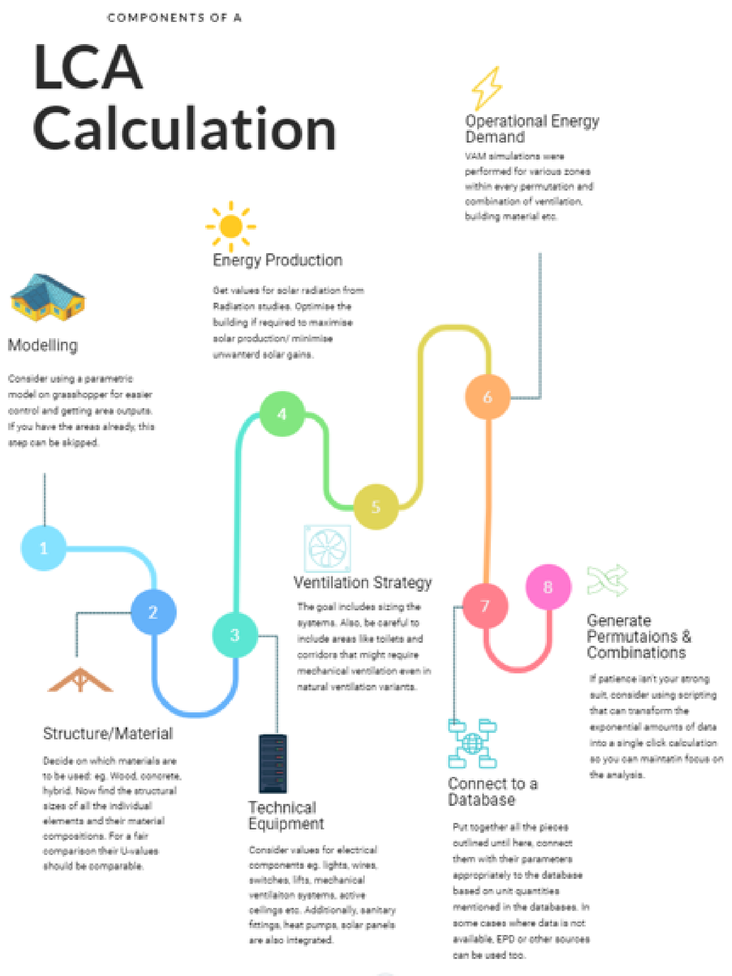
The carbon-balancing potential of wood- or concrete structure office buildings, based on embodied and operational carbon footprint

Life Cycle Analysis



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1. Abstract

To prevent global temperatures from rising above 2°C to avoid, irreversible climate change, global anthropogenic emissions must be reduced, and fossil fuels must be phased out as soon as possible. The built environment accounts for a major share of carbon emissions. This can be attributed to both building operations and building construction. So far, a lot of effort and studies have been done to address consumption for building operation. Since not many studies have a holistic view of the lifecycle in total combining construction and operation phases, this paper addresses this question. This study evaluates the embodied carbon over the full life cycle of a typical office building in Germany. For determining the building configuration with the least impact, permutations and combinations of the typologies along with factors like construction material choice between wooden construction or concrete and the number of floors of the building were considered. Further variations are ventilation strategies, energy supply strategies, along with considerations for decarbonization of the public electricity grid. For the study, embodied carbon in construction, carbon emissions during the operation phase including emissions from the user-related energy demands have been considered with a focus on balancing the carbon emission through on-site renewable energy production.

Keywords: Embodied carbon, carbon neutrality, carbon-neutral, life cycle, life cycle analysis, LCA, operational carbon, wood vs concrete, on-site energy, production, embodied carbon office, construction carbon.

2. Construction Phase

2.1. Introduction

The research began with the search for the answer to the question: How many floors could be built in a new office building located in Germany while achieving carbon neutrality in the next 20 years? What are the possibilities? To prevent global temperatures from rising above 2°C to avoid, irreversible climate change, the building industry has a significant role to play.

The operational energy consumptions of the buildings have been of primary focus over past several years. The energy demands have been significanly lowered and the building envelope has been optimized for efficiency. The next step to curb environmental impact would be to reduce the embodied carbon in building materials along with the operational energy. It also involves strategies for meeting the energy demand through low carbon sources.

2.1.1. What is LCA?

Life-cycle assessment or LCA (also known as life-cycle analysis) is a methodology for assessing environmental impacts associated with all the stages of the life-cycle of a product, process, or service. For instance, in the case of a building, environmental impacts are assessed from raw material extraction and processing (cradle), through the building's construction, operation and renovation, to the recycling or final disposal of the materials composing it (grave).

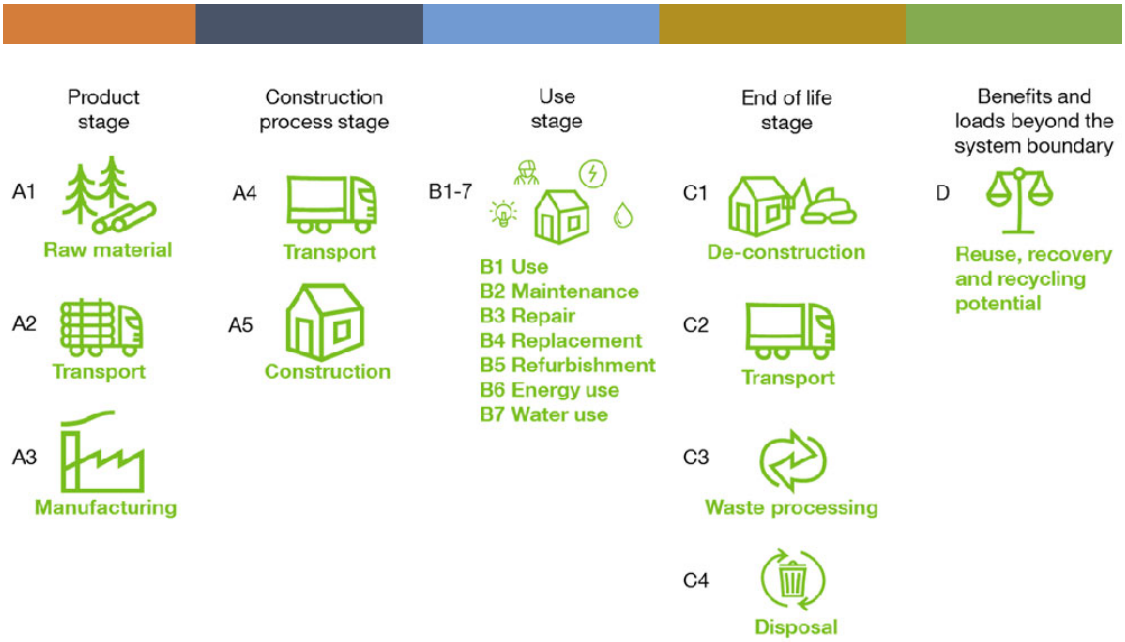

Fig. 1.1: Phases of a Life Cycle Assessment.

2.1.2. Benefits of LCA

The method of life cycle assessment is one of the most effective ways to find out the impact on the environment resulting from construction methods, energy concepts, components, and products – essentially, all aspects of planning that take place in the construction of a new building, a renovation or a modernisation project.

