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Life Cycle Assessment of Recently Constructed "Climate Protection Neighbourhoods" – Which Lessons can be Drawn?

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Abstract. The results of a life cycle assessment of five recently finished housing projects in Northern Germany - all of them part of two certified climate protection neighbourhoods - point out the necessity of combining a variety of different carbon reduction approaches in order to reach carbon neutrality. The analysis presented here focuses on both, embodied and operational carbon emissions, as well as embodied and operational energy, over a period of 50 years. Both residential areas examined do not tap the full potential of their environmental impact reduction as they focus on single strategies only: one development limits the reduction of carbon emissions for heating and domestic hot water supply to a max. of 7.5 kg GHG emissions per m^2 and year, by means of conventional solid construction. For the other estate the developers encouraged timber construction by requiring a minimum share of the construction volume of 70% timber. Comparing both approaches shows, that climate friendly construction can only be achieved by combining different ways and means, e.g. easily demountable hence reusable timber structures with a high level of energy efficiency and a carbon free heat supply. The results drawn from this study are designated to serve as a basis for discussion of the development of ambitious and climate responsible housing standards in Bremen.

Keywords. Climate Protection Neighbourhoods, Life Cycle Assessment, Decarbonisation of Heat Supply, Demountable and Reusable Construction, Renewable Materials

1. Introduction

The building sector's responsibility for carbon emissions, hence climate change, is known well enough. Some city planning institutions and investors are reacting by implementing pilot housing schemes based on energy efficiency and sustainability requirements that clearly exceed existing regulatory requirements.

For instance, in the northern German city of Bremen, the local agency for climate protection ("energiekonsens") defined a climate protection label for new urban neighbourhood) s, the so-called "Klimaschutzsiedlung" (climate protection neighbourhood)) that restricts carbon emissions for heating and domestic hot water (DHW) supply to a maximum of 7.5 kg CO_2-eqv. per square meter [5]. This benchmark, however, disregards emissions embodied in construction materials and induced by traffic and transport. Such embodied and induced emissions are gaining importance with increasing energy efficiency and emission-free energy generation. Hence, the entire building life cycle needs to be accounted for in order to address the building sector's responsibility for climate change adequately.

2. **Projects**

The two residential areas examined in this study are both inner city developments within the Free Hanseatic City of Bremen in northern Germany. Both are at a certain distance from the city centre (Figure 1) but can easily be reached by public transport.

