A NEW TOOLSET FOR A HOLISTIC EARLY STAGE PARAMETRIC LCA STUDY

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ABSTRACT

The climate crisis raises the question whether energy targets of building regulations should be more holistic by considering also embodied energy of materials. While focusing on thermal and daylight user comfort in order to reach ambitious energy and greenhouse gas targets simulation tools must efficiently and more holistically guide the planning process starting in the early design phases when the major decisions are made. The sensitivity of various parameters also needs to be studied to find the most appropriate solution.

In this case-study embodied energy of materials based on the Ökobaudat are calculated for a low-tech office building using Grasshopper and Rhinoceros. In parallel, dynamic thermal building and system simulation are applied with TRNSYS 18 and Radiance in a parametric multizone building model. Both variants are put into one context with various lifespans. In total up to 100 years are analyzed to indicate the highest energy consumers for optimization.

INTRODUCTION

Political targets for reduction of greenhouse gas emissions are given by the European Union in steps for 2030 and 2050. The key target for 2030 is to cut of at least 40% in greenhouse gas emission compared to 1990 and a change to total net-zero greenhouse gas emissions in 2050 (European Commission, 2020). The building industry constitutes a major source of global greenhouse gas (=GHG) emissions (IEA, 2019). In the past decades a focus on energy efficiency for heating, cooling and electricity was the consequent answer to the problem of high energy consumption of buildings. In combination of a widely non-renewable energy mix this consumption led to immense GHG emissions. Nowadays the efficiency of energy systems and quality of building envelopes of new built structures are highly maximized. Also, the energy mix of electricity is changing towards a primarily renewable energy supply. Thus, we can see an increasing importance of the energy embodied in the structure itself (i.e. Röck, M. et al., 2020). Aiming for net zero buildings by 2050 a far-reaching rethinking in the building sector must be achieved. By understanding the main factors of a building contributing to the overall greenhouse gas emissions, appropriate design decisions can be taken. For this, it is necessary to extend the considered system boundary from conventional energy analysis towards an overall life-cycle assessment.

Life cycle assessments (=LCA) is a tool that depicts the embodied energy of products by describing »the environmental and climate-related effects of a product during its entire life cycle – from the extraction of raw materials to the production of the materials, the manufacturing of the product, its usage through to all processes at the end of the product life cycle.« (Ökobaudat, 2019)

The intentend is to consider not only one building material product, but the building as a whole, with the processes of construction and demolition, renewal of individual components, operational energy and other aspects. These impacts have to be evaluated and compared. The buildings performance legitimizes the buildings construction, thus has to be optimized by evaluation of comfort in parallel. Computer modeling and simulation software can accomplish the connections between these aspects and the building design.

In this paper a new approach of holistic building impact and performance analysis is described targeting to efficiently guide the planning process for carbon net-zero buildings from the early beginning. The aim is to detect major sources of greenhouse gases in order to efficiently reduce the overall GWP of a building and getting a deeper sense for the consequences of different building materials and assemblies in combination with the building performance.

METHODOLOGY, BOUNDARY CONDITIONS, SIMULATION MODELS

Methodology

For the LCA of this case study data of the Ökobaudat 2020 was used for calculation of embodied energy of the building. This is complemented with the simulation results for the energy demand by applying dynamic thermal building and system simulation with TRNSYS 18 in a parametric multizone building model using TRNLizard for Rhinoceros and Grasshopper.

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Thermal and visual (daylight) comfort analysis were carried out to well inform the design process.

The basis for the life cycle assessment is provided by DIN EN ISO 14040 and DIN EN 15804. These standards define the structure of a building's life cycle split into the modules A to C, the modules of production (A1-A3), construction (A4-A5), use (B1-B7) and end of life (C1-C4). Each of these modules are subdivided for example in production of raw material supply (A1), transport (A2) and manufacturing (A3). Benefits by recycling and reuse of certain materials or products are not allowed to be considered in the LCA, but can be described as additional information by module D.

