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Dominik Maierhofer [a], Martin Röck [a,b], Marcella Ruschi Mendes Saade [a,c], Endrit Hoxha [a,d], Alexander Passer [a,*]

[a] Graz University of Technology, Working Group Sustainable Construction, Graz, AT, Austria
[b] KU Leuven, Faculty of Engineering Science, Department of Architecture, Leuven, BE, Belgium
[c] Graz University of Technology, Institute of Structural Design, Graz, AT, Austria
[d] Aalborg University, BUILD - Department of the Built Environment, Aalborg, DK, Denmark

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ABSTRACT

Buildings constructed today need to be nearly-zero energy/emission buildings (nZEB) during operation. Amongst strategies to meet today's nZEB performance requirements are passive building concepts. However, it is unclear to which degree such concepts aid buildings to achieve net-zero carbon targets. To address this research gap, we conduct a life cycle assessment (LCA) of the passive nZEB concept '2226' based on its original prototype office building in Austria. We deploy a quantity takeoff and the measured end-energy demand to calculate the embodied and operational GHG emissions. In line with the recent draft of the building LCA standard EN15978, we split energy usage into building-integrated and non-integrated systems. Embodied GHG emissions make up about a third of the total life cycle GHG emissions (33%), and operational energy use accounts for two-thirds (67%) of the life cycle GHG emissions, considering the current Austrian energy grid mix. The contextualisation with the literature shows better performance in comparison to existing building standards, yet no reduction is achieved compared to buildings with similar nZEB ambitions. The measured end-energy analysis shows that two-thirds (68%) of the operational GHG emissions are allocated to building-integrated systems, i.e., those regulated by today's EU Energy Performance of Buildings Directive. Almost a third (30%) of the operational GHG emissions can be allocated to non-integrated systems, currently being reported as optional in the latest draft of the standard EN15978. We recommend extending the system boundary of building LCA including these end-energy uses by non-integrated systems in future building regulation and building LCA practice.

1. Introduction

The contribution of building construction to global greenhouse gas (GHG) emissions is widely acknowledged. A recent report developed by the International Energy Agency (IEA) identified buildings responsible for 37% of global energy consumption and GHG emissions, of which 27% were related to building operations and 10% to construction materials' manufacturing [1]. Moreover, the global urban population is expected to grow significantly in the next decades [2], which — as predicted by [3] — will require the construction of approximately 82 billion square meters in urban areas by 2030, an area corresponding to over half of the world's current building stock.

The decarbonisation efforts of the European Union (EU), which signed the Paris Agreement, are expressed in the creation of an ambitious GHG emission reduction target, namely 91–94% below 1990 levels until 2050 [4]. These figures highlight the current pressure faced by policymakers and all the different stakeholders involved in the building sector to reduce GHG emissions generated during buildings' life cycles [5]. In fact, according to [6], in no other sector is the potential for lowering the energy need below business-as-usual levels as significant as in buildings [7,8]. The challenge to lower GHG emissions according to targets set within the Paris Agreement is two-fold: (i) reducing emissions associated with the energy demands during the operational phase of buildings, for which several different technologies already exist and are increasingly applied [9–13] and (ii) lowering so-called embodied GHG emissions, associated with the manufacturing, maintenance and end-of-life of building materials, which are found to be a hidden major issue for effective decarbonisation of the built environment [14], in part

* Corresponding author.
E-mail address: alexander.passer@tugraz.at (A. Passer).

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due to the lack of implementing readily available low carbon alternatives.

In order to overcome these challenges, the reduction in GHG emissions of buildings with the goal to achieve nearly-zero energy buildings (nZEB) and net-zero energy buildings (NZEB) is widely investigated in the scientific literature [15–22]. The metastudy by [23] gives a comprehensive overview of the research in the NZEB field. This study analyses the performance of 34 case studies in hot and humid climates, focusing on active building systems, the integration of energy efficiency, and renewable energy utilisation. Another metastudy by Röck et al. [14] assessed and harmonised the environmental performance of 238 case studies from 54 publications in relation to the embodied and operational impacts of buildings and emphasised the increasing relative importance of embodied emissions in relation to more energy-efficient buildings. Hoxha & Jusselme [10] investigated the emissions of a highly energy-efficient building in Switzerland and further extended the system boundary to the included furniture and appliances. The assessed building called 'smart living lab' emphasises the vision of the '2000-W per capita society' proposed by the Federal Institute of Technology in Zurich. The base assessment of the building appeared to be net-zero, yet they show that in such highly efficient buildings, up to 30% of the life cycle GHG emissions can be allocated to appliances and furniture if this is included in the assessment scope. Gomes et al. [24] give insights into the relationship between operational and embodied emissions of an innovative photovoltaic-powered Living Lab in Campinas, Brazil, based in a cooling-dominated climate and emphasise the relative importance of embodied emissions in highly energy-efficient buildings. Muñoz et al. [25] conducted a study on the energy efficiency of an innovative school building and demonstrated the importance of a whole life cycle approach in the design and optimisation of highly energy-efficient buildings.

Innovative new concepts to achieve nZEB or NZEB goals are not only being investigated at the building level. Various studies are also examining individual-specific systems for their potential mitigative influence on the overall emissions of a building. In relation to passive envelope and façade systems, Omrany et al. [26] conducted an extensive review of different passive wall systems and explored the potential in relation to the reduction of energy consumption as well as improving the thermal performance of buildings. The study assessed literature regarding the applicability of Trombe Walls, Autoclaved Aerated Concrete walls, Double Skin walls, PCM wall systems and Green Wall Systems. All systems assessed show the possibility to lower the operational energy demand when applied on the building level. On the other hand, Luo et al. [27] provided an extensive review of active building envelope technologies and investigated their applicability to improving building energy performance. Both passive and active systems show the possibility to lower the life cycle emissions of buildings by mitigating operational energy demand. Furthermore, the question of NZEBs also relates to the material level of buildings. Intensive research has been undertaken in relation to lowering the GHG emissions of building materials and achieving carbon sink effects via the uptake of carbon through the life cycle of buildings in order to achieve net-zero emissions in the built environment [28–31].

Architects, engineers and scientists are continuously developing approaches to achieve nZEBs and aim for NZEBs, with this requirement being already proposed in the latest draft of the energy performance of buildings directive in Europe [32]. In view of approximately 37% of global GHG emissions currently attributed to the building sector and the need for rapid reductions in GHG emissions, the development of various approaches to reach the final goal of NZEB are of great importance and require rapid implementation in the practical economy. In this paper, we analyse one of these innovative approaches for nZEB, the so-called '2226' passive building concept, through the example of its original prototype, a six-storey office building 'be 2226', built in 2013 in Lustenau, Austria.

2. Objectives and research questions

The objective of this paper is to critically analyse the innovative passive nZEB building concept '2226' regarding its climate impact via the initial prototype building 'be 2226'. The case study has already been used in previous research projects such as PEF4Buildings [33] in order to test distinct LCA Methodologies on the building level (i.e. Product Environmental Footprint Method) and the IEA EBC Annex72 [7,8] for the assessment of LCA results in different countries with the goal to push harmonisation measures for building LCA. On the other hand, we use the building to test our hypothesis of the concept of it being a suitable solution for effective climate change mitigation. In addition, the life cycle inventory, and the impact assessment, which were also the basis for the previous studies, are published as part of this study. We use this initial prototype building of the concept '2226' to answer the following research questions:

- What are the life cycle GHG emissions of the building 'be 2226'?
- How do the results compare to other sustainable building concepts? Is this passive building concept achieving a reduction in GHG emissions during the life cycle compared to similar approaches?
- How does this building concept fit into the discussion of a net-zero carbon built environment?