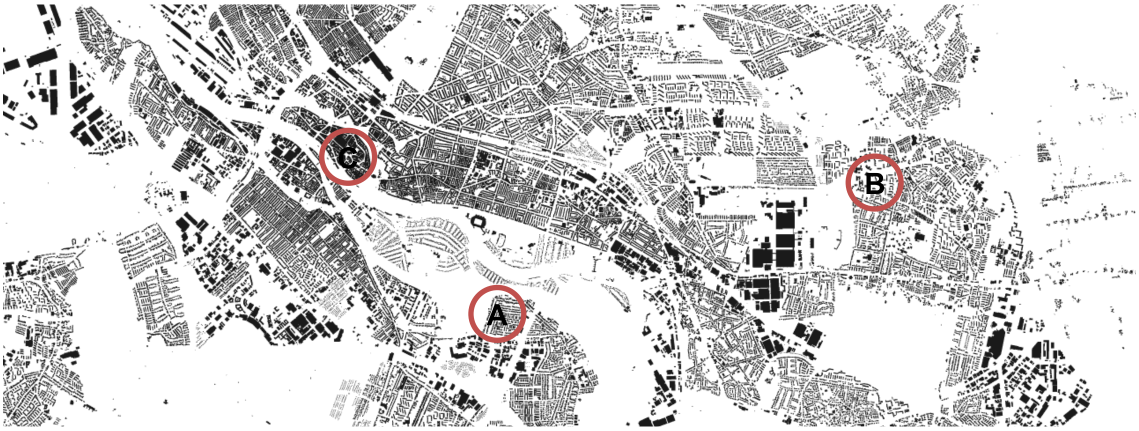


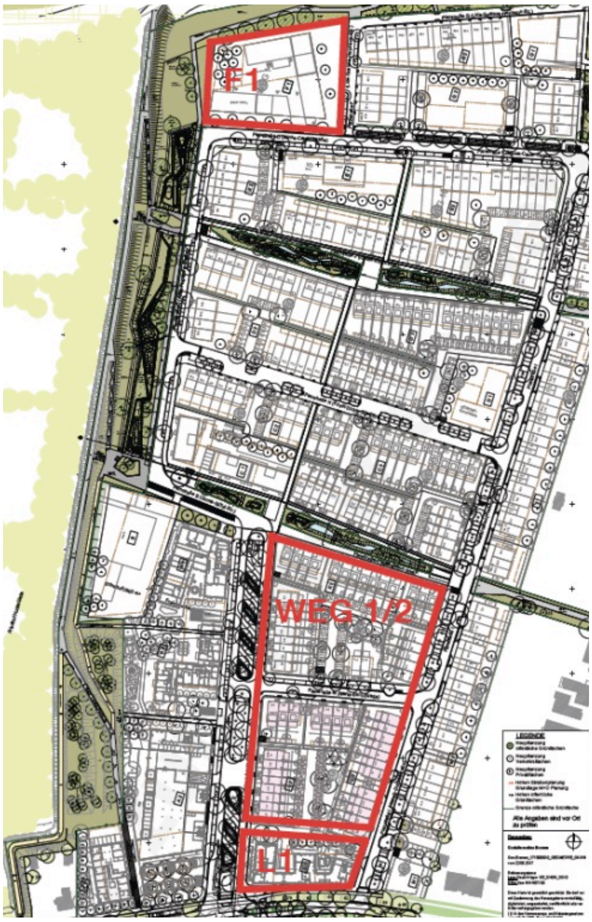
Figure 1. City plan showing the two urban development areas under examination (A: Gartenstadt Werdersee, B: Stiftungsdorf Ellener Hof, C: City Centre) (image source: schwarzplan.eu)

2.1. "Gartenstadt Werdersee"

The garden city "Gartenstadt Werdersee" is currently under construction at the southern shore of a local recreation area called "Werdersee", where a sidearm of the Weser River is dammed up into a lake (Figure 1). The area is developed as a "climate protection neighbourhood" by a consortium of various investors. It consists of both, terraced and multi-family houses in conventional mineral construction. For this analysis, the following projects were selected:

- **L1:** apartment block L1 is located in the southern area of the district. It is a multi-use building with an underground parking and commercial units on the ground floor and apartments on the upper floors. For the exposed masonry of the core-insulated exterior walls the plot's excavated soil was used.
- **F1:** apartment building F1 consists of three individual building parts with shared underground parking and is located in the northern part of the area, in close vicinity of the dike/lake. The exterior walls are partly cladded with a thermal insulation composite system (ETICS), partly core insulated with a clinker facing. Building part 1 was examined as representative for the whole block, the underground car park was split up proportionally to the respective living space.
- **WEG 1 and 2**: terraced houses WEG 1 and 2 are built from mineral materials with thermal insulation composite system (ETICS) – either with a plaster or clinker finish - house "Eek" was examined in two versions: as end-of-terrace and as mid-terrace house.

The heating energy for all buildings is supplied by a common combined heat and power plant (CHP), run with natural gas (37%) and bio methane (29%). The remaining 34% are supplied by a natural gas operated boiler.



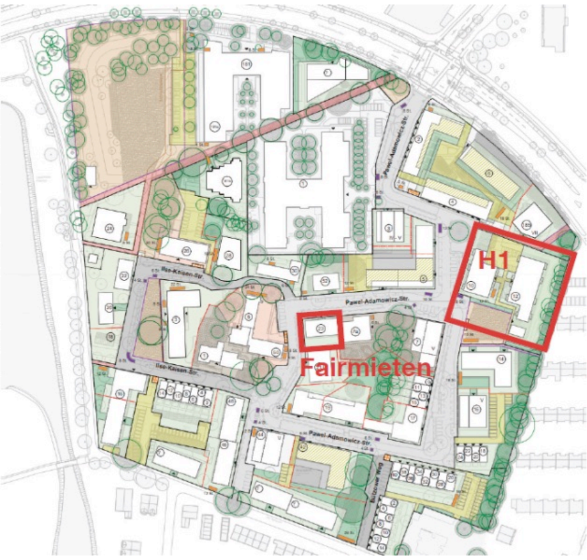


Figure 2. Site plans of the two urban development areas examined in this study (not to scale), left: “Gartenstadt Werdersee with site “L1”, “F1” and “WEG 1/2” (for a detailed description see 2.1.) (image source: Freie Hansestadt Bremen, SKUMS Ref. 30/31), above: “Ellener Hof” with “Fairmieten” and “H1” (see also 2.) (image source: [2])

2.2. Socio-ecological model district “Ellener Hof”

In the eastern Bremen district of Osterholz, the “Bremer Heimstiftung” (housing foundation) is currently developing a socio-ecological model district with around 500 new residential units on a site of roughly 10 hectares. All buildings will be built in timber hybrid construction and according to ambitioned energy efficiency standards. The primary energy demand of the buildings is limited to 40% compared to current legal requirements [3][2]. For the present study two buildings, one already constructed the other one in planning, were chosen as examples:

- The **Fairmieten** project is a cooperative housing project that is to be built in hybrid construction with reinforced concrete structural elements and timber frame walls.
- **H1** consists of three building parts, two residential buildings (house 1 and 2) and a bicycle shed. The residential buildings are being erected by an Austrian company using an in-house developed timber construction system. The basic structure of the building is a timber skeleton with a basic grid of 1.40 x 1.40 m, cladded with prefabricated timber façade elements.

