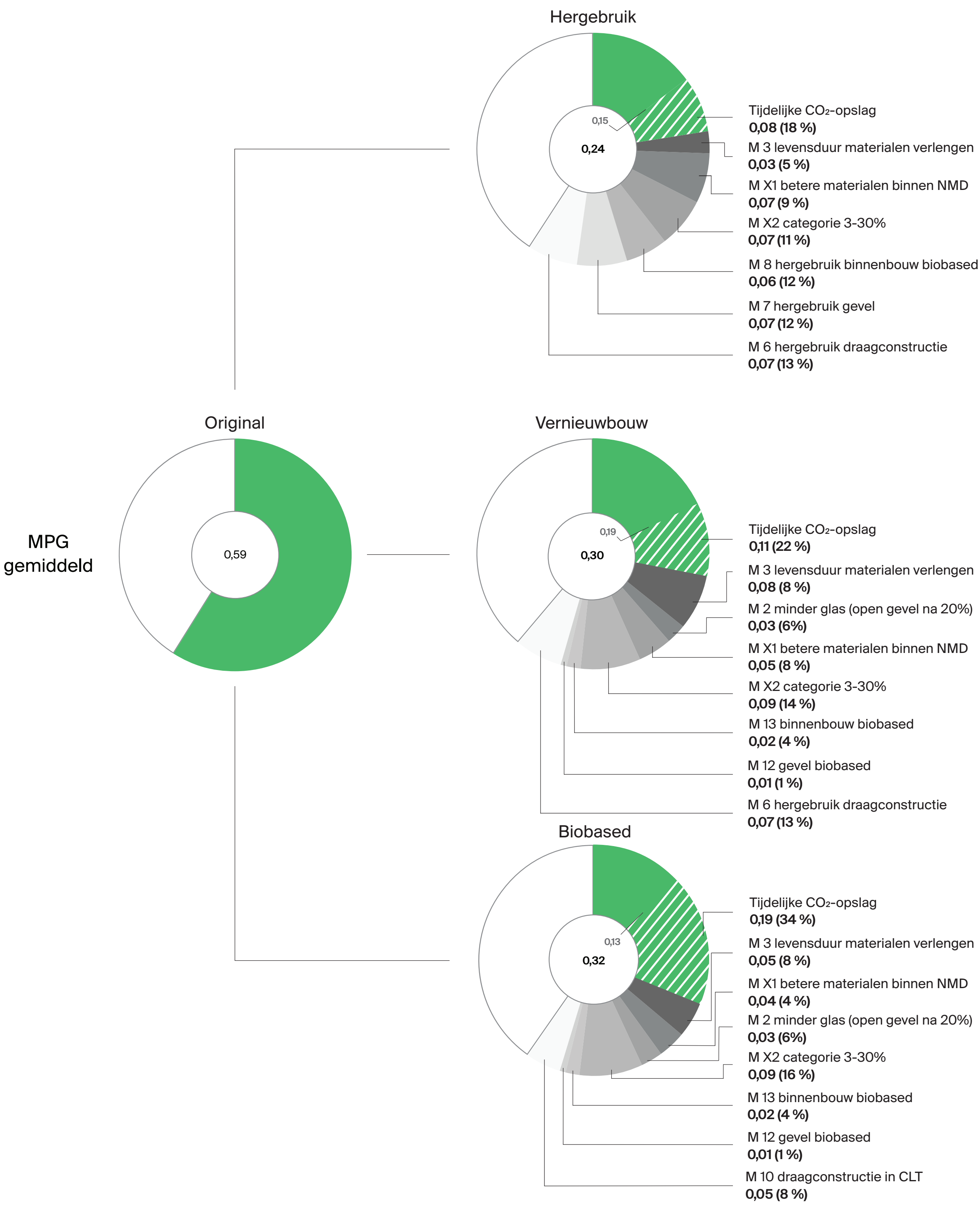


FIGURE 51

Average results MPG
Steps to Zero

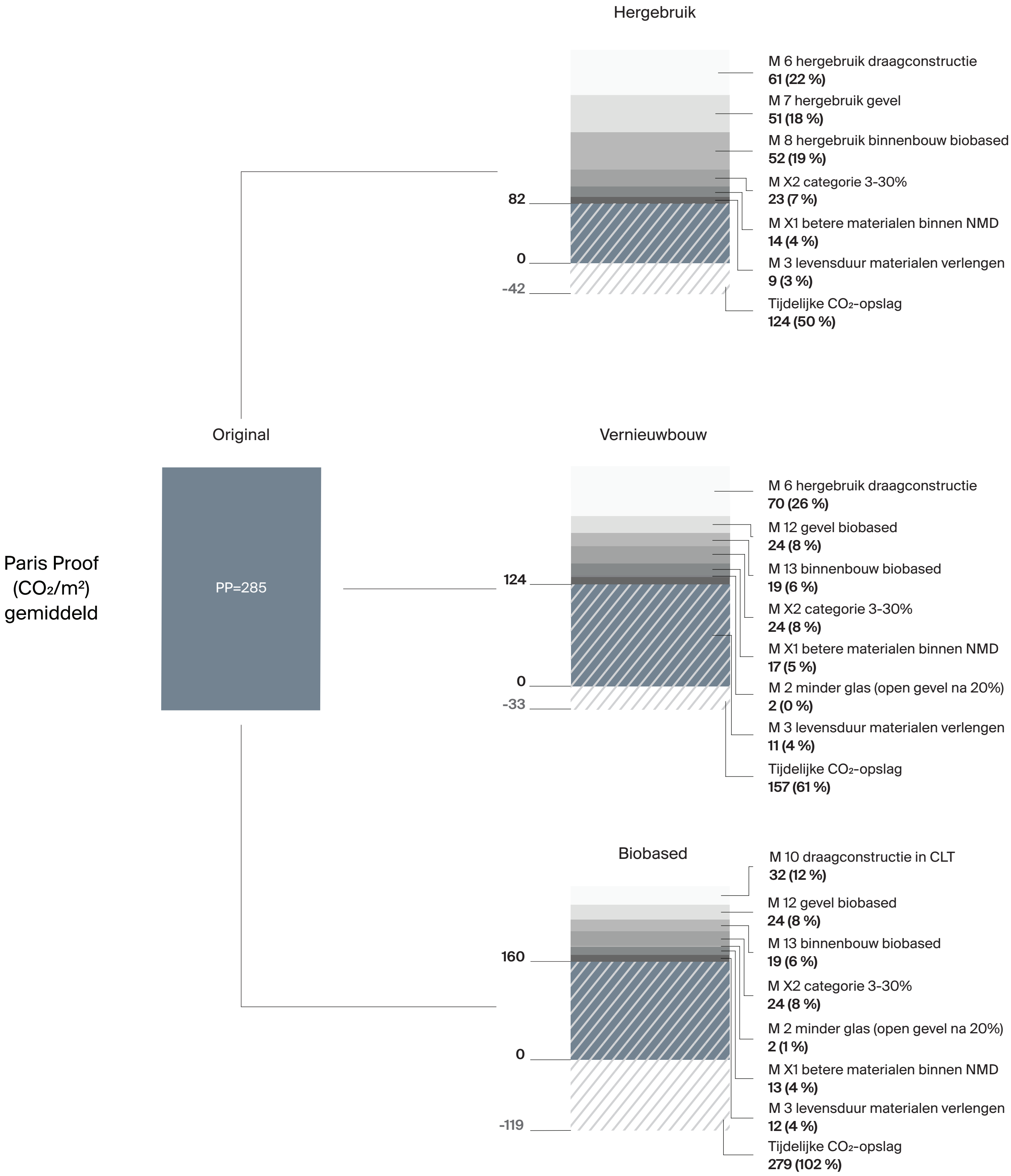


FIGURE 52

Average results PP Steps to Zero

CHAPTER 4 CONCLUSIONS

Important note: In the study, the measures were simplified. In practice, a building is integrally designed with the right materials in the right place. The simple replacement of materials will often be accompanied by additional measures, with extra environmental impact, to achieve a good quality building.

Our conclusions based on this study are:

Based on current data, biobased materials do not necessarily score better in MPG calculations, while other studies have actually shown that there is a lot of profit to be made with biobased materials because the MKI is generally low. But that depends on the individual product. Also, in the processing of biobased materials many activities still take place that are also not always energy efficient. Think of the drying of CLT wood or transport over long distances. Only if CO_2 storage could be included would it pay off. The basis for such calculations has been laid with the new EN1508-A2, which shows biogenic carbon sequestered in the EPD per phase.

Reuse, on the other hand, has great impact, while in practice it is still very difficult. Often some elements can be reused, but a whole structure or facade is not yet realistic. The potential is great, but requires a transition to standardized construction, digitalization and careful disassembly. The good score now is also related to the method of calculation, namely the application of a flat rate factor of 0.2. It is clear that the reasons for this is the complexity of really checking the impact of reuse. While it makes intuitive sense, it also opens doors for abuse if, for example, actually new materials are defined as reused when they would otherwise be destroyed (e.g., incorrectly produced window frames). This is where material passports and Carbon Accounting, i.e. tracking of emissions and their amortization, could be a solution direction.