The two substantial advantages of a life cycle assessment are:

1. It helps those in charge of a project to make better informed decisions in the planning and implementation process.

2. It stimulates innovation by highlighting opportunities to create products and buildings with higher environmental quality and better efficiency

Life cycle assessments help building contractors:

Good LCA results can be employed in communication with their clients and official bodies as well as for the purposes of sustainability certification, and can be put forward as a argument when seeking approval for grants.

Life cycle assessments help architects and specialist designers:

The knowledge of the environmental impacts that have resulted from the manufacturing of components, the environmental impacts that result from ongoing operation and the environmental impacts and potential that can result from possible recycling at the end of the useful life facilitates the planning of buildings that are more environmentally friendly.

2.1.3. Steps for finding out life cycle assessment of a building.

1. Identify all masses of the components used or planned for use in the building (in the case of renovations, only the components used in the renovation project are

required).

2. Allocate typical replacement cycles for the components used or planned for use in the building from reference lists.

3. List energy consumption and energy sources for the (planned) ongoing operation using the energy certificate or calculations of energy requirements.

4. Combine the masses and energy flows with LCA data from the ÖKOBAUDAT database(fig 1.2) or EPDs.

5. Generate totals for all selected LCA indicators.

6. Prepare and evaluate the results of the calculations for target groups.

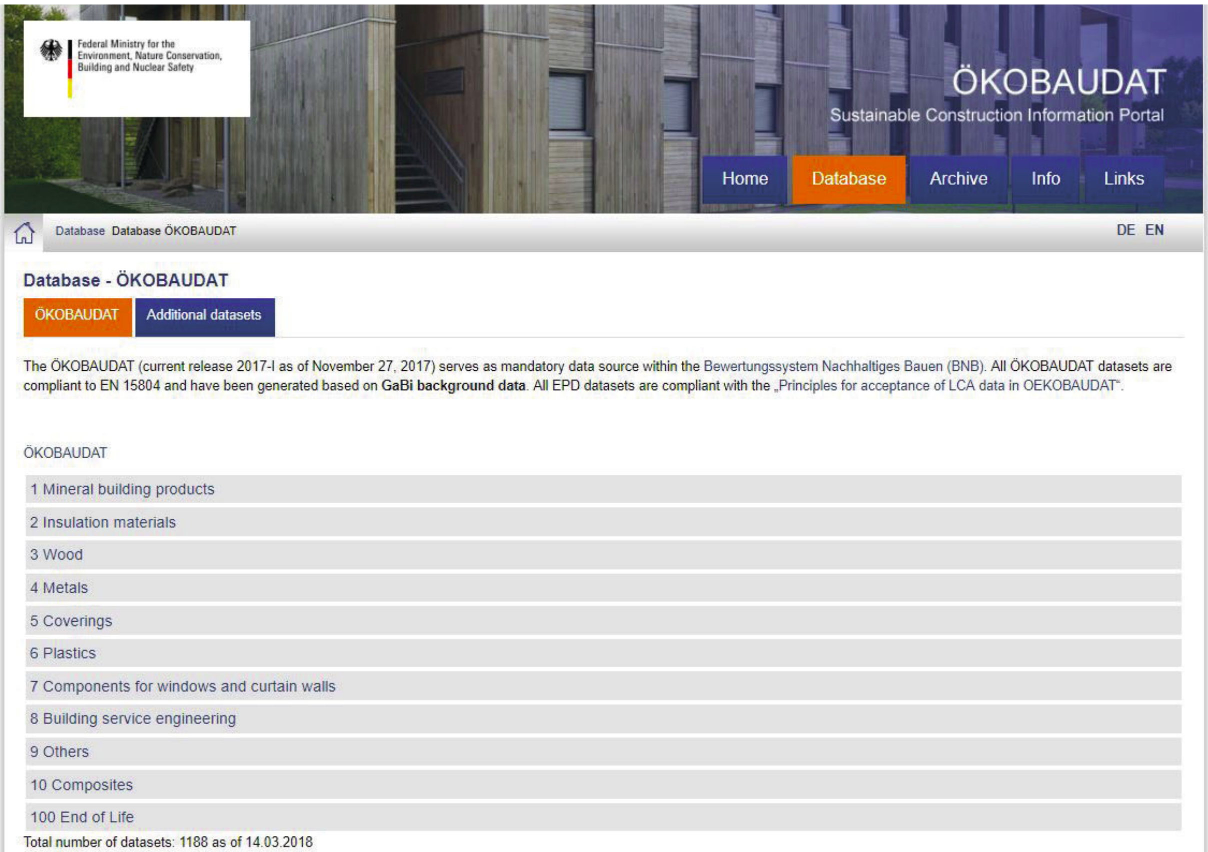

Fig. 1.2: The ÖKOBAUDAT database with life cycle assessment data for the construction sector

Source: http://oekobaudat.de/datenbank/browser-oekobaudat.html

2.1.4. Architecture and Building Materials

This study consists of 384 variants. The architecture of a typical office building was modelled parametrically with a design from Bernd Liebel Architects. It is a typical office space with different floor levels and a basement.

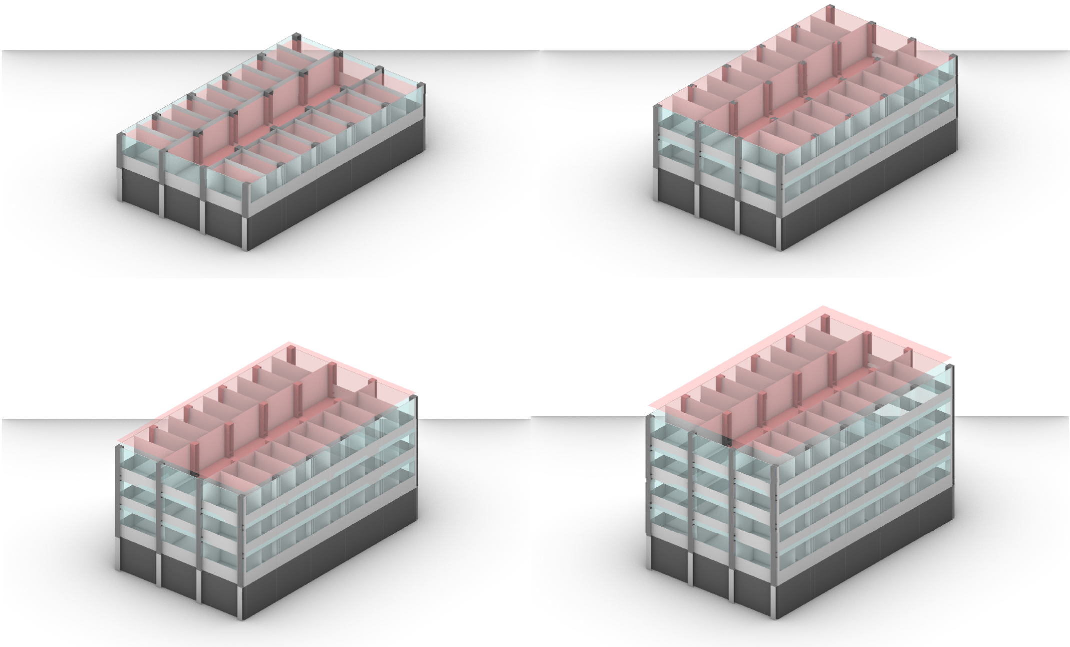

Fig. 1: A parametric architecture model was developed on Grasshopper and Rhino to allow easy calculation of material quantities as an input for the LCA study.