3. Method and material

3.1. Life cycle assessment

The assessment methodology conducted in this paper is a Life Cycle Assessment (LCA) and follows the requirements of the standard EN 15978:2011 [34]. Yet, it has been adopted in relation to the most recent draft version of this standard from prEN 15978–1:2021–09 [35]. LCA is a methodology to assess the environmental impacts and resources used throughout a product's life cycle, i.e., from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal [36] and is extensively used to assess the environmental impacts of buildings [37–40]. The scope of the paper is the building itself (core and shell), excluding the surroundings. The system boundaries consider life cycle modules of the product stage (Modules A1-A3), the transportation of the materials from factory to site (Module A4), the replacement in Module B4, the operational energy usage in Module B6, the operational water usage in Module B7 as well as the end-of-life Modules C1, C2, and C3–C4. The considered life cycle modules are illustrated in Fig. 1. The LCA background database used in this assessment has been the ecoinvent 3.8 [41]. The method used to calculate the environmental indicator 'Global Warming Potential' is the method 'EF method (adapted) v.1.0', developed by the European Commission. The calculation is conducted in the LCA software SimaPro (version number 9.3.0.2). A description of further environmental indicators, as well as the resulting emissions of the case study building for these indicators, are attached to the supplementary material of this paper but are not explicitly explained in this paper.

The term 'operational energy use' in the most recent standard prEN 15978–1:2021-09 is put together by three distinct sub-modules [35]:

1) Module B6.1: The energy used by building integrated systems (services) that are regulated. 'Regulated' in this regard means energy demand from building integrated systems (services) covered by the EU Energy Performance of Buildings Directive (2018/844/EU) (EPBD) and its national implementation. This covers energies required for heating, cooling, ventilation, humidification, dehumidification, domestic hot water, and fixed (installed) lighting.
2) Module B6.2: The energy use of building integrated systems (services) that are not regulated, meaning the energy usage of other building-related technical systems that are not covered by the EPBD, but are necessary for the technical and functional performance of the

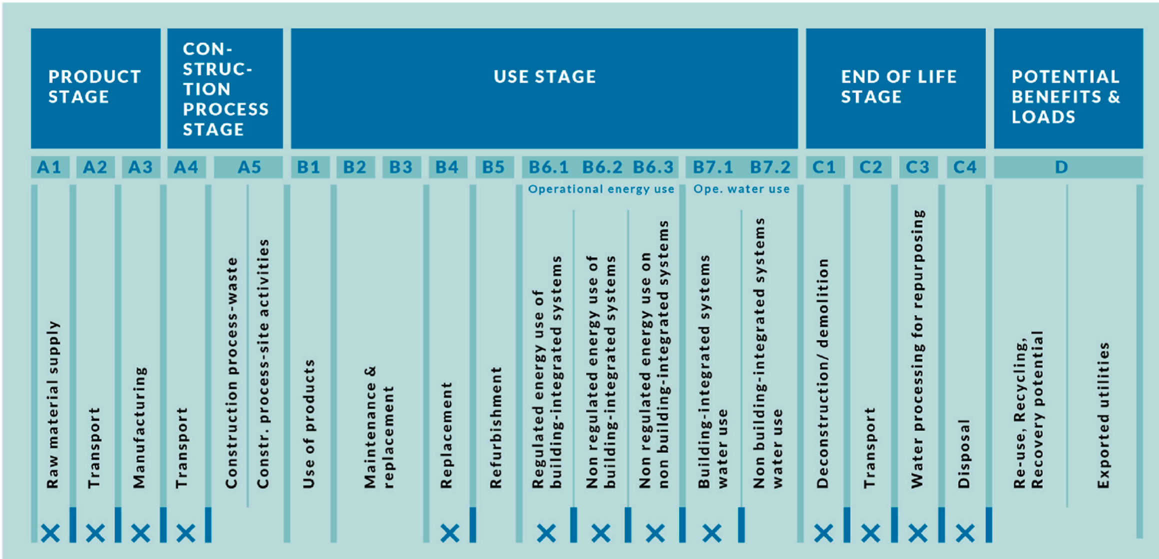

Fig. 1. Life cycle modules of buildings as defined by the most recent version of the standard prEN 15978–1:2021–09 [35].

building such as transport methods (e.g., escalators, elevators), communication systems, security installations or building services.

3) Module B6.3: Other energy use related to building user activities such as plug-in appliances; computers, washing machines, refrigerators, audio-visual equipment, plug-in lighting, and production or process-related equipment used in the building. The standard states that Module B6.3 may be reported optionally as additional information to the assessment.

Energy allocated to Module B6.1 and to Module B6.2 thereby forms the energy demand from 'building integrated systems'. Therefore, the energy demand in Module B6.3 is allocated to the category 'non-integrated systems'. On the other hand, the energy consumed by services allocated to Module B6.1 can be seen as 'regulated services', while the energy consumed by services that are allocated to Modules B6.2 and B6.3 is considered to be consumed by 'non-regulated service'. The topic of the operational energy use in buildings allocated into the distinct types of Module B6 is illustrated in Fig. 2.

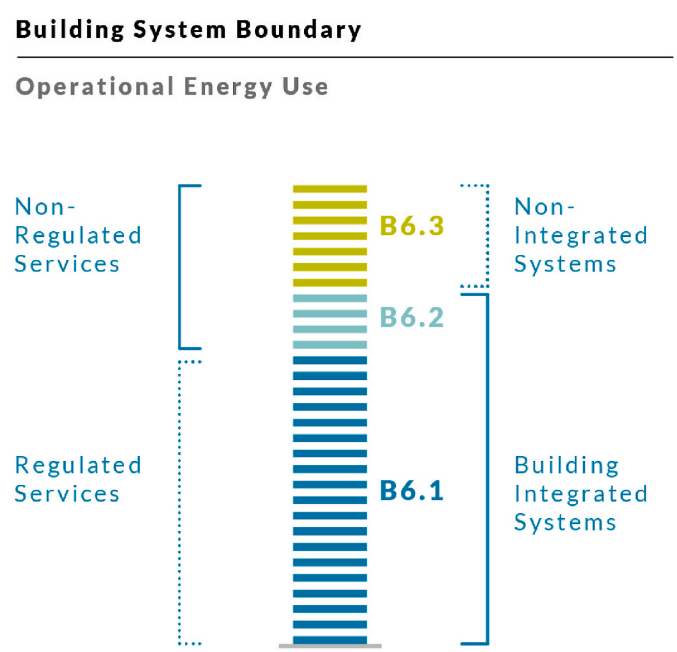

Fig. 2. Building system boundary for operational energy use according to prEN 15978–1:2021–09 [35] and the allocation of Module B6's distinct sub-modules.

3.2. Case study: Office building 'be 2226'

The case study is the office building 'be 2226', situated in the business district 'Millennium Park Rheintal' in Lustenau, Vorarlberg, Austria and has been completed in the year 2013. The innovation of this office building is the application of a design concept with no heating, air-conditioning, or ventilation systems installed. The thermal condition within the building, in general, is influenced by 1) the outdoor conditions (temperature, relative humidity, wind, and solar radiation), 2) the internal heat gained via the users of the building itself, and 3) other heat sources such as lighting and appliances e.g., computers and servers. The concept ensures temperature stability between 22 °C and 26 °C using the 'high-mass' of the building itself to store thermal energy gains in the mass. It is designed with about 80 cm exterior walls. Further, windows are placed on the inner side of the wall, thus the thick walls provide shade in summer to mitigate externally induced heat by the sun (see Fig. 3).