The indicators for the negative environmental effects are defined by the DIN EN 15804 and include the global warming potential (GWP), total use of renewable primary energy resources (PERT) and the total use of non-renewable primary energy resources (PENRT). These indicators were all considered, but this case study focusses on the GWP.

For the first module of manufacturing (A1-A3) the data provided by Ökobaudat for each building material was applied. The modules A4 and A5 address the construction on site, including transport. For a first overview the data provided by the Ökobaudat was used as far as available. Additional information on transport and process energy on the construction site (e.g. heavy machinery and heating) can be included as generic data provided by the Ökobaudat, but was not considered here.

In this case study the usage phase of a building distinguishes between the use of the materials and the energy demand for operation. The material-based modules are defined by the DIN EN 15804 as use, maintenance, repair, replacement, refurbishment (B1-B5). Missing data of these modules led to the approach to consider the replacement of individual materials due to their individual limited lifetime. This data was substituted by multiplying the available life cycle data for the modules A and C of the materials that has to be replaced within the period of consideration. For example: cement screed flooring has to be renewed after 50 years. In a life cycle assessment over a span of 100 years, the manufacturing, construction and end-of-life data for a material is taken into account a second time in module B-material. The information on the materials individual lifetimes were provided by the BBSR 2017 and compared with the French dataset Inies 2020. For mechanical systems life spans were taken from the VDI 2067:2012.

The operation of the building requires energy for electricity, heating and cooling. This operational energy is described in the module B6 as the result of the dynamic thermal building and system simulation with TRNSYS 18. The required water supply is described in the module B7 and was not considered in this case-study.

The end of life modules (C1-C4) were provided by the Ökobaudat database. As for construction, the data for demolition and transport can be supplemented with generic data on processes provided by the Ökobaudat, but were not considered in this case-study.

The recycling potential (Module D) can be also analyzed and additionally be depicted as further information within the type of diagram used in this study. This can help to evaluate additional positive aspects of certain building structures and materials but was also not considered in this case-study.

The concept of the life cycle modules defined by the DIN EN 15804 serves as the basis for the selected type of results diagram. The sunburst diagram adopts the modules in a circular arrangement as shown in Figure 1 for a point in time. This diagram gives a proportional weighting for each module, the respective components and materials that can be seen in the chapter "Results". In addition, a sequence chart visualizes the increase of the overall global warming potential of the building over a life span of 100 years, subdivided in different materials, respectively in types of energy demand.

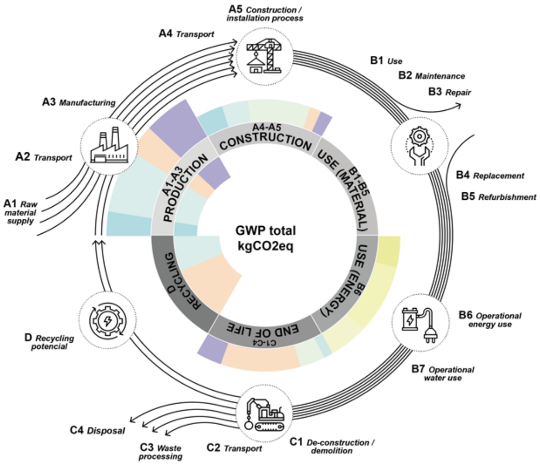

Figure 1: Life cycle assessment and visualization approach based on DIN EN 15804

Boundary Conditions

The approach in this case-study was to analyze the 100 years life cycle of a monolithic light concrete office building with reduced materials and systems (here called low-tech) and compare it to a passive house structure and ventilation system. The aim was to find out the optimums for planning a fully functional and comfortable building with minimal ecological footprint.

The system boundary was set on the global warming potential and energy consumption of a building considering operational and embodied energy. Therefore, other environmental impacts like toxicity, change of land use, impact on microclimate etc. were not considered.