27% of the heat supply in Ellener Hof is provided by a district-owned bio-methane-powered CHP, the remaining 73% is covered by the municipal energy supplier’s (swb) district heating, based on 51% hard coal, 44% waste, 3% P2H and 2% sludge [7] . The systems conversion to more environmentally friendly energy sources is in planning (Figure 3) [6].

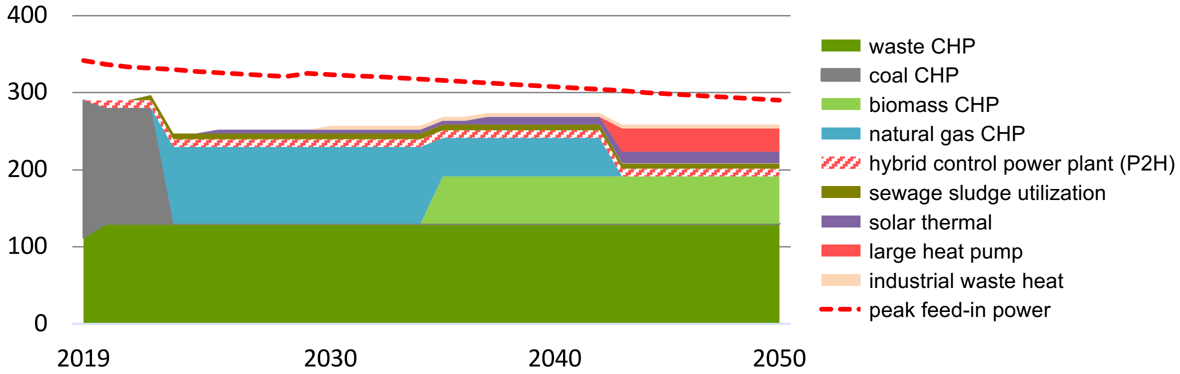


Figure 3. District heating in Bremen: installed heat output [MW] today (2019) and probable future development until 2050 (image source: [6])

3. Methodology

3.1. System Limits and Boundary Conditions

A life cycle assessment (LCA) was carried out for a study period of 50 years, as specified for building certifications in Germany. The spatial system boundary forms the outer edge of the building, including the underground car park. If only one representative part of a building complex was analysed, the area of the underground car park was distributed according to the living space.

The results are broken down into foundation, supporting structure, facade and interior fit out. They are also presented according to the life cycle phases as stated by EN 15978: production (A1-3), operational energy use (B6), replacement (B4) and disposal (C3/4). Phase D (benefits and loads outside of the system boundary) is considered separately.

3.2. Calculation Method and Data Base

The calculations are based on Ökobaudat 2020 II [1], a publicly accessible database of the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB). Where available, data from the neighbourhood) s' own energy supply and/or the municipal energy supplier was used for the building operation (B6), since electricity and district heating do not correspond to the average electricity and district heating mix in Germany.

For the dismantling phase, the materials were assigned end-of-life scenarios specified by the German Sustainable Building Council (DGNB) [4]:

- metals are recycled and attributed a recycling potential (e.g. aluminium)
- mineral building materials are processed as rubble (e.g. concrete, sand-lime brick)
- all materials with a calorific value are burned to generate energy (e.g. wood, plastics, etc.)
- materials that can only be landfilled are disposed of (e.g. mineral wool)

4. Results

4.1. The Buildings in Comparison

Figures 4 and 5 show the results of the examined objects in comparison.

4.1.1. Non-renewable Primary Energy Demand (PE ne). It is noticeable that the PE ne demand for the thermal operation of the buildings roughly corresponds to the PE ne embodied in the construction. This underlines the relevance of the embodied energy demand in highly energy-efficient buildings.