The indoor air quality in the building is monitored with sensor-controlled ventilation wings of the windows, which open automatically as soon as the CO_2 concentration or the temperature in the room rises above set limit values. When it is hot, the windows open at night to cool the building with natural draughts. As control hardware, the building has sensors in the respective rooms as well as a weather station on the roof, which are connected to a central facility server via a permanently wired bus system. The facility server evaluates the data obtained, and the result of this evaluation controls the opening of the ventilation flaps. Similar concepts have already been analysed in the literature and are still a topic of fundamental research [42,43]. For more details on the office building 'be 2226', we refer to the official publication by Aicher et al. [44].

The functional equivalent for this LCA study, as recommended by the outcomes of the PEF4Buildings project [33,45,46], is one office building, excluding the surroundings (What?) with a gross floor area (GFA) of 3.201 m^2 (How much?). The building applies a passive nZEB concept, following technical and functional requirements (How well?). The study is observing a reference study period (RSP) of 60 years (How long?), used within the Level(s) pilot phase [47]. Thus, the functional unit is a 1 m^2 gross floor area (GFA).

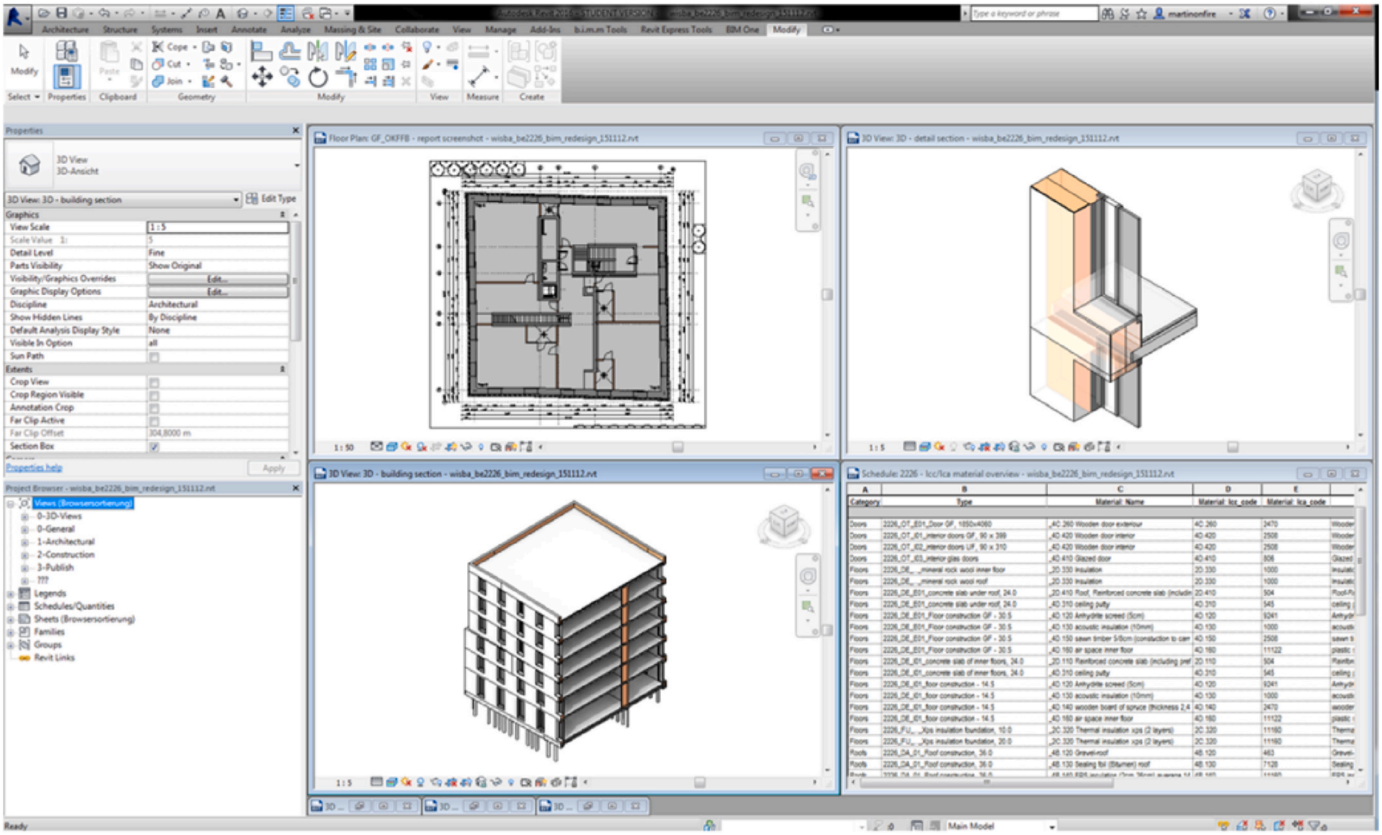

Fig. 3. BIM-Model of the case study building 'be 2226'.

3.3. Life cycle inventory

The quantification of the building elements and materials for the life cycle inventory in this assessment has been done based on a BIM-Model of the building. The BIM-Model was created using the software Autodesk Revit and was remodelled based on information provided by the architects of the 'be 2226' office building. The data exported from the BIM-Model has then been post-processed to provide the quantities of each individual material per building element. The obtained results from this BIM-based quantity-take-off represent the inventory quantities for the life cycle Modules A1-A3, B4, C1 and C3–C4 in the assessment.

The scenario for the transport distances in Module A4 is based on the report Environmental Profile of building elements [update 2017]' developed by Belgian researchers [48]. In this regard, we use a Belgian literature source, as to our knowledge it is currently the best estimate to take since no respective data is available for Austria yet.

The scenario for the reference service life of the building parts for Module B4 is assumed according to the BNB-Service Life catalogue for the building parts and the catalogue VDI 2067 for the HVAC and electrical installations [49,50]. These are the requirements of the German DGNB System [51]. The number of replacements of the building elements is thereby calculated to the rounded-up nearest whole integer according to the standard EN 15978:2011 [34].

The scenario for the operational energy usage for Module B6 in this observation is modelled via the total measured three-year average end energy usage in the building between the years 2013 and 2015. This energy demand represents the energy required in the whole building and therefore, the total operational energy demand for Module B (including B6.1, B6.2 and B6.3, see section 3.1). It is assumed that this energy demand remains constant over the 60-year RSP. At the time of conducting this assessment, no exported energy has been available. We use data from 2013 to 2015 as these measurements have been provided by the building owners.

The values for the scenario of operational water usage in Module B7 were calculated using the water calculation tool provided by the Joint Research Centre of the European Commission (JRC) for the Level(s) Pilot Phase [47]. In order to obtain accurate data for water consumption, the users of the case study building at the time of this assessment have been contacted to provide data on the water consumption.

The scenario for the transport distances of individual materials for the end-of-life Module C2 is again taken by the application of data from the OVAM Report 'Environmental Profile of Building Elements' by Belgian researchers [48].