The low-tech approach is based on the idea to minimize the complexity of the building aiming for a maximum of resilience, durability and adaptability by reducing the number of different building materials and supporting user interactions. The passive performance is maximized to minimize the demand for active systems. Few but durable building materials minimize the need for renovation. Passive solutions for thermal comfort and ventilation are complemented by individual controlled systems that are easy to handle and simply convertible to the current needs over the lifetime of the building. The studied low-tech solution has a monolithic façade which is made of lightweight concrete, fulfilling most of the requirements for statics and insulation considering a U-value of 0.35W/(m².K). Concrete cap ceilings are complemented with sand on top to increase thermal capacity. The pitched roof is made of lightweight concrete and covered with PV. The active system of this solution considers heating devices and exclusively passive natural ventilation supported by ceiling fans. Fresh air supply is considered due to manual operable windows in the façade. Night flushing in combination with an adequate window fraction, opening areas and thermal mass provide summer comfort.

This low-tech monolithic structure is compared to a standard passive-house structure in hybrid wood-concrete construction. Passive house standards aim for minimized operational energy demands regarding heating, cooling and electricity. Comparing the relevance of operational energy to the embodied energy for materials in the building structure the LCA was carried out for a passive house structure and compared to the low-tech structure. Heating demand is low due to the waste heat usage in both cases, with 12.4 kWh/(m².a) for the light concrete building and 6.4 kWh/(m².a) for the passive house. Cooling demand is in both cases quite similar at 3 kWh/(m².a). Electricity consumption for building operation and plug loads in the light concrete variant is 21.8 kWh/(m².a) vs the passive house with 25.8 kWh/(m².a) not considering the electricity for the servers.

The choice of wood as building material should give an understanding on the different global warming potentials of wood and concrete based structures in contrast. This alternative variant fulfils the passive house standard in Germany. It combines concrete floors with wooden façades and wooden roof structure, the latter covered with PV. The mechanical system for this passive house considers an integrated decentral ventilation unit with heating, cooling and high-efficient heat recovery. Manual window ventilation for day flushing is also considered.

The total building operation energy numbers in the results charts consider artificial lighting, computers, pumps, fans, servers, heating and cooling. The window to wall ratio is 20%. The office spaces are planned to be open-space offices, with an average occupation density of 13m²/person including meeting rooms and single offices. Windows have no external movable shading device, but are positioned on the inner façade side. The architectural form and window sizing is optimized by parametric study to provide adequate solar protection and keep daylight levels appropriate. As glare protection manual interior devices will be provided on demand. Artificial lighting is provided using LED and a peak power of 10W/m² plus manual ON/OFF control is considered. Computers are considered with an average electrical power of 120W/workplace. Servers of 3kW electricity consumption are integrated in the cores next to the restrooms. During appropriate times this internal heat gain is used within 400m² office space, which results in a specific heating power of 7.5 W/m². The 100% annual electricity consumption of the servers is considered in the total annual energy numbers for electricity. As weather data the TRY 2015 dataset for Heidelberg main station was applied. The windows allow for tilting or complete opening to provide night and day flushing. In the simulation model a stack ventilation model was considered. Sizing of openings are for night flushing 5 ACH and day flushing with 3 ACH. Within the office spaces ceiling fans are installed for comfort through accelerated air speed to allow for an operative temperature threshold increase of 3K in comparison to typical cooling setpoint temperatures for office spaces.