Comparing the buildings in “Gartenstadt Werdersee”, it is hardly surprising that the total PE ne content of the end terrace house is highest, followed by the middle terrace house. The multi- family

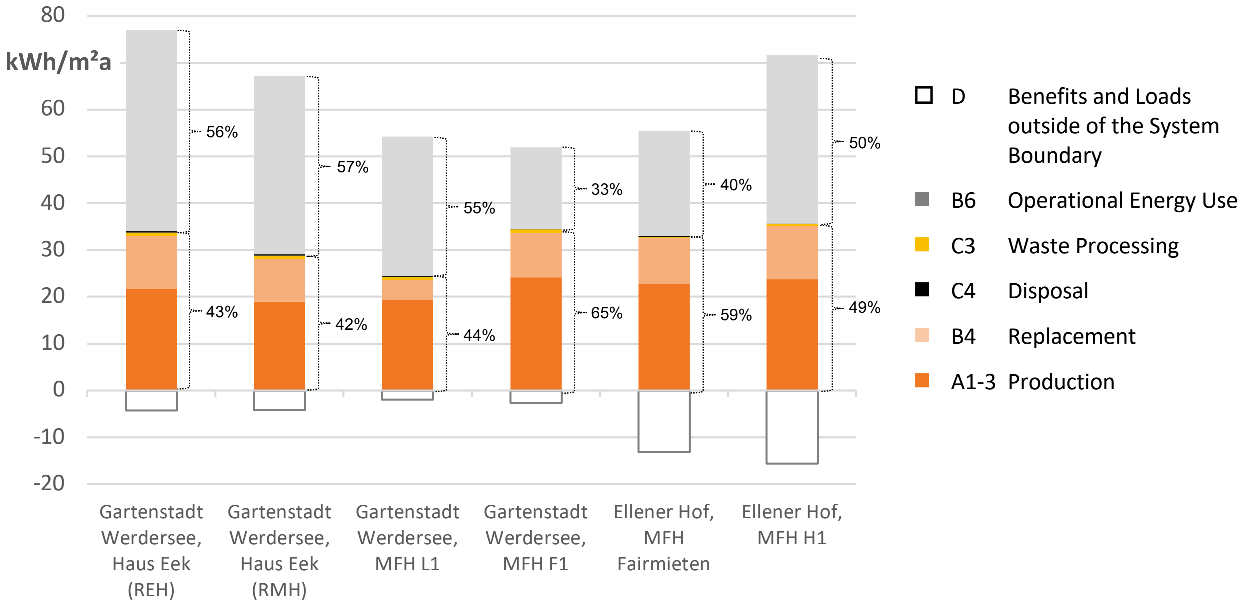


Figure 4. Non-renewable Primary Energy (PE ne) Demand in Comparison (life cycle phases per EN 15978)

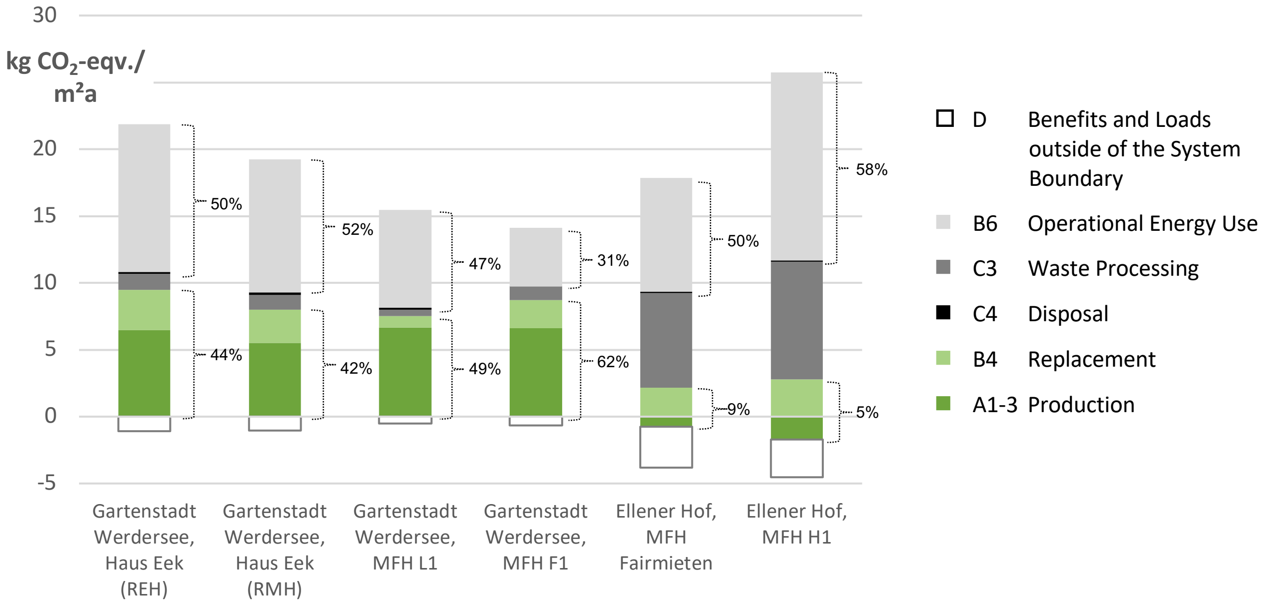


Figure 5. Global Warming Potential (GWP): Greenhouse Gas (GHG) Emission in comparison (life cycle phases per EN 15978)

houses have a significantly lower total PE ne content, reflecting the impact of their compactness: apartment buildings have a much lower A/V (exterior surface area to volume) ratio than mid-terraced houses, a detached single-family house (not examined here) is certainly the most unfavourable in this regard.