The percentage allocation to the different waste processing measures (i.e., landfill, incineration, reuse, recycling) to model the scenario for the end-of-life Module C3–C4 also has been obtained via the application of the same report by Belgian researchers [48]. As it is stated in the report, we assumed that with the exception of soil, all construction and demolition waste, whether it is sorted on site, transported from the construction/demolition site to a sorting facility/collection point (e.g., metal dealer or crusher) and from there, is eventually further dispatched to recycling, reuse facility, incineration, energy recovery or landfill. Again, we use the Belgian literature source due to the lack of data availability for Austrian End-of-Life Scenarios of building materials. We are aware that this indeed induces systematic uncertainty in our calculations.

The background processes for this LCA study are taken from the ecoinvent 3.8 database using the SimaPro LCA software and have partly been remodelled in order to better represent Austria. An overview of the applied processes for the impact assessment as well as their modifications is given in the supplementary material of this paper.

3.4. Scenario for operational energy usage

Considering the fact that no heating, cooling and ventilation systems are installed in the building, parts of the operational energy demand accounted for B6-1 are zero, when calculated according to the existing standards (e.g., the energy certificates mandator in the Austrian building approval). A study conducted in 2011, which is not published but available to us, analysed the energy efficiency of the building concept ’2226’ by simulating one exemplary room of the building. This study also simulated that no energy is consumed for heating and ventilation of this particular room. The study states that the remaining primary energy demand for the operation of the building is 60 kWh per m^2 energy reference area and year, required for domestic hot water supply, artificial lighting, and auxiliaries.

Due to the technical appearance of the building, only the energy carrier ‘grid electricity’ is used for the remaining systems to ensure operation. For this paper, the value of the real consumed energy of the whole building, measured between 2013 and 2015 has been given, providing the figure for a three-year-average end energy consumption of 131.581 kWh/a. With all this information available, we "reverse-engineered" the primary- and end-energy demand allocated to the distinct Modules B6.1, B6.2, and B6.3, by applying factors from the literature. We started with the measured end-energy-demand and calculated the value for primary energy demand using the conversion factor of 1.63 Austrian electricity grid [52]. With the simulated primary energy demand acc. to the internal study in 2011, we recalculated the value for the end energy demand in B6.1 respectively. The value for the simulated energy demand in this regard has been recalculated to fit the reference area of this paper (GFA) with a factor of 0.7563. For Module B6.2, the energy required for the built-in elevator is considered. Here, we used a literature value for the operational energy demand of an elevator given by the paper of Salmelin et al. [58] and recalculated it for a six-storey building. The remaining energy demand possible to allocate to Module B6.3 is therefore the difference between the total measured end energy demand and the two results of the allocated energy demands to Modules B6.1 and B6.2.

With this approach, we were able to calculate the distinct shares of certain Modules on the measured three-year average end energy consumption. The end energy consumed by services within Module B6.1 amounts to 89.117 kWh or 68% of the annual energy consumption. The end energy demand for the elevator in Module B6.2 results in 2.400 kWh per year in our calculation, thus 2% of the energy consumption. Finally, the remaining appliances consume 40.065 kWh — 30% of the total end energy consumed within the case study building. The calculated values are also listed in Table 1 in order to provide an overview for comparison. Regarding this, we want to mention that the reverse-engineered values do not necessarily represent the real allocation to the distinct Modules of B6, yet this approach manages to provide an overview and a result to enable discussions.

4. Results

4.1. Embodied GHG emissions

The results for the embodied emissions in Fig. 4 are shown in the unit of $kgCO_2eq$ per m^2 Gross Floor Area ($kgCO_2eq/m^2_{GFA}$). The first results discussed here are the ones presented in Fig. 4 in the middle column. The major embodied GHG emissions are caused in the product stage of the buildings’ materials due to the extraction of raw materials as well as the transportation and the manufacturing of the building materials. This results in emissions of 270 $kgCO_2eq/m^2_{GFA}$ for Module A1-A3 and therefore amounts to 67% of the total embodied GHG emissions calculated. The scenario of replacement of building materials in Module B4 resulted in emissions of 66 $kgCO_2eq/m^2_{GFA}$. The scenario for transportation of the materials from the respective factory to the building site in Module A4 causes emissions of 28 $kgCO_2eq/m^2_{GFA}$. Observing the results of the assumed scenarios of the end-of-life modules of the building, the deconstruction of the building causes emissions of 5.2 $kgCO_2eq/m^2_{GFA}$ (Module C1), the transportation 8.2 $kgCO_2eq/m^2_{GFA}$ (Module C2) and the waste processing and disposal causes 26 $kgCO_2eq/m^2_{GFA}$ respectively (Module C3–C4).

Observing the emissions in the distinct life cycle modules in relation to the element contribution on the left column in Fig. 4, further details of the embodied GHG emissions can be obtained. The higher GHG is induced by the contribution of the structural systems (’2E – Vertical building constructions’, ’2D – Horizontal building constructions’ and ’Foundations, floor constructions’), accounting for about 70% of the initial emissions in Modules A1-A3 and 47% of the total embodied GHG emissions calculated. Module B4 GHG emissions, on the other hand, are mainly driven by the replacement of the building elements associated with ’4C - Façade systems’, ’4B - Roof cladding’ and ’3G - Telecommunication and information technology systems’.

Finally, the GHG emissions are also allocated to distinct material categories on the right column in Fig. 4. It can be observed that the material ‘Brick’, used for the construction of the exterior as well as interior walls, stands out as the major contributor of embodied GHG emissions over the whole life cycle of 99 $kgCO_2eq/m^2_{GFA}$. Other materials, that play a significant role regarding the embodied GHG emissions are ‘Concrete’ (96 $kgCO_2eq/m^2_{GFA}$), ‘Plastics’ (49 $kgCO_2eq/m^2_{GFA}$), ‘Lime Plaster’ (46 $kgCO_2eq/m^2_{GFA}$), and ‘Wood’ (35 $kgCO_2eq/m^2_{GFA}$). The total embodied GHG emissions of all materials over the whole life cycle result in 404 $kgCO_2eq/m^2_{GFA}$.

The major amount of the embodied GHG emissions of the case study building is caused in the product stage of the materials in the life cycle Module A1-A3. In the case of the ‘be 2226’ building studied in this

Table 1
Overview of "reverse-engineered" energy demand (end- and primary energy demand) in different Modules of B6. The end energy demand represents the measured three-year-average end-energy consumption of the building ‘be 2226’ between 2013 and 2015.

Module	End Energy Demand				Primary Energy Demand			
	kWh/a	kWh/ $m^2_{GFA}a$	%	Description	kWh/a	kWh/ $m^2_{GFA}a$	%	Description
B6	131.581	41.1	100%	Measured three-year-end-energy consumption (100% grid electricity)	214.478	67.0	100%	Measured three-year-end-energy consumption multiplied by a factor of 1.68 acc. to Austrian Standard OIB RL 6 to get the primary energy demand
B6.1	89.117	27.8	68%	Calculated from the simulated energy demand and using a conversion factor of 1.63 for Austrian grid electricity according to Austrian Standard OIB RL 6, to get the end energy demand	145.260	45.4	68%	Simulated primary energy demand (60 kWh/ $m^2_{NFA}a$), recalculated to gross floor area (3.201 m^2) with a factor of 0.7563
B6.2	2.400	0.7	2%	End Energy Demand for Elevators per year, stated by Salmelin et al. [58], recalculated for a 6-floor building	3.912	1.2	2%	Calculated from end energy demand of elevators using a conversion factor of 1.63 for Austrian grid electricity acc. to OIB RL 6 to get the primary energy demand
B6.3	40.065	12.5	30%	Difference between the total result in B6 and the reverse-engineered energy demands in B6.1 and B6.2	65.306	20.4	30%	Difference between the total result in B6 and the reverse-engineered energy demands in B6.1 and B6.2