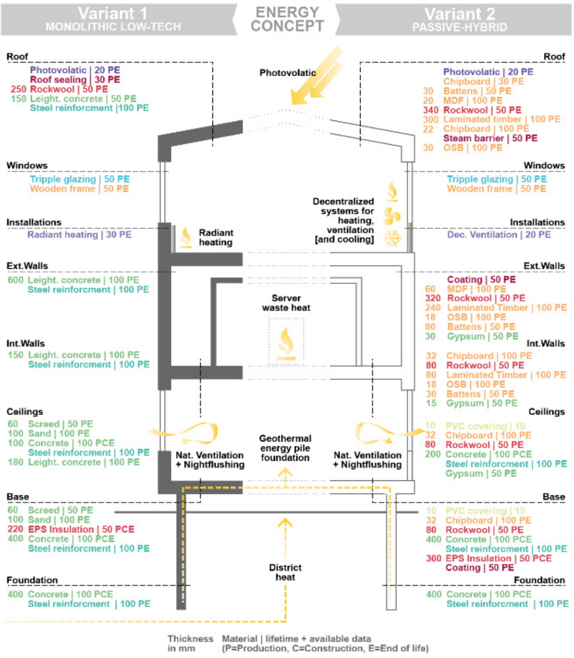

Figure 2: Individual material assemblies and climate concept for Variant 1 and 2 and Energy concept of both variants. The colors are based on material type and are corresponding to the analysis diagrams.

In both systems geothermal energy is used via activated pile foundations considering an EER of 5 for heating and EER of 4 for cooling. In addition the waste heat generated by the server units within the office spaces are integrated as basic space heating. Photovoltaics on the entire roof is used to minimize annual electricity demands from the grid.

In this case-study two scenarios of PERT, PENRT and GWP throughout the analysis period were considered regarding the fraction of renewable energies. In the first scenario the static factors according to building code DIN 18599 were applied continuously throughout all the years. In the second scenario the constant increase of the overall renewable energy supply fraction from the grid was considered to reflect political renewable energy targets predicted by a BMU study of 2011.

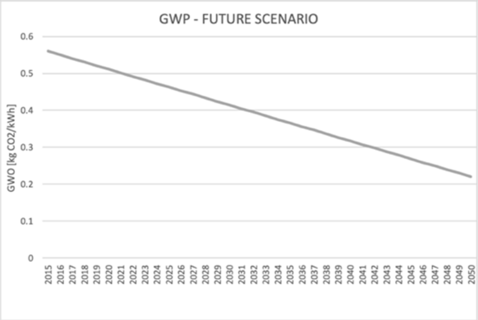

Figure 3: GWP change factor of german energy-mix for electricity

Grasshopper Tool

The boundary conditions described are gathered and merged using a 3D Rhinoceros model as interface between the spatial design and a Grasshopper toolset. This toolset gives a more user-friendly interface to assign material information from the Ökobaudat or other sources to the geometrical information of a 3D Rhino model. A parametric model is set up linking all detailed construction material definitions for embodied energy assessment in combination with thermal and daylight simulation via TRNLizard. Based on this thermal comfort, daylight quality, shading effects and energy consumption are directly linked with embodied energy in materials to determine the information for the LCA. The toolset allows to assign layers into an assembly and link this information to geometrical surfaces. At the end massing is summed up according to various aspects like single materials, phases, assemblies, etc. that gives the opportunity to analyze more precise sources of higher energy demands.

The building elements are considered as suggested by the simplified calculation method according to the DGNB 2018. (exterior walls including doors and windows; roof; floors/ceilings including floor construction and coverings; base plate including floor construction and coverings; foundation; interior walls and doors; heating, cooling and ventilation; other technical building installations (e.g. photovoltaic))

All these building elements were initially modeled as 2D surfaces without thickness. The LCA tool uses the areas from the Rhino-model and combines them with the information applied within the Grasshopper tool, which in this case makes use of the Ökobaudat dataset. For this, detailed sections of each building assembly are needed. The selection of every material in each assembly is necessary. The indicator data of these materials are selected from the Ökobaudat dataset or can also be individually defined according to more specific manufacturer information and other databases as desired. Information on layer thickness and life-time per material are added. All this information is compiled and calculated for the LCA modules A1-A5, B1-B5 and C1-C4 as available. Simultaneously, the Rhino model is used for the TRNSYS simulation. The resulting data provides the energy demands for electricity, respectively heating and cooling used in the LCA module B6. The energy demand is converted into the global warming potential in kgCO_2eq.