2.1.5. Structure/Materials

To determine the carbon impact between buildings with various numbers of floors, we need to understand the correlation with structural sizes of elements. This was done with parametric input from Arne Künstler of Imagine Structure. (fig.2) On the left is an example of a 6-storey concrete building with a concrete basement and the corresponding structural sizes for columns and slab thicknesses. Corresponding image on right shows the same information for a wooden construction.

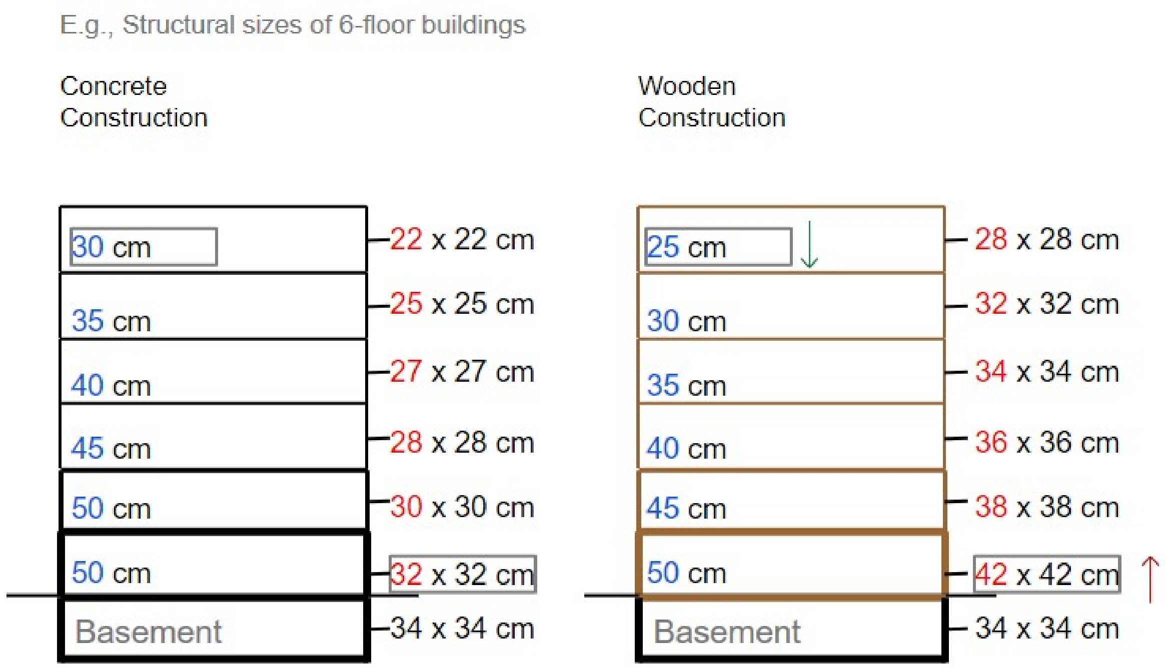

Fig. 2: Changing column sizes and slab thicknesses based on material and floor height.

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2.1.6. Material Compositions

Along with structural sizes, material compositions of elements like insulation vary between wooden and concrete construction. The assemblies for walls/roof/floor plate etc. were designed in a way that they have similar u-values.

Fig. 3.1: Material composition for an external concrete value.U-value= 0.189 W/m²

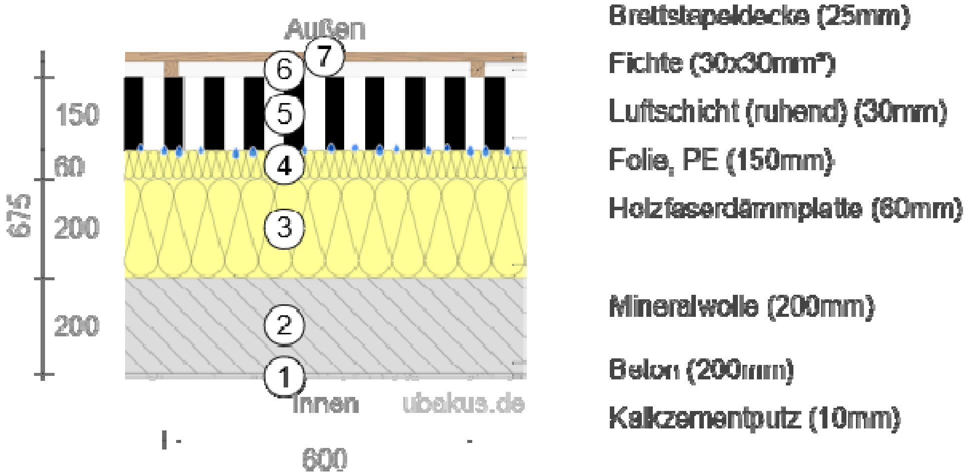
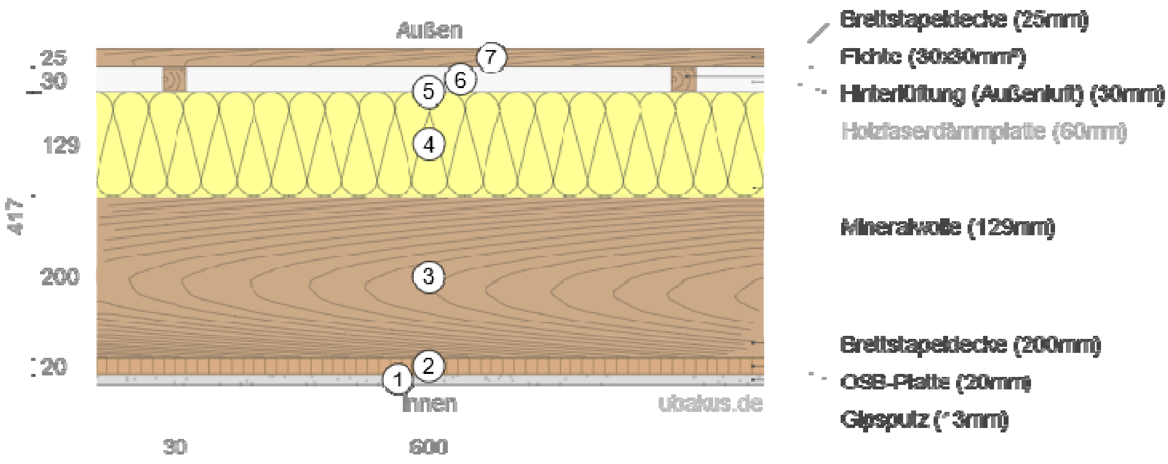


Fig. 3.2: Material composition for an external wood value.U-value= 0.187 W/m²



We define 15 build-ups for walls, floors, external walls etc. The materials were then scaled up to the entire building.

2.2. Technical Equipment

Technical equipment consists of a large proportion of the total embodied CO2 of a typical office building in Germany. These range from the cables and wires used in the offices to the heat pumps and geothermal systems. The resulting carbon balance will help in making decisions on the return on carbon investment of certain systems over the life cycle of the buildings.

Difficulties: Data on technical systems is difficult to find. There are various options available and there needs to be strong technical research to select the appropriate systems for the building and size them correctly. Certain data from Ökobaudat showed surprisingly low values that could not be explained. Hence, in the case of electrical components, mechanical ventilation and sanitaryware; data from KBOB was used instead. Ökobadat was also missing data on Active ceilings which was then incorporated from an EPD available from the manufacturer.