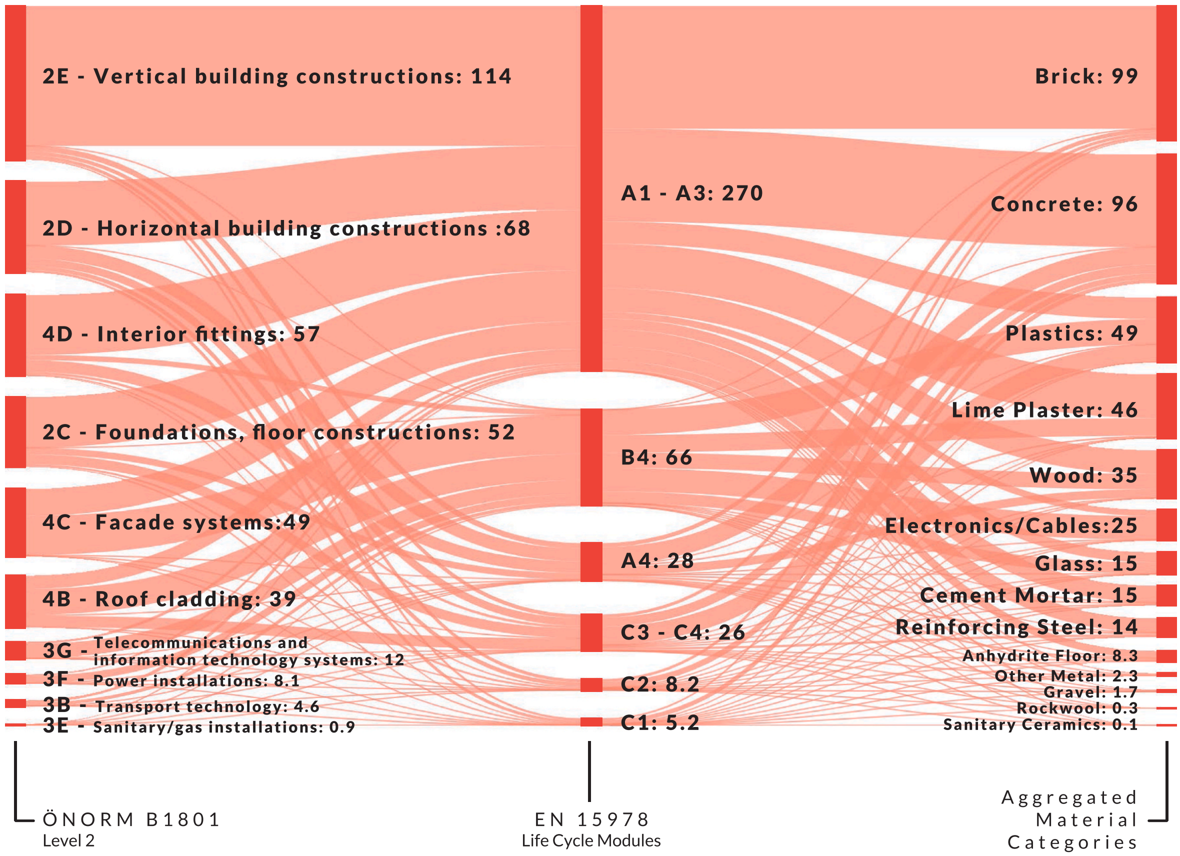

Fig. 4. Embodied GHG emissions of the case study building 'be 2226' in $kgCO_2eq/m^2_{GFA}$. The left column represents the classification of the emissions according to the categories of the Austrian standard ÖNORM B1801 — Level 2. The middle column contains the allocation of the emissions into the distinct life cycle modules according to EN 15978. The right column represents the allocation of the embodied emissions into aggregated material categories.

paper, the majority of embodied GHG emissions, therefore, stem from the structural systems of the building (i.e., 'Vertical building constructions', 'Horizontal building constructions' and 'Foundations, floor constructions'), which are responsible for more than two-thirds (70%) of the GHG emissions from materials production and close to half (47%) of the embodied GHG emissions overall.

4.2. Life cycle GHG emissions

With the energy demand allocated to the distinct Modules of B6 and reverse-engineering the energy demands allocated to the distinct Modules of B6, as shown in section 3.4, it is now possible to observe the full life cycle of GHG emissions related to the building. The study period in this sense is the RSP of 60 years chosen within the goal and scope definition. The emissions are calculated using the standard "scenario" in building LCAs: constant energy demand and a constant energy mix throughout the 60-year period studied.

The emissions allocated to Module B6.1 result in 9.47 $kgCO_2eq/m^2_{GFA}a$, for Module B6.2 0.26 $kgCO_2eq/m^2_{GFA}a$ and for Module B6.3 in 4.26 $kgCO_2eq/m^2_{GFA}a$ respectively. In sum, the operational energy usage results in total emissions of 13.98 $kgCO_2eq/m^2_{GFA}a$. The emissions caused by the operational energy usage take a share of 67% of the total life cycle GHG emissions and therefore, share the largest amount of GHG emissions throughout the life cycle. The results are presented in Fig. 5.

Looking at the life cycle GHG emissions, the operational energy consumption is responsible for the majority of the life cycle GHG emissions within the system boundary of the 'be 2226' building (67%), when calculated with the standard "scenario" of constant energy demand and a constant energy mix throughout the RSP of 60 years.

5. Discussion

5.1. Literature comparison

For the purpose of comparison with the values in the literature, the previously mentioned paper by Röck et al. [14], will be used as a reference. This study is chosen since it provides a comprehensive source for the distribution of building emissions in the relevant literature. The paper harmonises the results into three different building standards for residential and office buildings per m^2 of GFA for an RSP of 50 years. 'Existing Standard' refers to buildings constructed before the tightening of legal requirements for building operation. The 'New Standard' refers to buildings following current standards regarding operational energy performance, which are legal requirements. Finally, the 'New Advanced' standard in this paper includes passive houses, low-energy buildings, or near/net zero energy or emission (NZEB) buildings. In this context, the building 'be 2226' can be allocated to the 'New Advanced' standard. It is important to note that the results in the study chosen for comparison are not harmonised in relation to the climate, the scope of life cycle modules as well as LCI data and therefore contain systematic uncertainties.

To compare the results of this paper with those of the metastudy, the results must also be harmonised to an RSP of 50 years. This is done according to the harmonisation process in Röck et al. [14]. Following the high mass concept of the case study building, it is assumed that no significant changes in relation to the exchange rates of elements for the emissions in Module B4 - replacement occurs if the RSP is switched from 60 years to 50 years. Therefore, the embodied emissions in B4 of 60 years are considered as a proxy and are also simply recalculated for the 50 years RSP.