The tool generates predefined dynamic plots to show in a sequence the impacts over the 100 years analysis period. Specific lifetimes can be analyzed in depth by a sun burst chart indicating the weight of materials per assembly and phases. Grid based daylight analysis and thermal comfort studies extend the life cycle assessment in visualizing the impact and performance of the building solution. The following Figure 4 shows the information workflow used for the integrated LCA in this study.

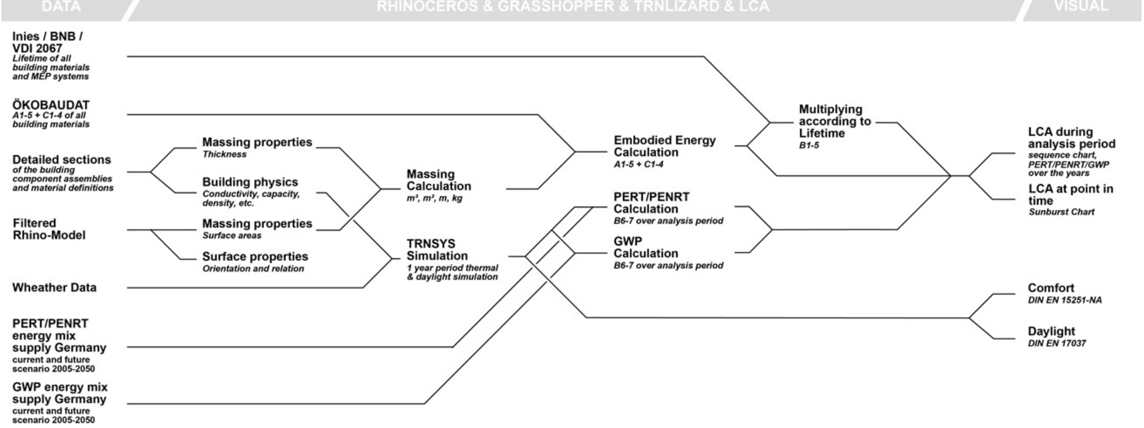

Figure 4: Workflow of integrated LCA tool for Rhinoceros and

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RESULTS AND OPTIMIZATION

Thermal and daylight simulation

The two different cases described were analyzed for thermal comfort, daylight qualities and energy consumption. To make these different solutions comparable in regards to comfort and energy consumption it was assumed that in both cases the same summerly comfort limit according to the DIN 15251-NA are achieved by applying cooling and ceiling fan effects. By ceiling fans the comfort can tbe optimized according to the DIN 15251 standard, that allows to increase the upper threshold by 3K. In the following visualization this 3K was instead reflected by an operative temperature reduction of 3K to reach the solid red line. As worst case the ceiling fan cooling potential is considered in the low-tech variant as cooling energy. The following Figure 5 shows the resulting comfort.

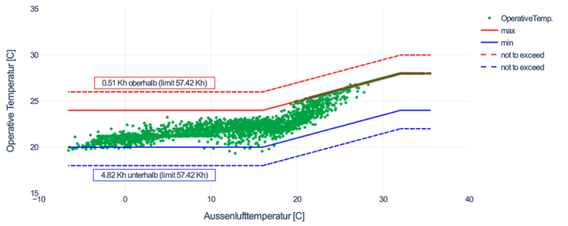

Figure 5: Thermal comfort results, Variant 1 (Low-tech monolithic light-concrete)

Daylight simulations were carried out considering the criteria for daylight autonomy of the DIN EN 17037: 2019. Neighboring buildings were considered and led to partly less daylight in the first floor along the façade, those spaces are not to be used as permanent working spaces. The windows were optimized to maximize daylight using a parametric study . In the first floor the results show that almost 89% of the whole floor area has more than 100lx and 68% is above 300lx, which fulfills daylight autonomy criteria. Further optimization can be achieved by increasing the window heights in the first floor.