In earlier studies, the assumption of technical equipment = 30% of the total embodied carbon of building at the construction phase was used. One problem with this approach is that wooden buildings have negative embodied carbon at construction phase. 30% of that would be a negative number that does not make sense. Secondly, the results show: e.g., for concrete construction, 4 levels where the embodied carbon is 228 kgCO2/m2, Technical Systems account for up to 60-80% of Total Embodied Carbon.

The components were calculated based on inputs from norms or inputs from experts. The systems were calculated based on load curves from thermal simulations. They include:

Structure Class	Name of the Element	Phase A	Phase B	Phase C	Phase D
Technical Equipment					
	Electrical Components (KBOB)	22	0	1	0
	Heat Pump	6	0	0	0
	Active Ceiling (Heating/cooling)	23	0	0	-13
	Mechanical Ventilation-Offices (KBOB)	19	0	1	0
	Mechanical Ventilation-Internal Spaces (KBOB)	10.5		0	
	Sanitary (KBOB)	3	0	1	0
	Lift	2	0	0	-1
	PV Panels	131	0	5	-16
	Energy Distribution (KBOB)	7	0	1	0

Fig. 3.2: kgCO2 eq/m² values for each technical element

2.3. On-site Energy Production

For understanding the impact of the building once it is built, the operational energy balance is one of the biggest indicators. The heating, cooling and electricity demands of the building, as well as the sources of the energy, determine the final balance. On-site energy production is favoured with photovoltaic panels on the roof as well as façade. Even though PV panels initially add to the embodied carbon of the building, they balance out by avoiding emissions from using the electricity grid mix.

Optimization studies were run on grasshopper using Ladybug Tools to maximize the PV production for the building.

2.3.1. Boundary Conditions

The study location was chosen as Stuttgart due to its horizontal annual radiation value being an average of extreme north and south locations of Germany. The assumptions for other important conditions are stated below along with a table indicating final areas:

- Orientation of the building was 45° N
- PV coverage: Roof 80%, Façade 40% (window-to-wall ratio 60%)
- PV efficiency: 20%
- Study location: Stuttgart, Germany (1093 kWh/(m²/a))

No. of Floors	2	3	4	5	6
Floor Area	776 m²	1164 m²	1552 m²	1940 m²	119 m²
PV Roof Area	310 m²	310 m²	310 m²	310 m²	310 m²
PV Façade Area	238 m²	357 m²	476 m²	595 m²	714 m²

2.3.2. Photovoltaic Production

Photovoltaic production is on-site renewable energy production that helps in avoiding carbon emissions by avoiding the use of energy from the electricity grid. However, these panels have embodied carbon at the time of production.

The panels need to be replaced every 25-30 years, however, we cannot predict the embodied carbon of panels that will be manufactured in 2050. Hence the study is restricted to 20 years.

The values of total production go on increasing with an increase in the number of floors as the façade panels produce proportionately more. However, looking at the production per meter square of floor area, we see a decline in production with an increase in the building height as the production from façade is not as high as the roof.

The graph fig(6.1) shows the energy production specific to the gross floor area in kWh/m². The graph fig(6.2) shows total energy production in MWh for different floor numbers.

No. of Floors	2	3	4	5	6

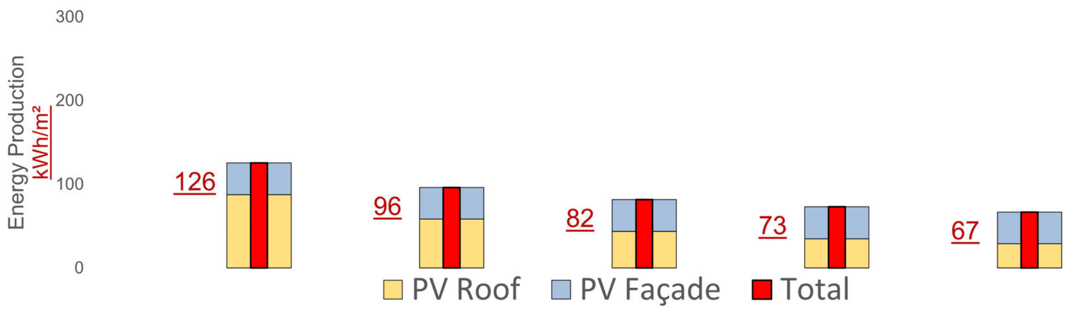


Fig. 6.1: Specific Energy production with PV roof and Façade (kWh/m²)

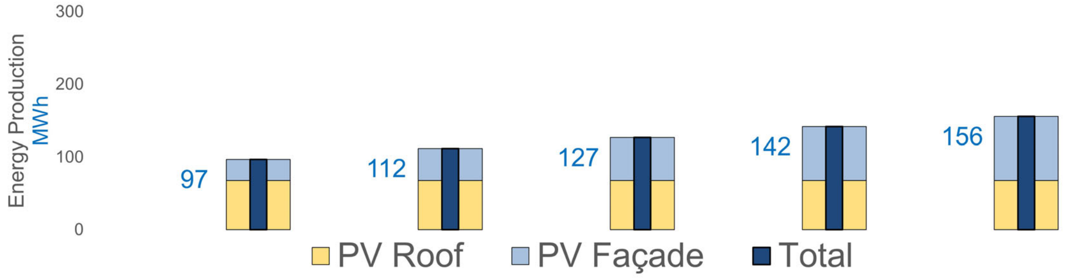


Fig. 6.2: Total Energy production with PV roof and Façade (MWh²)

2.4. Climate and Energy Concept

2.4.1. Facade Performance

- External shading with light deflection is used on windows with a Shading factor of 75%.
- Window to wall area in the study is 60% glass and 40% façade area.
- High performance Triple glazing windows are considered for the study.

2.4.2. Natural ventilation

Natural ventilation consists of the following:

- Chilled/ heated ceiling
- Geothermal piles and heat pump

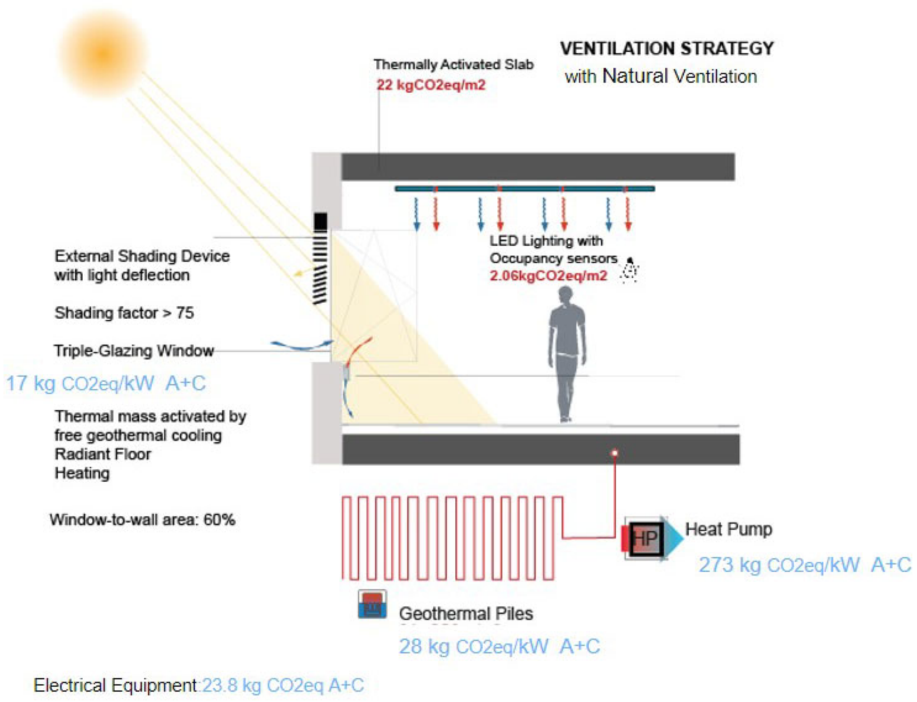


Fig. 6: Natural ventilation climate and energy concept

2.4.3. Mechanical ventilation

Systems need to be sized according to the schedule, occupancy and number of users. Mechanical ventilation consists of the following:

- Decentralized ventilation with heat recovery system.
- Chilled/ heated ceiling
- Geothermal piles and heat pump

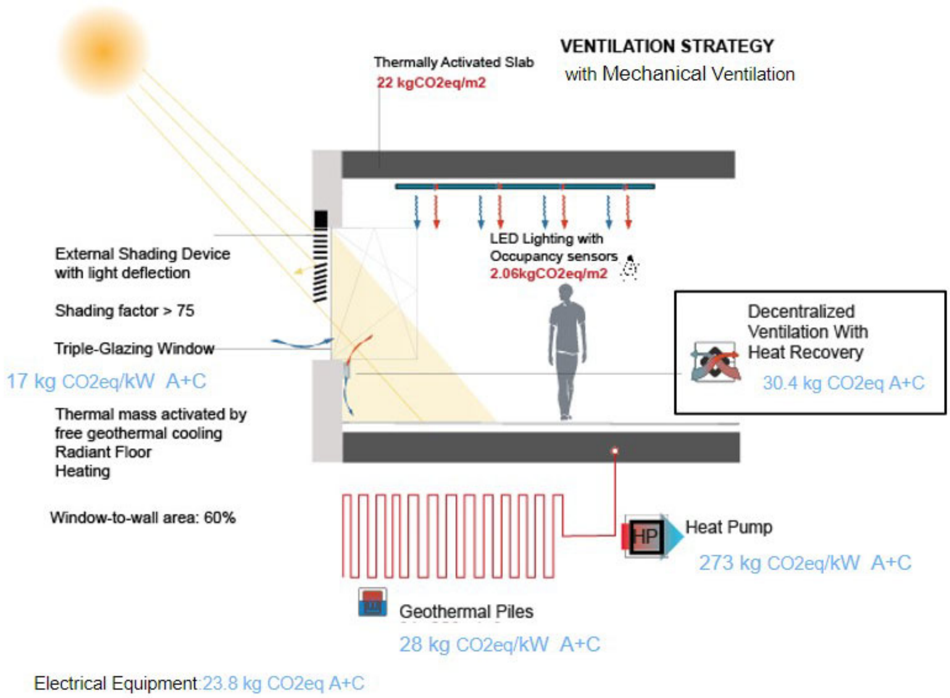


Fig. 7: Mechanical ventilation climate and energy concept

3. Operational Energy

For understanding the impact of the building once it is built, the operational energy balance is one of the biggest indicators. The heating, cooling and electricity demands of the building, as well as the sources of the energy, determine the final balance. On-site energy production is favoured with photovoltaic panels on the roof as well as façade.

The calculation of these numbers required thermal simulations which were run using TRNSYS. The challenge faced here is a large number of variants in the study as well as the equalization of the wooden/concrete variants to be fair in terms of U-values.

The operational energy demands did not very much between the wooden and concrete variants. The main difference is due to the thermal mass properties of the materials.

The PV panels produce more electricity as compared to the energy demand. We observe that (Fig. 8) in the case of a building with PV panels on the roof and façade, the net energy balance is negative, and we are producing more than consumption but this trend decreases with the increasing number of floors.

No. of Floors	2	3	4	5	6

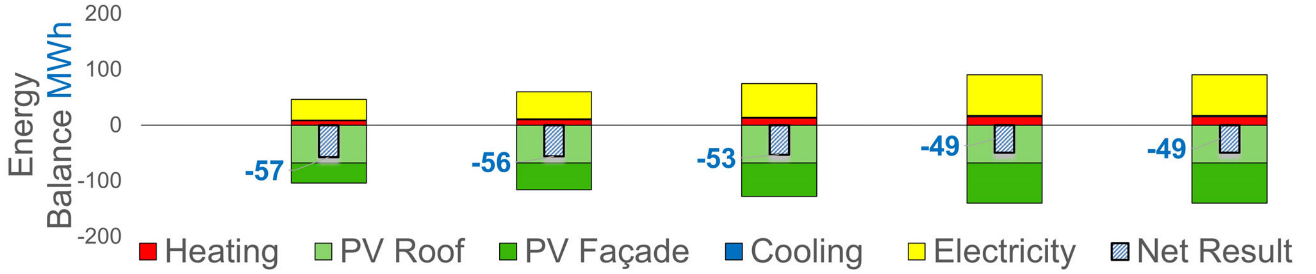


Fig. 8: Energy balance for different floor heights.

4. Carbon Life Cycle Analysis

4.1. Variants

Permutations and combinations of the boundary conditions lead to a total of 384 variants. The reason we chose 20 years as a span is that the aim is to bring down carbon emissions by 2040. Additionally, renovation numbers for materials after 20 years are unknown. E.g., we cannot predict the embodied carbon in solar panels manufactured 25 years from now on.

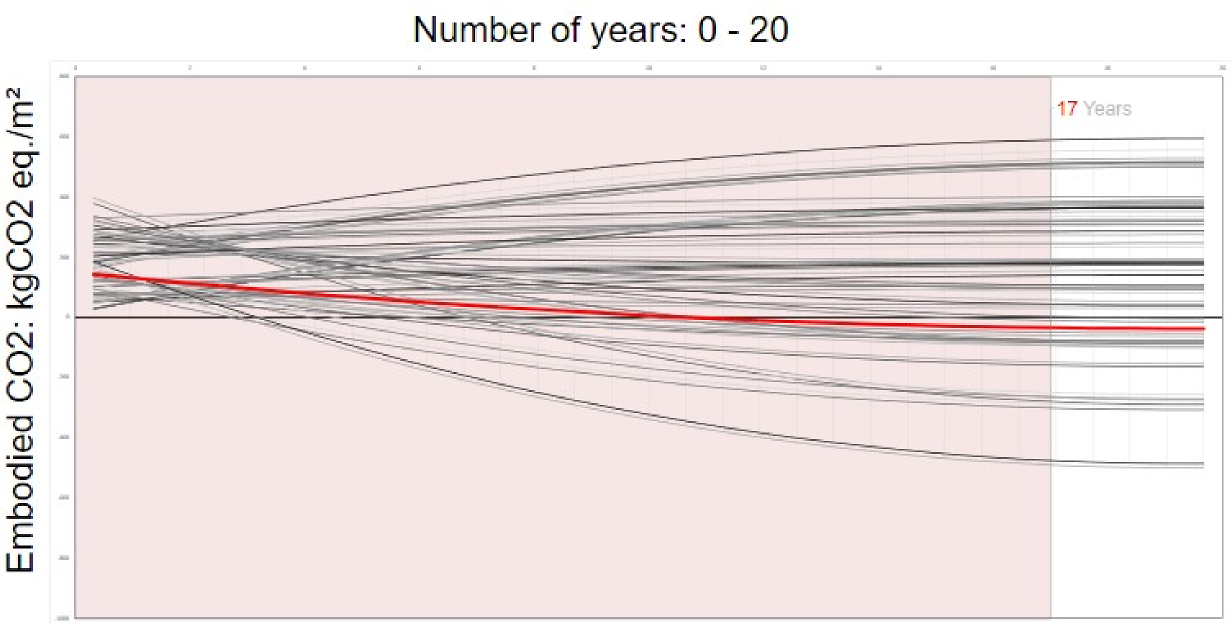


Fig. 9: Permutations and combinations of the study based on the parameters mentioned till now. The graph shows the instantaneous embodied carbon numbers for each variant against the number of years.