Technical systems are an important thing to consider. Here, through reparability, adaptability and detachability, life spans could be significantly extended, without necessarily sacrificing efficiency (which, incidentally, is often a paper reality).

At all events, design remains one of the most important levers. A well-designed building requires little energy because, for example, the form factor is already advantageous. Building with wood requires detailing that does justice to the material. This can prevent the use of toxic treatments and also bring down the MPG. Design also affects material efficiency, sizing, and opportunities for replacement and efficient maintenance. Finally, well-designed buildings last longer. Extending the life span leads to reduce the environmental impact, which does not yet include the impact of new construction avoided.

The same applies to urban planning. Living and building in a compact but qualitative way is possible and saves multiple times. A better ratio of shell to surface area means that a building needs less infrastructure, that the loss area is smaller and thus, for example, has to meet lower insulation requirements.

Finally, more data will also lead to better informed decisions in the choice of materials and design. One step in this direction is to make the EPDs used in the context of the NMD public and transparent. This will enable better assessment of similar products as well, for example if the transport distance or energy source of a plant is different.

Moreover, the available information on reused materials will also stimulate a larger market for reused building materials as supply and demand can be better matched and there is more insight into technical performance. This mainly requires standardization, as the basis has been laid, for example through now widespread use of BIM.

The effects of measures are often comparable in the two calculation methods MPG and Paris Proof, but there are also important differences. Particularly if biogenic CO_2 storage is included.

Nowadays, this is only the case for materials whose EPD has been drawn up according to the new EN 15804 +A2. If the calculation is based on an MPG calculation, then either all materials should be calculated according to the new standard, or the biogenic CO_2 storage should be added manually (as also done in this report). It is then important, however, that possible newer EPDs are sorted out first.

Because Paris Proof deliberately focuses on CO_2 and also on a much shorter term, materials with a short life cycle (such as building systems and glass) have much less negative impact. Also, other environmental aspects such as toxicity and biodiversity loss are not included, which is at least as big a threat as climate change. In our opinion, the calculation method Paris Proof is therefore complementary to the MPG and cannot replace it.

The role of a general increase in the sustainability of the energy network continues to be important. On the one hand in the production of building materials and transport. Generally available sustainable energy will also reduce the CO_2 emissions of products (even steel). We have also seen that external energy supply is an important aspect in the environmental performance of buildings. Particularly because fewer PV panels will then be needed to generate the operational energy of a building.

At the same time, generating renewable energy takes up a lot of space (on land or at sea), which in turn is at the expense of nature and biodiversity. It therefore remains relevant to build in an energy-efficient way and to use low-energy materials.

For biobased buildings, besides the possibility of temporary CO_2 storage, the materials come from renewable sources and at the end of their life should ideally also be biodegradable, so truly ‚Cradle to Cradle'. Moreover, they often provide a healthier living environment. However, building and designing with biobased materials requires a careful and materially just form of detailing. Otherwise, many thermal or chemical processes must be used to artificially preserve the materials, which in turn cancels out the positive effect.

And then the key question: Is it possible to create a building with 0 (zero) impact?

Of course not. Because everything we do has an impact somewhere. We can and must try to keep it as low as possible. And at the same time, we have to look for positive effects that we can achieve. So that could be temporary CO_2 storage, which we use to help make sustainable forest management and other bio-based agriculture attractive, but it could also be reducing the need for mobility or increasing biodiversity and nature improvement. If we then add that together, it is absolutely possible to not only end up at zero but even make a net positive contribution.

SOURCES

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

Barbour, E., Davila, C.C., Gupta, S. et al (2019). Planning for sustainable cities by estimating building occupancy with mobile phones. Nat Commun 10, 3736. https://doi.org/10.1038/s41467-019-11685-w

Röck M., et al. (2020). Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation, Applied Energy.

Bijleveld M. (2021) Kennisnotitie Circulair Zuid Holland Biobased bouwen. CE Delft, Delft.

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

Churkina, G., Organschi, A., Reyer, C.P.O. et al. Buildings as a global carbon sink. Nat Sustain 3, 269–276 (2020). https://doi.org/10.1038/s41893-019-0462-4

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

DGBC (2021): Position Paper Whole Life Carbon, versie 1.1

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

Fraanje, P. et al. TNO, SGS, LBP Sight, NIBE (2021). Onderzoek nadere duiding van de baten en lasten in module D van de Bepalingsmethode milieuprestatie bouwwerken. TNO R11800, Utrecht.