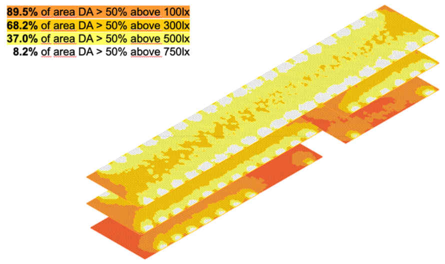

Figure 6: Daylight autonomy thresholds based on DIN EN 17037

Life Cycle Assessment

Life cycle assessments for both variants were performed. The following Figures 7 and 8 show sunburst diagrams for the low-tech light-concrete office building and the passive house wood-concrete-hybrid structure after 10 years (corresponding to the political targeted year of 2030). Colored by material or energy type corresponding to the concept drawing Figure 2, the diagrams visualize the impact of individual building components and materials for each life time module.

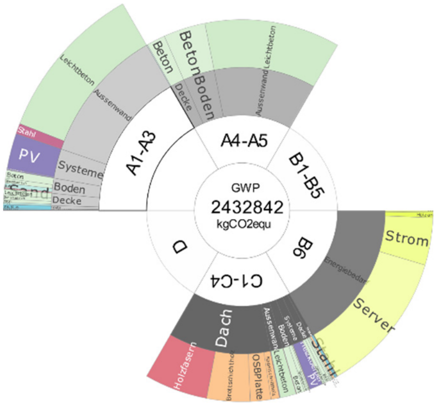

Figure 7: Variant 1 (Low-Tech) LCA after 10 years

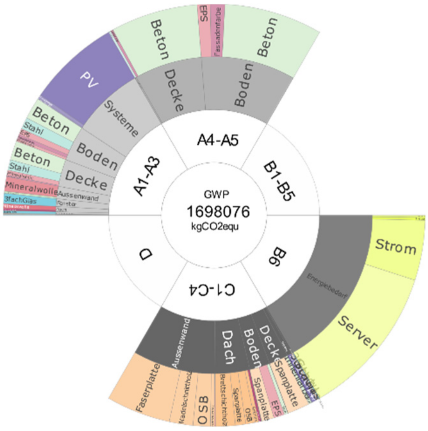

Figure 8: Variant 2 (Passive-Hybrid) LCA after 10 years

The first variant shows the highest GWP in the manufacturing stage (from cradle to gate) while the second variant's manufacturing stage is playing an equal role to its end of life stage. This can be explained by the way the Ökobaudat data balances the carbon sink effect of wood. By giving wooden materials a positive credit for the stored CO_2 in the module A1 and equalizing it in the end-of-life phase, the dataset reflects the realistic assumption that greenhouse gas is stored in wooden materials until released at disposal.

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The overall GWP during 10 years of the passive-wood structure is around 30% smaller than the monolithic lightweight concrete structure. The GWP of the construction phase and operational energy differ only slightly. The energy concept utilizing the waste heat generated by the server leads to a minimal heating demand. By this, the heat energy saving effects of the passive house are negated by the increased electrical fan power demand for ventilation. This makes the passive-house variant more resource-intensive in terms of operational energy compared to the low-tech variant. Thus, the 30% savings in GWP can be attributed to the embodied energy of the building materials. As it can be seen in detail for each building element, concrete and reinforcement are major contributors to the GWP. Important to mention is that the LCA data provided by the Ökobaudat are fragmentary for most materials. Especially, data on process energy used by transport to the construction site (A4-5) are rarely available as shown in the concept drawing Figure 2. E.g. only for concrete, EPS and painting data, on the construction phase was available. Thus, no final assumptions can be made. Data on the recycling potential are not calculated in this case-study but could describe further benefits for one variant or another.