5. Embodied Carbon Balance

Explain parameters here

5.1. Phase A, Year 0

Looking at the year 0 of the simulated buildings, which is the construction stage. On the Y-axis are charts for increasing floor heights. On the left value for concrete variant and the right is wooden construction. On the top are numbers specific to floor area in kgco2/m2. On the lower graph, the absolute embodied carbon in tonnes. Concrete buildings seem to have significantly higher embodied carbon in comparison with wooden alternatives. Technical systems add up a significant amount. Up to 57% in the case of 6 storey concrete buildings. PV panels on the roof as well as the facade add up a significant chunk too.

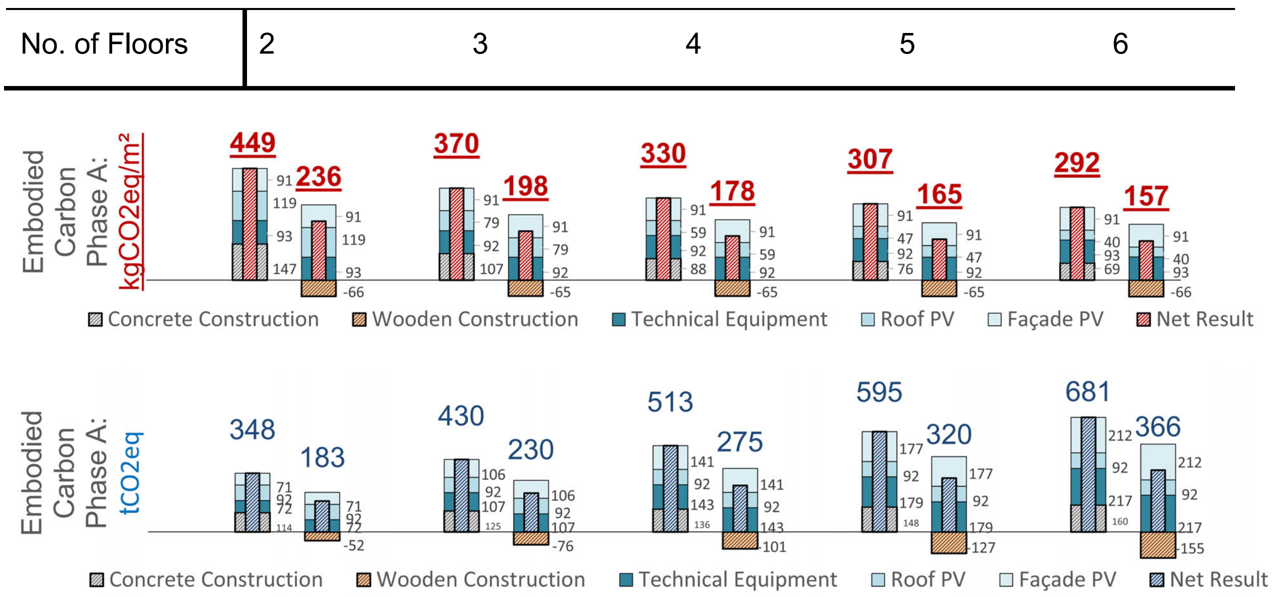
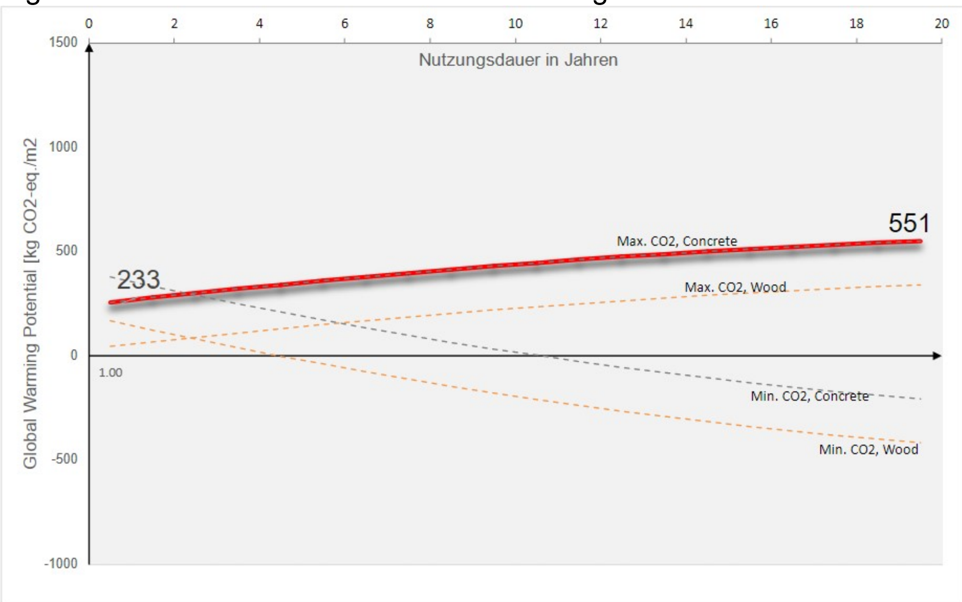


Fig. 10: Embodied carbon of wooden and concrete buildings at year 0. On the left bar value for concrete variant, on the right are wooden equivalent variants.

5.2. Phase A+B, Year 0-20

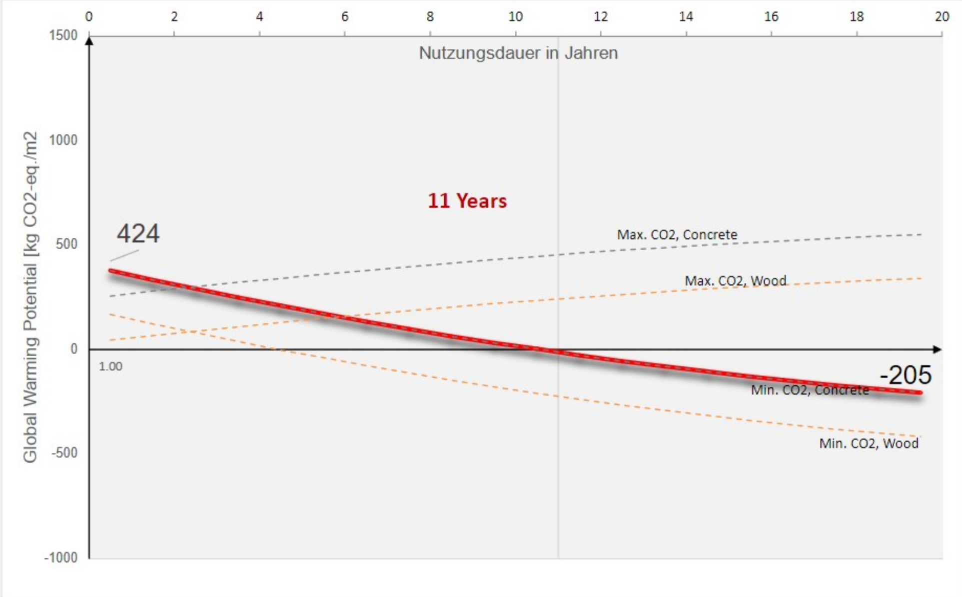
Let's look at a scenario in the next 20 years: The first variant we look at is the office building that ends up with the highest embodied carbon. Concrete building with 2 floors and mechanical ventilation without any PV panels. We start at 233 kgCO2/m2 in the construction stage and that increases to 551 kg/m2 at the end of year 20. This is the worst performing variant in concrete buildings.