Friant M. C., Vermeulen W.J.V., Salomone R. (2020) A typology of circular economy discourses: Navigating the diverse visions of a contested paradigm. Resources, Conservation and Recycling 161: 104917. https://doi.org/10.1016/j.resconrec.2020.104917

Hu, Ming. (2021). Beyond Operational Energy Efficiency: A Balanced Sustainability Index from a Life Cycle Consideration, Sustainability 13, no. 20: 11263. https://doi.org/10.3390/su132011263

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

IPCC, 2022: Summary for Policymakers. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.001

International Resource Panel (IRP) (2020). Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future. Hertwich, E., Lifset, R., Pauliuk, S., Heeren, N. A report of the International Resource Panel. United Nations Environment Programme, Nairobi, Kenya. https://www.resourcepanel.org/reports/resource-efficiency-and-climate-change

KAW (2020). Ruimte zat in de stad. https://www.kaw.nl/projecten/onderzoek-ruimte-zat-corporatievastgoed/

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

Le Den X, Steinmann J, Röck M, Birgisdottir H, Horup L H, Tozan B, Sørensen A. Towards EU embodied carbon benchmarks for buildings - Summary report, 2022, https://doi.org/10.5281/zenodo.6397514

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

Nagler, F., (2012). Voordracht “Einfach Bauen”, 29. Sep. 2012. INSERT STUDIE Link

Platformcb23. (2021). Circulair ontwerpen: Werkafspraken voor een circulaire bouw. https://platformcb23.nl (benaderd 18/05/2022)

Pomponi, F. et al. (2020). Buildings as a Global Carbon Sink? A Reality Check on Feasibility Limits, Sciencedirect. https://doi.org/10.1016/j.oneear.2020.07.018

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

Renger B. C., Janis L. Birkeland & David J. Midmore (2015) Net-positive building carbon sequestration, Building Research & Information, 43:1, 11-24, DOI: 10.1080/09613218.2015.961001

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

Stephan A., et al. (2022). Towards a multiscale framework for modeling and improving the life cycle environmental performance of built stocks.

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

Spitsbaard M en Leeuwwen M.v. (2021). Paris Proof Embodied Carbon – Rekenprotocol. https://www.dgbc.nl/publicaties/de-berekening-achter-paris-proof-materiaalgebonden-emissies-49

Sve Rokseth L. En Manum B. (2021). Patterns of Dwelling Types, Location, and Spaciousness of Living in Norway. Critical Remarks on the Practice of Measuring Energy Performance per Floor Area Only. Buildings 11 (9): 394. DOI:10.3390/buildings11090394

United Nations Environment Programme (2021). 2021 Global Status Report for Buildings and Construction: Towards a Zero emission, Efficient and Resilient Buildings and Construction Sector. Nairobi. https://globalabc.org/resources/publications/2021-global-status-report-buildings-and-construction

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

Werner, F., Taverna, R., Hofer, P. et al (2006). Greenhouse Gas Dynamics of an Increased Use of Wood in Buildings in Switzerland. Climatic Change 74, 319–347. https://doi.org/10.1007/s10584-006-0427-2

W/E adviseurs (2016). TKI KIEM – Kwaliteit door Integrale evaluatie van Energie- en Milieuprestaties van gebouwen. TKIGB01016.

Zhong, X., Hu, M., Deetman, S. et al (2021). Global greenhouse gas emissions from residential and commercial building materials and mitigation strategies to 2060. Nat Commun 12, 6126. https://doi.org/10.1038/s41467-021-26212-z

WEBPAGES

https://ethz.ch/en/news-and-events/eth-news/news/2019/07/how-trees-could-save-the-climate.html (18/05/2022)

https://www.vpro.nl/programmas/tegenlicht/lees/artikelen/2020/follow-up-hennep.html (18/05/2022)

EPDS

2020-01-14_Scheuten-Glas-Nederland-Iso-Glass-Unit-Venlo_M-EPD_MIG

MR-102.1_Trina-Solar_EPDTSM-DE15M-II_TSM-DE17M-II-0PV-Backsheet-Panels

MRPI-EPD_X-LAM -Cross laminated timber-German market_FINAL

Stora Enso EPD CLT 2021

HR++Islatieglas in aluminium frame (NIBE Database)