The PE ne demand for replacement (B6) of apartment block L1 is significantly lower than of terraced house Eek. This reflects the execution quality of the exterior walls: due to the clinker facing of L1, the insulation does not need to be renewed within the observation period of 50 years, in contrast to the ETICS of the terraced house.

If only the non-renewable PE content is considered, timber construction (Ellener Hof) does not show any significant advantage compared to conventional mineral construction (Gartenstadt Werdersee). This however, changes when considering the global warming potential (see 4.1.2).

4.1.2. Greenhouse Gas (GHG) Emissions. In principle, the phenomena discussed with regard to the PE ne demand can also be observed here (A compact design has a positive effect on the environmental impact, as does the choice of high-quality material and construction). However, the advantages of timber construction become visible: trees store CO2 while growing, therefore function as a natural carbon storage. In the carbon accounting approach used by Oekobaudat this results in the negative emission values for the production phase (A1-3) of the two timber buildings examined in "Ellener Hof".

This captured CO2 is released at the building's end of life (EoL) due to the specified disposal routes (see 3.2.). This indicates clearly the importance of considering the demolition of a building as early as in the planning stage. Components and materials can only be reused, and unnecessary emissions can only be avoided, with a recycling-friendly design that enables sorted dismantling.

The ratio of embodied and operational GHGs is similar to the 1.1 ratio of conventional mineral construction for PE ne. In this respect, timber buildings clearly benefit from their capacity to store CO2, as production and replacement only account for 5% to 9% of the total GHG emissions.

4.2. Cumulated Emissions

For achieving the essential climate protection goals, it is not sufficient to minimize the environmental impacts of the building sector over the entire life cycle of buildings. Some of this life cycle lies in the future, whereas global warming requires rapid action. Consequently PE ne and GHGs should be considered taking into account the point in the life cycle at which they occur, illustrated below with the help of two example projects apartment buildings L1 and H1 - comparing solid construction with timber construction.

4.2.1. Non-renewable Primary Energy Demand (PE ne). Figure 6 shows the PE ne demand of both projects over their entire life cycle in comparison. The embodied PE ne resulting from the production phase (A1-3) is broken down into foundation, supporting structure, building envelope and interior fit out.

Garden City Werdersee, apartment building L1

The embodied non-renewable PE resulting from the construction phase (A1-3) of apartment building L1 adds up to a total of approx. 968 kWh/m^2, thereof

- 186.8 kWh/m^2 (approx. 19%) resulting from the foundation,
- 318.5 kWh/m^2 (approx. 33%) from the structure,
- 375.2 kWh/m^2(approx. 39%) from the building envelope and
- 87.2 kWh/m^2 (approx. 9%) from the interior fit out.

The buildings operational non-renewable PE demand (B6) is around 1.5 times as much, with an annual 29.7 kWh/m^{2}a summing up to a total of 1.485 kWh/m^2 over a period of 50 years.

For the recycling (C3) or disposal (C4) of the construction, another approx. 44 kWh/m^2 is required. The potential for reuse, recovery and recycling (D) adds up to approx. 95 kWh/m^2.

In total, around 2.453 kWh/m^2 of non-renewable primary energy is required for the construction, operation, recycling and disposal of the building. Taking into account the recycling potential, this amount is reduced to approx. 2.402 kWh/m^2 (Figure 6, left).