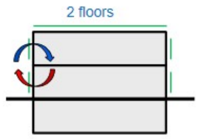
Fig. 11: Concrete variant with the highest embodies carbon at year 0.



Number of Floors	2	3	4	5	6
Photovoltaik Panels	No PV	Roof PV		Façade PV	
Ventilation System	Mechanical			Natural	
Construction Material	Concrete			Wooden	
Decarbonization of Grid	Linear: 50 yrs			ISE	
Phases	A	B	C	D	

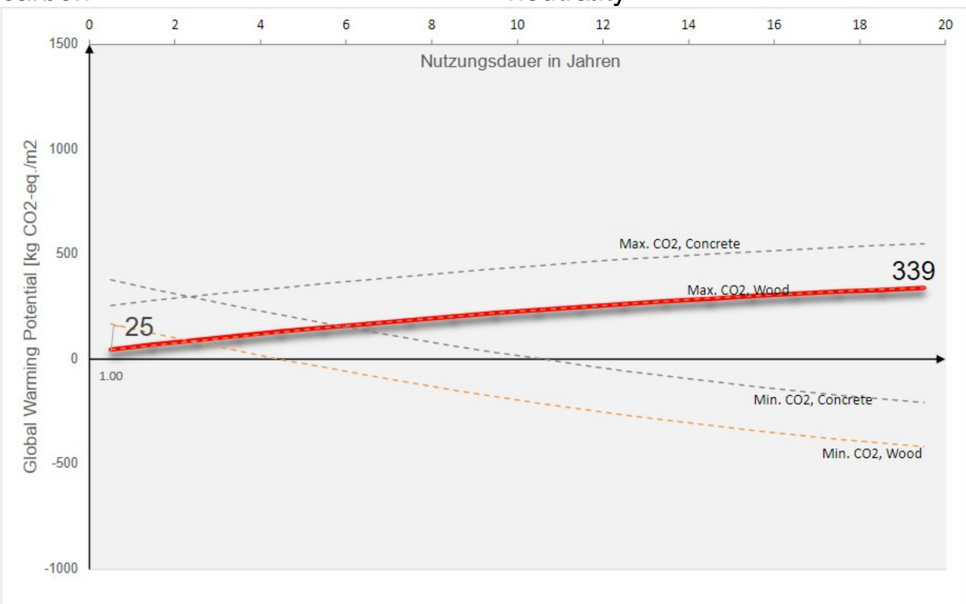
Fig. 12: With 2 floors, we reach carbon neutrality in 11 years. This is the best performing variant in Concrete buildings.

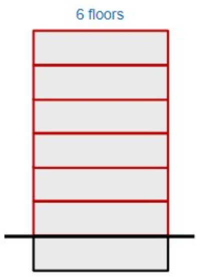




Number of Floors	2	3	4	5	6
Photovoltaik Panels	No PV	Roof PV		Façade PV	
Ventilation System	Mechanical			Natural	
Construction Material	Concrete			Wooden	
Decarbonization of Grid	Linear: 50 yrs			ISE	
Phases	A	B	C	D	

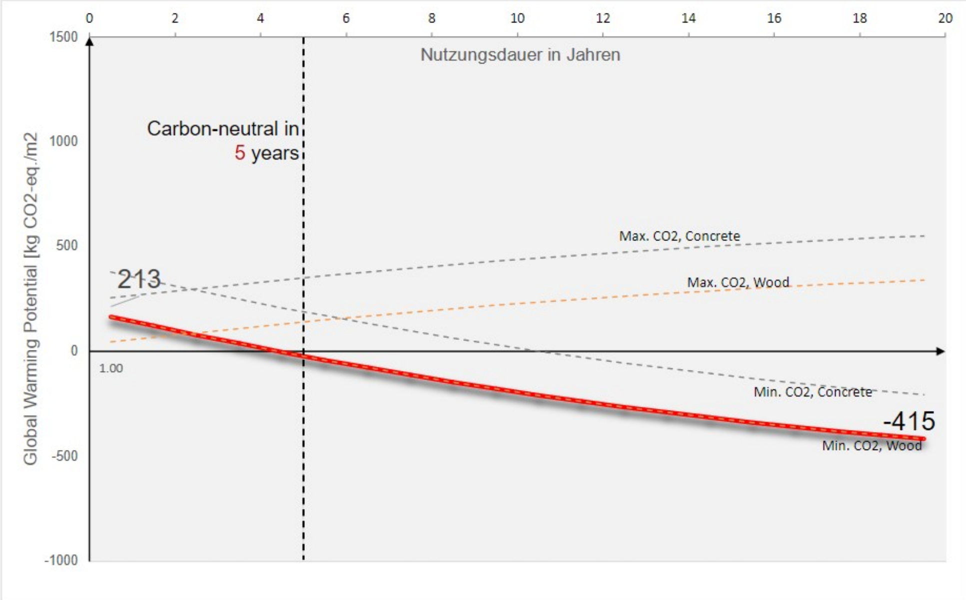
Fig. 13: Wooden construction has similar patterns however the initial point changes significantly due to the lower embodied carbon in the case of wood, making them reach carbon neutrality earlier.

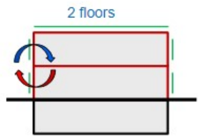




Number of Floors	2	3	4	5	6
Photovoltaik Panels	No PV	Roof PV		Façade PV	
Ventilation System	Mechanical			Natural	
Construction Material	Concrete			Wooden	
Decarbonization of Grid	Linear: 50 yrs			ISE	
Phases	A	B	C	D	

Fig. 14: The best performing variant in wood reaches carbon neutrality in just 5 years.