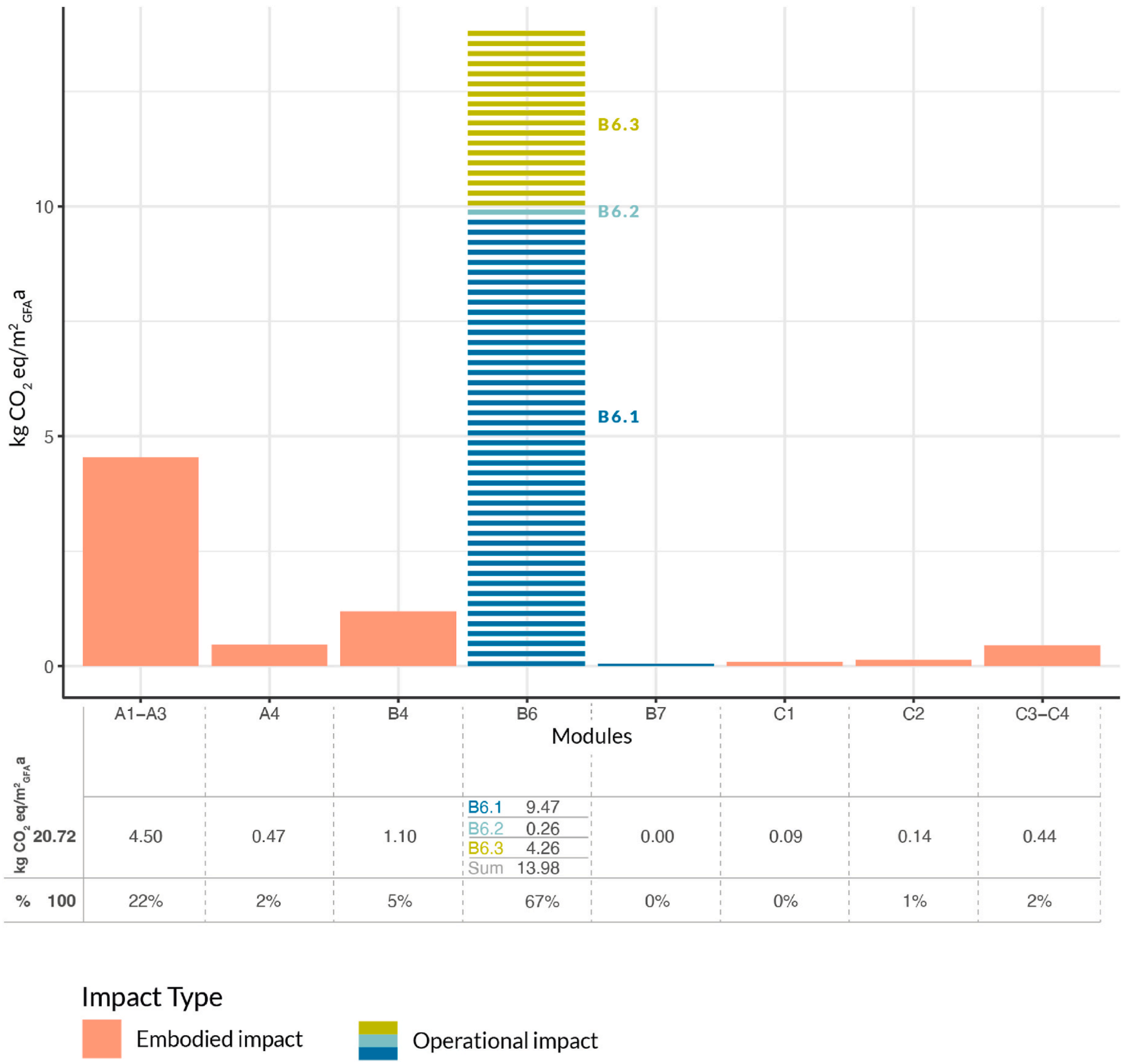

Fig. 5. Full life cycle GHG emissions of the case study building 'be 2226' per life cycle module. Module B6 operational energy usage is divided into distinct sub-modules. The emissions of B6 have been calculated using the emission factors of the Austrian electricity grid from the ecoinvent database.

The harmonised results for embodied and operational emissions in the context of the reference data from the meta-study are illustrated in Fig. 6. In this figure, the distributions of both residential and office buildings are illustrated since the concept '2226' is currently applied for both building archetypes.

If we compare the results of embodied emissions, we notice that these emissions (7.86 $kgCO_2eq/m^2a_{50}$) are significantly lower compared to office buildings in the 'Existing Standard'. Yet comparing these further with the office buildings within the two standards 'New Standard' and 'New Advanced' Standard, it can be observed that the results of the building are close to the median of the reference data set. This indicates that for embodied emissions, despite the abandonment of HVAC systems in the case study building, no mitigation of embodied emissions can be achieved compared to concepts with similar ambitions. It seems that the savings due to the abandonment of HVAC systems are offset by the additional emissions due to the 'high-mass' concept. Thus, it can be concluded that no reduction in embodied emissions can be achieved by the concept '2226' compared to similar nZEB and NZEB buildings.

With regard to the operational emissions, the comparison for the building is not straightforward. The reasons for this are the allocation issues regarding the distinct sub-modules of B6 already explained in the method. In current LCA studies, the operational energies are often calculated based on the applicable standardisation regulations, which take into account only the energy consumption of building integrated systems (Modules B6.1 and B.6.2, see also Fig. 2). Therefore, two comparisons are drawn here. First, the operational emissions in Modules B6.1 and B6.2, which are usually considered in current LCA studies, and second, the total operational emissions in Module B6 including Module B6.3 (see Fig. 6 on the right side).

Observing the emissions in B6.1 and B6.2 (9.73 $kgCO_2eq/m^2_{GFA}a$), as well as the total emissions in B6 (13.98 kgCO2eq/m2GFAa), shows that the operational emissions of the case study building are significantly lower compared to buildings in the 'Existing Standard', especially with regard to office buildings. In comparison with 'New Standard' and 'New Advanced' Standard, a more differentiated view is required. It can be seen that the emissions attributed to Modules B6.1 and B6.2 are again close to the median of the reference dataset from the literature. Thus, considering the common energy consumption of building integrated systems (B6.1 and B6.2), the concept '2226' achieves the same goals as similar concepts (nZEB), but no further reductions in operational emissions are achieved. From this, it can be concluded that the concept '2226' allows for significant improvement in comparison with existing standards, yet it does not achieve lower operational emissions compared