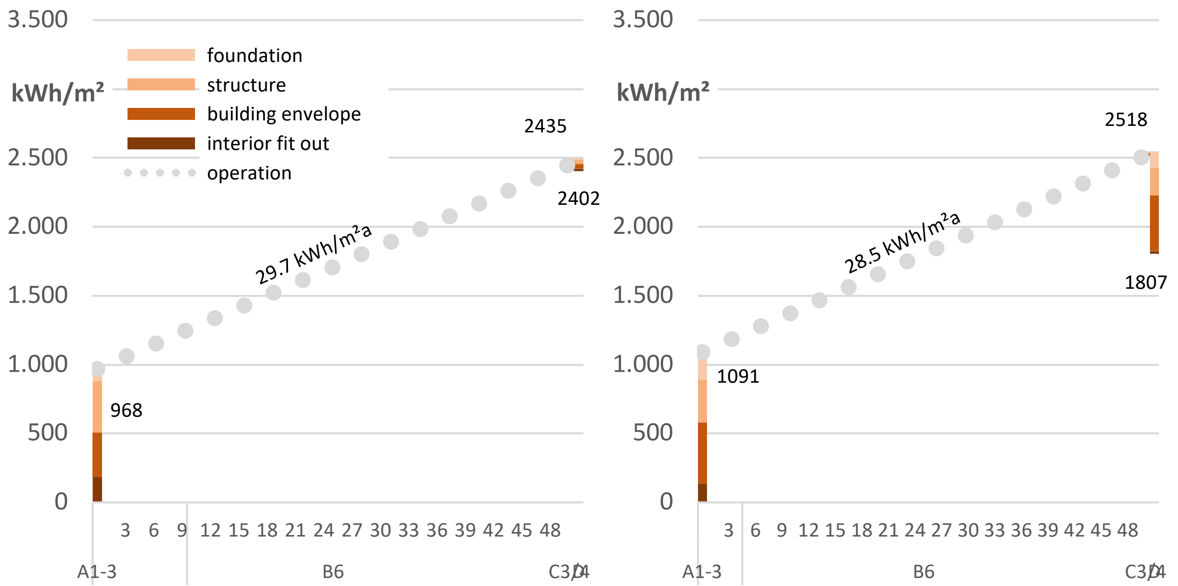


Figure 6. Non-renewable Primary Energy (PE ne) Demand for a period of 50 years (not considering B4 Replacement), left: L1, Gartenstadt Werdersee, conventional mineral construction, right: H1, Ellener Hof, timber construction (life cycle phases per EN 15978)

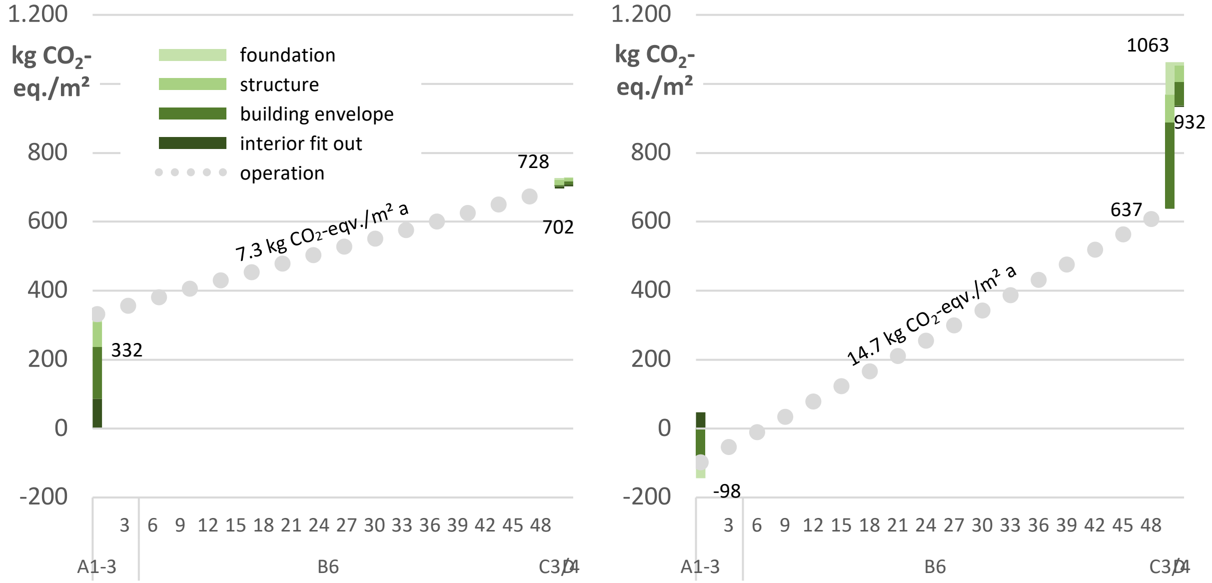


Figure 7. Greenhouse Gas (GHG) Emissions for a period of 50 years (not considering B4 Replacement), left: L1, Gartenstadt Werdersee, conventional mineral construction, right: H1, Ellener Hof, timber construction (life cycle phases per EN 15978)

Ellener Hof, apartment building H1

Regarding apartment block H1 an amount of approx. 1.091 kWh/m² of non-renewable PE results from the construction phase (A1-3), of which a

- 136.0 kWh/m² (approx. 12%) result from the foundation,
- 441.7 kWh/m² (approx. 41%) from the structure,
- 311.1 kWh/m² (approx. 29%) from the building envelope and
- 201.6 kWh/m² (approx. 18%) from the interior fit out.