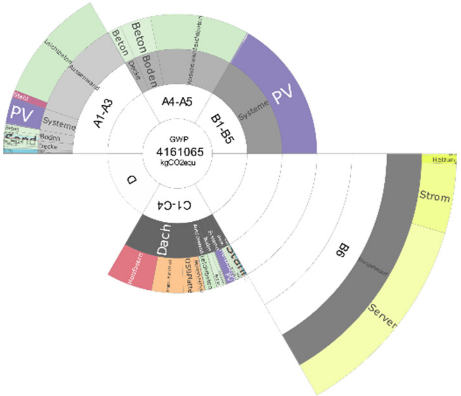

Figure 9: Variant 1 (Low-Tech) LCA after 30 years (2050)

After 30 years (corresponding to the political targeted year of 2050) some technical devices and photovoltaic modules have to be replaced (Figure 9). In addition, the operational energy demand summed up over the previous years and its weight increased. The positive effect of photovoltaic and the change of the German energy mix are not taken into account in these diagrams. Operational energy becomes now significantly more relevant. In order to reach the 2050 goals the hybrid structure of less embodied energy is preferable in this comparison. Due to the optimized energy concept, the building envelope in passive house standard does not bring significant improvements regarding operational energy but only increases the embodied energy of the structure. This holistic energy consideration shows where large quantities of GWP can be saved: by reducing server electricity and the material consumption of the building envelope.

To understand the long-term impact of both variants Figure 10 and 11 show the global warming potential life span of 100 years. Coloured by material or energy type the diagram shows the increase of GWP over time due to cumulative energy consumption in a linear way and the energy embodied in replaced materials as plateaus. After an expected life time of 50 years the wooden structure has to be renewed to a large extend. This refers mainly to insulation and sealing materials which can be minimized with the monolithic construction variant. This shows that further discussion on long-term impacts of each structure is needed beyond the 2050 goals.

The sequence charts display the negative GWP value of energy generated by the installed photovoltaics. Operational energy demand is the major contributor to a rising GWP. Due to the short energy payback time of photovoltaics, the further generated power is contributing significantly to reduce the overall GWP in the considered lifespan. By replacing non-renewable energy from the standard german energy mix this greenhouse gas neutral system can be considered indirectly as positive by replacing worst-case energy supply from coal source.

By applying the second energy supply scenario with increasing renewable energy, the expected global warming potential due to the operational energy is minimized as shown in Figure 12. In this scenario, reflecting targets by the European Union, the GWP of operative energy demand becomes negligible in approx. 60 years. Embodied energy becomes main factor of interest to reduce the GHG emissions by the building.

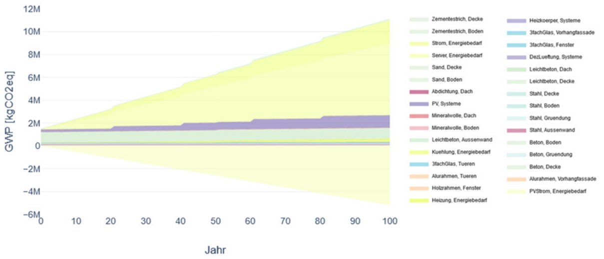

Figure 10: Variant 1 (Low-Tech) LCA study over 100 years life span; static energy mix

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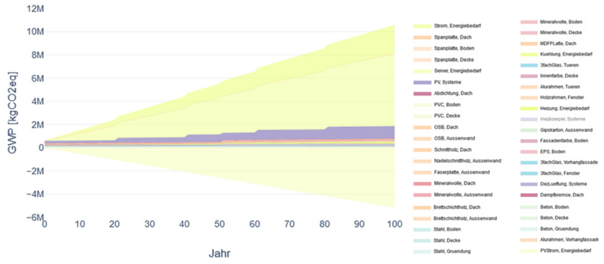

Figure 11: Variant 2 (Passive-Hybrid) LCA study over 100 years life span; static energy mix

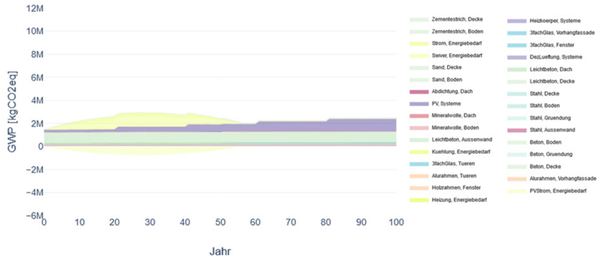

Figure 12: Variant 1 (Low-Tech) LCA study over 100 years life span; dynamic energy mix scenario based on BMU study