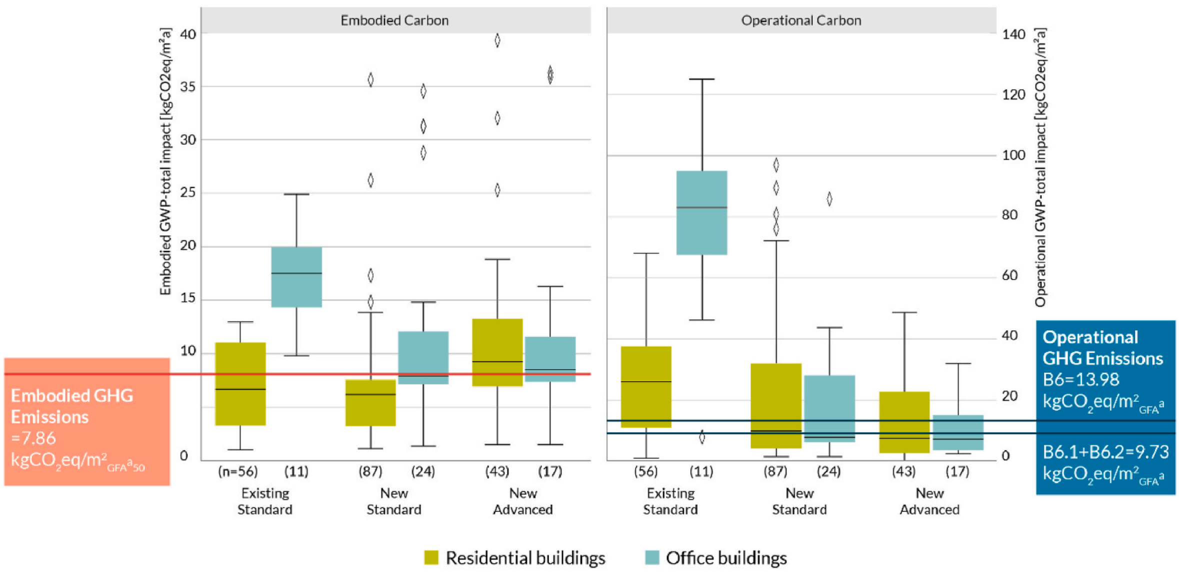

Fig. 6. *Life Cycle GHG emissions of the 'be 2226' case study building in comparison with literature values, based on [14]). The values for the operational energy demand are calculated with the Austrian electricity mix of 0.33 kgCO_2eq/kWh from the ecoinvent database. Taking the value for the European electricity mix of 0,39 kgCO_2eq/kWh, the results would be 18% higher, yet the conclusions would stay the same.*

to similar concepts in the 'New Advanced' standard.

However, if we now look at the total operational emissions in Module B6, we see that these are in the upper interquartile range of the reference data set both for 'New Standard' and 'New Advanced Standard'. The authors state that this gap is observed exactly due to the problem emission allocated to Module B6.3, resulting from the definition of the system boundary.

In this paper, all operational energy usage was considered, including all plug-in appliances. Since these demands are often not considered in LCA studies as they are not within the common system boundary of buildings, the values of the comparison data set appear to be lower. These findings open the discussion regarding the choice of the system boundary of such energy-efficient buildings, which will be explored in the following section.

5.2. Discussion on the operational emissions

In the discussion regarding the path to net-zero emission buildings, the topic of energy efficiency of the building in general still has to be seen as the major aspect and will always require a high level of the preliminary planning effort, which certainly went into the concept of the building 'be 2226'. While the solution is undoubtedly smart, the assessment of the concept shows that a full picture of energy usage throughout its operation is even more important for such high-level energy-efficient buildings. We are aware that this problem is already being discussed in the scientific community since other studies already found that the operational energy usage by plug-in appliances plays a significant role in the whole picture of the life cycle GHG emissions of buildings [10]. Yet, this paper provides another example to reinforce the significance of this issue.

To date, ignoring the energy usage by non-integrated systems (i.e., plug-in appliances) is typical practice in building LCA. This occurs to such an extent that according to the most recent standard prEN 15978–1:2021–09, the operational energy usage by non-integrated systems allocated to Module B6.3 may only be reported optionally as additional information [35]. But in relation to innovative building concepts like '2226', a misconception of the required results in the current assessment methodology seems to exist.

In general, it is evident that parts of the energy allocated to B6.3 are waste heat from the plug-in appliances, which in the case of the concept '2226' is used to heat the building in winter. Certain sources even state that almost all energy used for computers, servers etc. is actually converted to waste heat, which furthermore fuels the discussion of energy allocation. Arguing that this statement also has to apply for the plug-in appliances used within the building 'be 2226' and referring to our reverse-engineered energy allocation to the distinct sub-modules of B6, there is the potential to overlook a significant gap of up to 30% of operational energy usage (see also Fig. 7)

Stating this, it is clear that in the LCAs of such highly energy-efficient buildings, the energy allocated to Module B6.3 should be reported. One solution to avoid overlooking this gap in operational energy usage is to require the authorities to measure the actual energy demand of a building after three years and to compare it with the energy demand calculated in the energy certificates. Only when the calculated energy demand matches the measured energy demand, the authorities can approve the use of the building (see Swedish example [53]). For a truly effective energy and climate policy, this approach is indispensable, as otherwise, no control of the actual energy savings is possible.

Furthermore, a clarification of the allocation of waste heat in passive building concepts needs to be established within the life cycle assessment standards. The goal is to not oversee a large share of operational GHG emissions and cloud the conclusions and judgement on innovative buildings' actual environmental performance on the path to a net-zero built environment.

5.3. Discussion on the embodied emissions

As presented in the results section, the majority of embodied GHG emissions are caused by the structural systems of the building (i.e., 'Vertical building constructions', 'Horizontal building constructions' and 'Foundations, floor constructions'), resulting in more than two-thirds (70%) of the GHG emissions from materials production and close to half (47%) of the embodied GHG emissions overall. This raises questions concerning the high mass of the building concept '2226'. As shown previously, no further mitigation of embodied emissions can be achieved in comparison to similar concepts, given material production with current technology.

A large carbon investment is undertaken at the beginning of the life cycle, resulting in a so-called forefront 'carbon spike', also investigated in the paper of Röck et al. [14]. This initial 'carbon spike' is inevitable