Number of Floors	2	3	4	5	6
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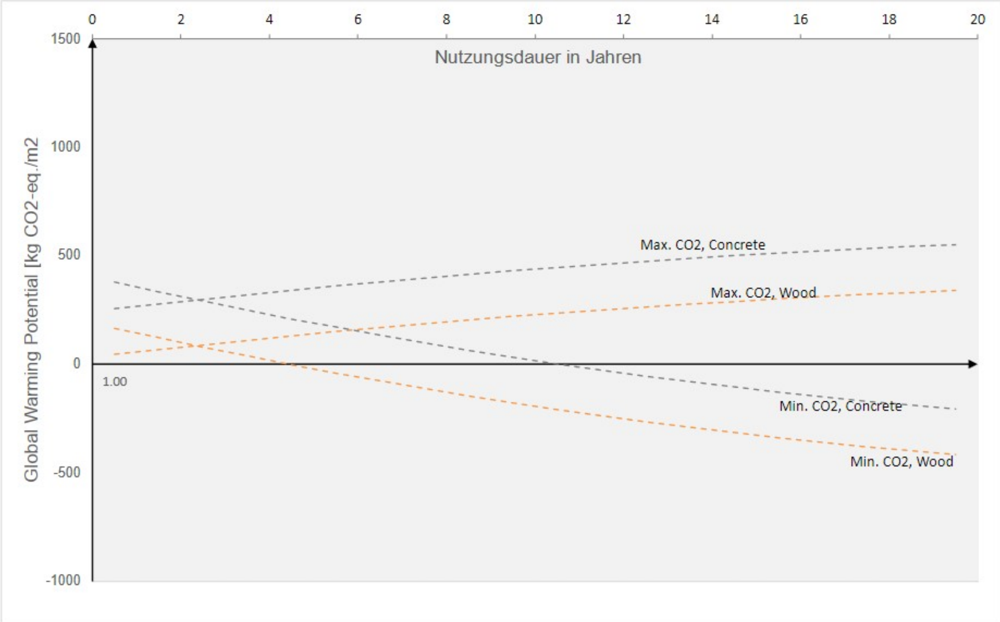
Ventilation System	Mechanical			Natural	
Construction Material	Concrete			Wooden	
Decarbonization of Grid	Linear: 50 yrs			ISE	
Phases	A	B	C	D	

6. Sensitivity studies

6.1. Factors affecting the study

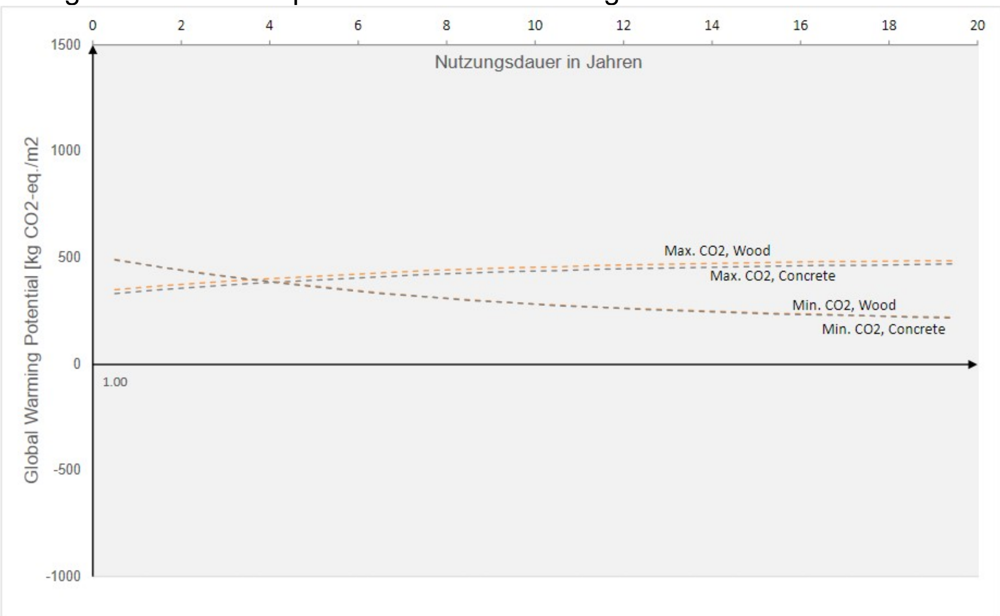
Fig. 15: We see the range of LCA with the concrete band having on an average about 250kgCO2/m2 as compared to wooden buildings.



Phases:
A B C

Number of Floors	2	3	4	5	6
Photovoltaik Panels	No PV	Roof PV		Façade PV	
Ventilation System	Mechanical			Natural	
Construction Material	Concrete			Wooden	
Decarbonization of Grid	Linear: 50 yrs			ISE	
Phases	A	B	C	D	

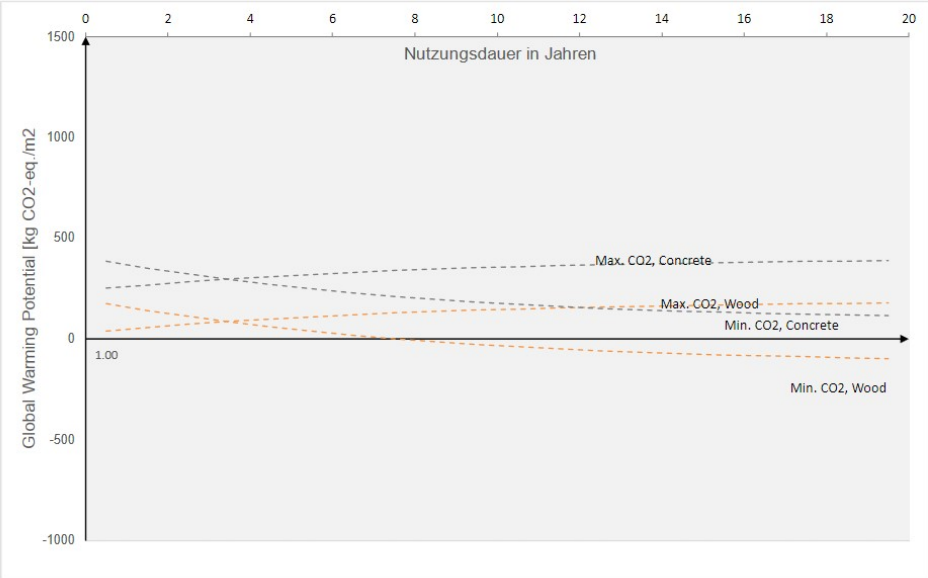
Fig. 16: We see the range of LCA with the concrete band having on an average about 250kgCO2/m2 as compared to wooden buildings.

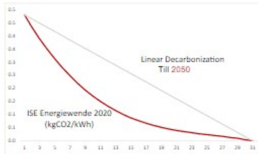


Phases:
A B C

Number of Floors	2	3	4	5	6
Photovoltaik Panels	No PV	Roof PV		Façade PV	
Ventilation System	Mechanical			Natural	
Construction Material	Concrete			Wooden	
Decarbonization of Grid	Linear: 50 yrs			ISE	
Phases	A	B	C	D	

Fig. 17: And here are the ISE Energiewende numbers for decarbonization which predict more aggressive decarbonization of the grid.





Number of Floors	2	3	4	5	6
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Ventilation System	Mechanical			Natural	
Construction Material	Concrete			Wooden	
Decarbonization of Grid	Linear: 50 yrs			ISE	
Phases	A	B	C	D	

6.2. Conclusions

Regardless of Wood/Concrete, it is possible to achieve a CO_2 neutral building in 20 years.

In wooden construction, it is easier to achieve, and we can build higher.

Phase C changes the picture, also we cannot predict embodied carbon of materials for renovation. E.g. what will be the embodied carbon in solar panels after 50 years?

Decarbonization of the grid affects the balance.

Technical systems need to be detailed further and it is hard to get information for some elements. (We combined data from Ökobaudat, KBOB and EPDs from manufacturers)

Further investigation: does it mean PV on façade is necessary? Do we as Transsolar need to start recommending Façade PV in future projects?

Green roof vs PV panels vs Terrace. Urban heat island effect?

Green Facade vs PV panels vs Larger openings.

Concrete only: up to 3 floors

PV on the roof only: up to 3 floors