DISCUSSION

This case-study shows how a more holistic analysis of a building at the early design stage can reveal potentials for improving building performance and reducing its impact. For example this case-study shows potentials like using server excess heat, that have to be seriously taking into consideration as part of integrated energy concepts. As energy consumptions are already at a very low level for new constructions the question of materials become more relevant. As this case-study shows, integrated low-tech solutions can be overall as performant as e.g. passive house systems with higher insulation levels. Robust solutions with longer lifespans can provide equal or even better performance. Also, in regards to rapid technological development, this could provide more freedom for architectural design not to be restricted by building services, as in common practice.

Also, this analysis of various parameters raises new questions we urgently have to address in view of the climate crises and the related political targets in reduction of GHG emissions to net-zero within the upcoming 30 years.

E.g. it becomes clear that embodied energy is crucial to address. The process of maximizing the share of renewable energy must be extended to the production and transportation of the materials. This is particularly true for energy power plants. As demonstrated in this study wooden buildings are by far not carbon neutral. The carbon is only stored for a certain life time and the positive effect of the carbon sink is linked to sustainable reforestation. Also, wooden structures need plenty of supporting materials to fullfill building physic standards. The right balance of materials has to be evaluated individually.

This raises the question of sufficiency and an increased focus on refurbishment rather than supporting new construction. Analysis of refurbishment life cycle assessments have to be developed considering the previous lifetime of the reused building structure.

Generally, actual building energy efficiency codes need to be extended for LCA studies of embodied energy and define limits and standardized comparative methods aiming realistically for the 1,5°/2°C temperature target. These should consider the entire life-cycle and should not be limited on individual modules. As this case-study exemplarily shows, a simplified cradle to gate analysis does not represent reality exhaustively and could lead to counterproductive decisions. Using the Ökobaudat data set for a cradle to gate analysis would take an excessively positive view of wood-based structures.

Due to a lack of LCA data on the modules A4-A5, scope for further GHG emission reduction cannot yet be identified. In a next step information on transport ways of major materials is crucial for evaluating most effective ways to reduce the overall GWP of a building. E.g. recent research showed that the long-distance transport of a rammed earth construction is about 84% of the overall embodied energy and has a significant impact (Nanz, L. et al. 2019). The same applies to processes of construction and demolition on the site.

Information from manufacturers about embodied energy need to become mandatory in the technical product sheet and have to be added to databases like Ökobaudat. Also information on individual lifetime data for each product should be enhanced. In order to realisticly analyze the holistic GWP of a building energy efficiency factors like the PERT, PENRT of the building code have to reflect the current energy mix and be more dynamic. Ideally that information should be updated annually, reflecting the trend for future scenarios considered in the LCA. Also, the effects of change of land-use should be analyzed, e.g. in the LCA module of construction. Further individual aspects that are not yet taken into consideration can make an enormous difference. e.g. building electronics meeting modern standards.

With respect on sufficiency the topic of comfort must be discussed openly and creatively as well. New technologies enable more individual, more local thermal comfort solutions. This may lead to radically new and more sufficient design approaches, that also should be analyzed and compared with such a dynamic and holistic tool.

Summarized, we see an urgent need for the availability of precise data and more realistic regulations to tackle and improve the real environmental impact of a building.

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Moreover, we need a new culture on implementing these tools in projects. By using open source programs as Rhino and Grasshopper, as well as parametric modelling to integrate the complexity of many parameters into one tool, the presented approach addresses the problems on current use of LCA-tools in a large scale as shown by Jusselme, T. et al. 2018..

OUTLOOK

In a next step the comparison will be extended by analyszing the refurbishment of an office building with a heritage façade. In addition the integration of other databases alongside the Ökobaudat and the overall usability of the tool and the type of output plots will be improved incrementally.

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