With an annual amount of 28.5 kWh/m² the non-renewable PE demand for heating and domestic hot water supply (B6) sums up to a total of approx. 1.425 kWh/m², exceeding the embodied non-renewable PE (A1-3) by factor 1.5, the same factor as building L1.

Another 31 kWh/m² is required for recycling (C3) or disposal (C4) of the construction. With 742 kWh/m², the potential for reuse, recovery and recycling (D) is significantly higher than in project L1, which is due to the calorific value of the wooden materials used.

In total, around 2.518 kWh/m² of non-renewable PE is required for the construction, operation, recycling and disposal of the building. Taking into account the recycling potential, the amount is reduced to approx. 1.807 kWh/m² (Figure 6, right).

4.2.2. Greenhouse Gas Emissions (GHGs). Figure 7 shows the GHG emissions of the two projects. The embodied GHG emissions (A1-3) are shown disaggregated into foundation, structure, building envelope and interior fit out.

Garden City Werdersee, apartment building L1
The embodied GHGs in apartment block L1 (A1-A3) aggregate to approx. 332 kg CO_2-eqv./m²:

- an amount of 86.3 k kg CO_2-eqv./m² (approx. 26%) result from the foundation,
- 151.0 kg CO_2-eqv./m² (approx. 45%) from the structure,
- 72.0 kg CO_2-eqv./m² (approx. 22%) from the building envelope and
- 22.7 kg CO_2-eqv./m² (approx. 7%) from the interior fit out.

For the thermal conditioning of the building (B6) an annual amount of 7.3 CO_2-eqv./m²a is emitted, summing up to a total of 365.5 kg CO_2-eqv./m², thus fulfilling the requirements for "climate protection neighbourhood) s" (see 1.). The greenhouse gas emissions for construction (A1-3) and operation (B6) are just about equal.

An amount of approx. 30 kg CO_2-eqv./m² is released by recycling (C3) or disposal (C4). The potential for reuse, recovery and recycling (D) adds up to 26 kg CO_2-eqv./m².

In total, approx. 728 kg CO_2-eqv./m² are caused by construction, operation, recycling and disposal of the building. Taking into account the recycling potential, this amount is reduced to a total of approx. 705 kg CO_2-eqv./m² (Figure 7, left).

Ellener Hof, apartment building H1
Due to its timber construction apartment block H1 achieves a carbon credit of approx. 98 kg CO_2-eqv./m² during the construction phase (A1-3). The timber construction stores approx. 144.7 kg CO_2-eqv./m², whereas the construction of the concrete of the foundation slab emits approx. 46.7 kg CO_2-eqv./m².

The thermal conditioning of the building leads to an annual amount of 14.7 kg CO_2-eqv./m²a, summing up to a total of 637 kg CO_2-eqv./m².

Approx. 426 kg CO_2-eqv./m² are again released for recycling (C3) or disposal (C4) of the construction,

- 2.4 kg CO_2-eqv./m² (approx. 1%) from the foundation,
- 329.5 kg CO_2-eqv./m² (approx. 67%) from structure and envelope, as well
- 94.0 kg CO_2-eqv./m² (approx. 22%) from the interior.

The potential for reuse, recovery and recycling (D) is around 130.2 kg CO_2-eqv./m²:

- 4.7 kg CO_2-eqv./m² (approx. 3.6%) from the foundation,
- 116.1 kg CO_2-eqv./m² (approx. 89.2%) from structure and envelope and
- 9.5 kg CO_2-eqv./m² (approx. 7.3%) from interior fit out.

In total, approx. 1.063 kg CO_2-eqv./m^2 are caused by the construction, operation, recycling and disposal of the building. Taking into account the recycling potential, this amount is reduced to approx. 932 kg CO_2-eqv./m^2 (Figure 7, right).

5. Discussion

5.1 Non-renewable Primary Energy Demand (PE ne).

Taking the buildings' full life cycle into account shows that, despite excellent energy performance, the larger share of the PE ne demand is caused by energy use for building operation (B6): the construction of the building requires roughly as much PE ne as approx. 33 years of heating and warm water supply.

5.2 Greenhouse Gas Emissions (GHGs).

Garden City Werdersee, apartment building L1

In the case of apartment block L1 (mineral construction) the amount of greenhouse gas emissions caused by production (A1-3) and operation (B6) of the building is approximately the same, i.e. the construction of the building causes as many emissions as 50 years of heating and domestic hot water supply.

Ellener Hof, apartment building H1

Result interpretation is slightly more complex for apartment building H1 (timber construction): the construction company has developed a modular timber construction system that allows a non-destructive dismantling of the building. According to the company, the single components can be recombined as desired without loss in value.