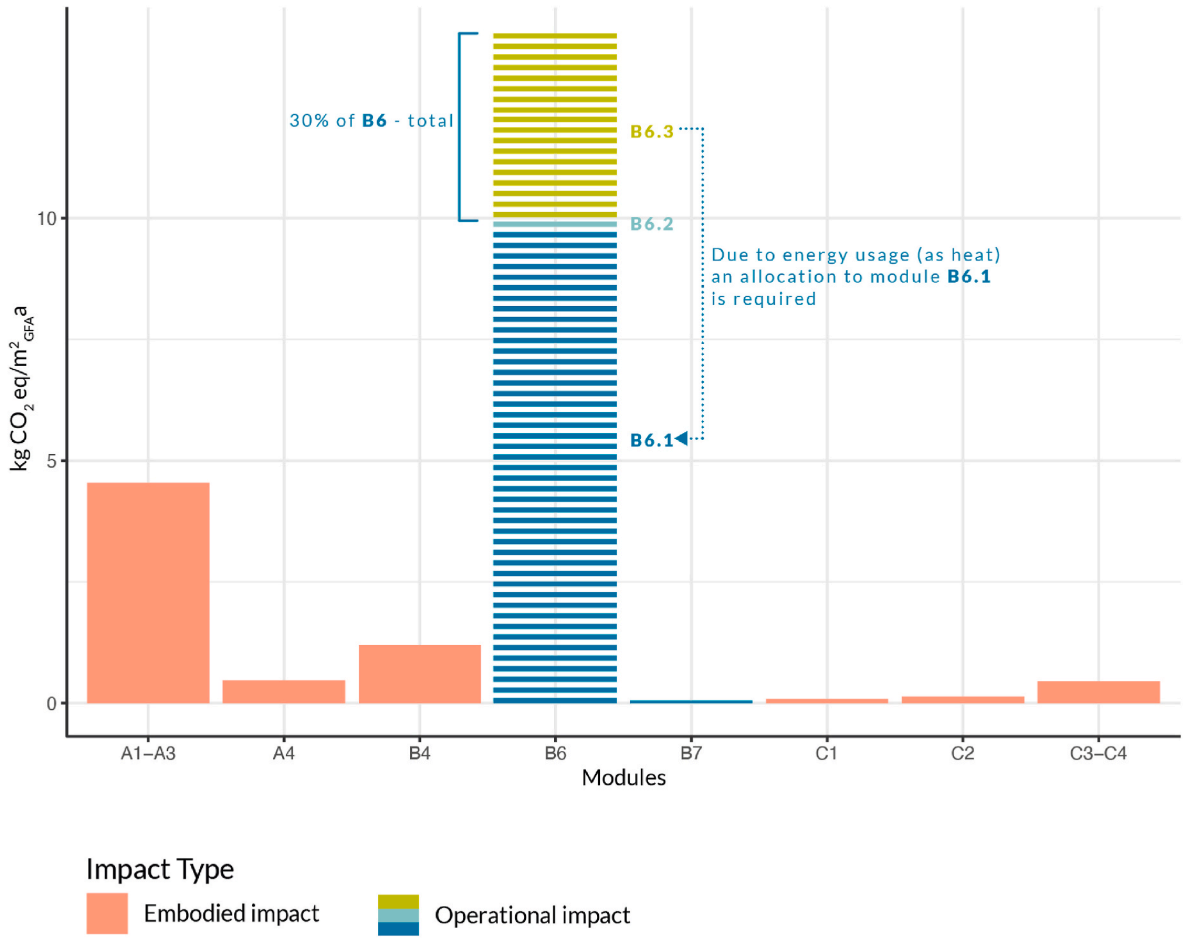

Fig. 7. Allocation issue in the operational energy emissions between distinct sub-modules of B6.

within the current high-carbon materials and stands in contrast to the efforts of fast decarbonisation of the whole building value chain. While the building concept is managing to significantly lower the operational energy demand throughout the life-cycle compared to existing building standards, the use of high-carbon materials (fired bricks, concrete, steel) seems to be unfeasible for mass application in the built environment in face of the ever-accelerating climate crisis and the remaining CO_2 budget [5]. Previous research showed the potential of considering embodied emissions during the design process, e.g., by visualising the contribution and improvement potential for different building elements [54] or by applying an optimisation algorithm to find optimal solutions from both an operational and embodied emissions perspective [55]. Further research is emerging that investigates these implications and looks deeper into e.g., alternative material options with low carbon and environmental impact, many of which are already available on the market — such as timber, straw, or hemp-based material alternatives [56] — yet require stronger uptake in design and construction practice. Finally, the question of the future production of the main material 'Brick' in a decarbonised economy arises.

5.4. General discussion

The field of action 'buildings', as buildings are now seen in the literature, is characterised by a variety of human activities (living, working, shopping, production, etc.). These activities are strongly anchored in human demands yet the importance of this field of action for society, the economy, and the environment is often overlooked. With the increasingly escalating climate crisis and the urgent requirement to reduce the emissions over the whole economy, the consideration of the field of action 'buildings' must be focused on. In the latest IPCC report of the Working Group III, it is stated that by 2050 up to 61% of global building emissions could be mitigated [57]. Regarding the global GHG budget, central positions are required for effective overall emission reduction, and one of these central positions is precisely the field of action 'building'.

The overarching goal, then, is to achieve the net zero emissions target across the entire economic landscape. A key component for achieving this goal are NZEBs. Yet, regarding the results of this paper, it is shown that the allocation of emissions from buildings, especially operational emissions, is still not clear and partially an open discussion. Especially in the case of NZEBs, it is essential to explore the system boundary beyond the standardised definitions to have a clear picture of the total emissions and to avoid incorrect conclusions in the planning of buildings. It is essential to include the total energy consumption, including B6.3, in the planning process of highly efficient energy buildings to get the whole picture. Otherwise, the term 'net-zero' might be just wrong. In addition, as already discussed in the part of operational energy, a regulative mechanism needs to be set up to verify the planned energy demand in the real operation of a building, to ultimately successfully lower the energy consumption in the total built environment.

The adequate functional unit must also be discussed. It is important to note — especially given the Covid-19 pandemic and the resulting lockdowns — that buildings should actually not have only one function in the future, for example, office buildings, but rather have multiple functions and not serve a single purpose. Furthermore, the total economic implications of such a building have to be taken into account. The constitution of the concept '2226' with the exclusive use of electrical end energy in the use phase allows a discussion regarding the embodied emissions of this electrical energy induced by power plants and the corresponding supply infrastructure. In terms of a "polluter pays" principle, these embodied emissions would also have to be attributed to the building and ultimately, to the end user as a per capita emission value. This, of course, again immediately opens the discussion with respect to the set system boundaries in the currently standardised prevailing life cycle assessment of buildings.

In general, the question of whether such discussions regarding the allocation of emissions are still necessary depends on if NZEBs are successfully adopted in the economy. In such a context, the discussion of whether the energy consumption is allocated to the building or the appliances is rather pointless. The overarching goal is to fight climate change by achieving net-zero emissions, across the whole economy and not only for buildings. This raises the question of whether sustainability assessments should be carried out not only for energy-efficient buildings but for entire systems or regions. A top-down approach can be to break down planetary boundaries to a regional quantification of the emissions in the field of action 'building', observing per capita emissions including also embodied emissions. The authors thereby recommend assessing neighbourhoods as well as regional or spatial LCA approaches. Further research in this area is required.

6. Summary, conclusion and outlook

6.1. Summary

In this paper, a life cycle assessment of the innovative building concept '2226' was carried out on the original application, the office building 'be 2226' in Lustenau, Austria. The building applies an innovative passive building concept in which thermal comfort is achieved in the building without the use of heating and cooling systems.

The results show that compared to conventional 'Existing Standard' buildings, a significant reduction in GHG emissions can be achieved over the entire life cycle, yet in comparison with concepts with similar ambitions (i.e., nZEB), no further reduction of GHG emissions can be achieved throughout the life cycle. In terms of embodied emissions, it appears that the main drivers of emissions are those in the production phase, specifically the bricks used in the exterior walls. This is not surprising, as the concept '2226' relies on high building masses to ensure thermal comfort.

The total operational emissions were considered on the basis of the measured 3-year average energy standard of the building. Using various literature sources, the total operational emissions have been "reverse-engineered" to the individual modules of the operational energy demand B6.1, B6.2 and B6.3. It has been shown that in the building concept, around 30% of the energy consumption and thus the operational emissions may be attributed to non-building integrated systems (i.e., plug-in appliances) in Module B6.3. Since this part of the operational emissions is often not included in the common system boundary definitions in building LCAs, the inclusion and assessment of these emissions, especially in such highly energy-efficient building concepts, is of great importance in order to obtain the right picture of the operational emissions.

6.2. Conclusion and outlook

In relation to the environmental performance of the case study, further assessments are required in relation to changing emissions in the operational energy demand, since future transformations in the energy market will affect the emissions via the operational energy demand and eventually become so low that the embodied emissions will contribute the major share of emissions over the whole life cycle. A critical investigation into the whole concept of high-mass buildings, therefore, has to be conducted in the context of future energy grids, the associated material production and energy consumption and carbon budgets.

Finally, for the LCA assessment of innovative highly energy-efficient building concepts, such as the concept '2226', a widening of the system boundary is required to get the entire picture of the GHG emissions. This becomes particularly important in the context of an ever-escalating climate crisis, as the focus can no longer be on reducing emissions from single buildings alone, but much more on a large-scale and rapid reduction of emissions in the entire field of action 'building' in order to contribute to the solution of the global climate crisis.

CRediT authorship contribution statement

Dominik Maierhofer: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Martin Röck:** Writing – original draft, Validation, Software, Resources, Methodology, Data curation, Conceptualization. **Marcella Ruschi Mendes Saade:** Writing – original draft, Validation, Supervision. **Endrit Hoxha:** Writing – original draft, Validation, Supervision. **Alexander Passer:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2022.109476.

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