Due to the relatively high operational GHG emissions of 14.7 kg CO_2-eqv./m^{2}a, the climate protection potential of the timber system construction seems not to be fully realized. These relatively high operational GHGs are caused by the building's energy supply: 27% of the required energy are provided by a district-owned bio-methane-powered CHP, with the remaining 73% by the municipal energy supplier (see also Figure 3).

If the life cycle analysis is based on the possible future path for the municipal energy supply as shown in Figure 3, the production and operation of the building cause only approx. 367 kg CO_2-eqv./m^2, a reduction by 172 kg CO_2-eqv./m^2.

The emissions caused by the construction and operation of building H1 roughly correspond to the amount of emissions caused by the construction of the comparison building L1 alone, as shown in Figure 8, right.

6. Conclusion

The results presented chapter 4 show that both climate protection approaches considered - the reduction of GHG emissions for space heating and domestic hot water supply in the climate protection neighbourhood) s and the use of renewable materials in the Ellener Hof model district - are successful in themselves. This is shown by a comparison with the requirements from the DGNB housing construction assessment system and the quality seal for sustainable housing construction (not included here). The requirements are largely met or (in some cases even significantly) exceeded. However, the results also reveal potential for improvement.

Building with renewable materials offers great opportunities and, at the same time, a risk of shifting emissions from the present to the future. The present study also shows the importance of keeping components and materials in the material cycle in order to avoid future emissions or at least delay them as far as possible.

Attenuating climate change will not work without converting the energy supply. The potential of low environmental impact from materials and high energy efficiency (and thus low GHG emissions) in building operation can only be fully exploited in combination with a high degree of decarbonisation of the building's energy supply.

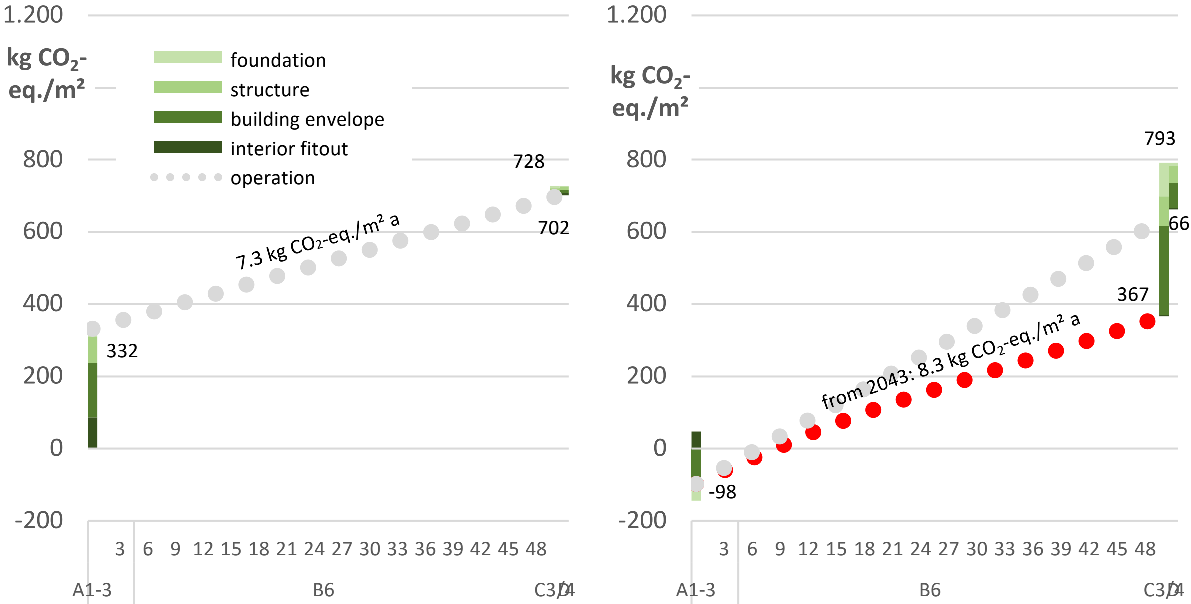


Figure 8. Greenhouse Gas Emissions (GHGs) for a period of 50 years (not considering B4 Replacement), left: L1, Gartenstadt Werdersee, conventional mineral construction, right: H1, Ellener Hof, timber construction, showing the future path for the municipal energy supply (life cycle phases per EN 15978).

Acknowledgements

We would like to express our gratitude towards the senatorial authority for climate protection, environment, mobility, urban development and housing (SKUMS) for commissioning this study, and all planners and building owners involved for patiently supporting us with information on their projects.

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