

Research paper

Development of a life cycle net zero carbon compact house concept

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ARTICLE INFO

Article history:

Received 22 March 2022

Received in revised form 25 August 2022

Accepted 28 September 2022

Available online 13 October 2022

Keywords:

Life cycle net zero carbon building

Building information modelling

Building energy simulation

Life cycle assessment

Life cycle cost

Compact house

ABSTRACT

The paper presents the development process of an innovative, prefabricated compact house, which aims at creating a net zero greenhouse gas emission building design over the whole life cycle. Building Information Modelling helped to quantify the required building materials. Dynamic building simulations were performed in DesignBuilder to calculate the energy demand of the building for the operational period. To evaluate the financial feasibility and the carbon balance of the building, life cycle assessment and life cycle costing were used. A heat and moisture transfer simulation was carried out to provide a more accurate analysis and to identify possible moisture problems.

The assessment showed that the ratio of embodied impacts and operational impacts is typically 1:2 for wooden buildings and 1:1.5 for brick buildings. Life cycle carbon neutrality could be achieved in both cases with additional photovoltaic panels installed on the roof. However, a major difference between timber and brick buildings is the time factor: while the initial emissions from the production of brick buildings are gradually offset with excess solar energy, timber buildings act as carbon storage with negative emissions over the study period and the carbon is only released at the eventual end-of-life stage. The necessary size of photovoltaics is largely influenced by the avoided grid impact: if dynamic decarbonization of the electricity mix is considered, the size of photovoltaics required is about 1.5 times larger to offset the environmental load of the construction due to the diminishing benefits.

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1. Introduction

1.1. General background

The rapid change in the Earth's climate on a global scale is one of the greatest challenges facing humanity today. It is widely accepted that human activities contribute to climate change in addition to natural sources of emissions (IPCC, 2021). International conventions have been established to slow down this process, which threatens the very existence of humanity (Delbeke et al., 2019). In these conventions, the reduction of greenhouse gas emissions (GHG), including carbon dioxide (CO₂), has been defined as an objective.

The construction and operation of buildings is a major emitter and has significant potential for emission reductions. According to the statistics of the International Energy Agency (IEA), buildings and construction are responsible for 36% of global final energy

use and 39% of energy-related CO₂ emissions (Anon., 2017a). Countries around the world have made significant efforts and achievements in the recent years to reduce the energy demand of buildings. The first directive on the energy performance of buildings was published in 2002 in the European Union (European Commission, 2002), which led to a mandatory definition of nearly zero energy buildings (nZEB) in 2012 (EC 2012/27/EU, 2012). However, the total remaining carbon budget requires net zero levels by 2050 and even more ambitious reductions in the built environment (Chandrakumar et al., 2020; Nematchoua et al., 2021). There have also been significant developments in customer demand and the availability of affordable technologies. In addition to energy efficiency measures, local energy production technologies have also emerged. As the operational energy demand is decreasing, the embodied energy associated with the construction of buildings has increased in proportion (Röck et al., 2019). These developments have led to the emergence of new targets and concepts focusing directly on reducing CO₂ emissions. There is no generally accepted standard for low CO₂ buildings, but several concepts exist depending on the target and system

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boundaries (Lützkendorf and Frischknecht, 2020; Shirinbakhsh and Harvey, 2021).

In the recent years there have been a number of studies focusing on the decarbonization of the building sector, which consists of two key parts: renovation of buildings to a carbon neutral level (Galvin, 2022; Amoroso et al., 2022) and setting requirements for new buildings in order to reach carbon neutrality (Zhang et al., 2021; Forde et al., 2021). As it is a complex challenge to reach carbon neutrality, some studies have focused on defining the boundaries of carbon neutrality based on case studies. Hua-Yueh showed that a residential building in Taiwan can reach carbon neutrality over its lifetime, however it requires lifestyle modifications apart from the sustainable design approach (Liu, 2019). For net zero energy buildings there were several studies which have analysed the possibilities for the holistic design considerations (Lan et al., 2019; Jabari et al., 2020), however they were mostly focusing on the operational energy demand and disregarding the whole life cycle approach until recently (Ahmed et al., 2022). Life cycle assessment (LCA) of an innovative nearly zero energy building in Austria found that embodied emissions and plug-in loads account for a large share of the life cycle greenhouse gas emissions (Maierhofer et al., 2022). A combined energy and environmental assessment analysed increased insulation vs. installation of photovoltaic power in nZEBs (De Masi et al., 2021). Grinham et al. prepared a study focusing on the sensitivity analysis of LCA approach in order to test the boundaries of the zero carbon concepts, and they found that apart from the building structures and technical system components the results are also greatly dependent on the electricity mix provided by the grid (Grinham et al., 2022). Ansah et al. examined the effect of climate change on carbon neutrality and found that due to global warming the energy demand and thus CO₂ emissions will be higher in tropical areas, whereas the heating in colder regions will account for smaller operational CO₂ emissions (Ansah et al., 2022). Some studies are focusing on the implementation of renewable energy sources to reach carbon neutrality. Liu et al. examined the applicability of PV systems in carbon neutral buildings in Hainan Province China, and the results showed that carbon neutrality could be achieved when using both rooftop and façade PV instalments (Liu et al., 2022). Krarti and Aldubyan examined the combined effect of installing both PV and wind turbine systems in Saudi Arabian housing units, they have concluded that the required built in capacities for renewable sources can be reduced by 50% by reducing the demand in the individual housing units (Krarti and Aldubyan, 2021).

This paper aims to explore the concept of carbon neutrality in buildings and investigate whether this can be achieved in a compact house design in a life cycle perspective. The novelty of the paper is the comprehensive evaluation including environmental, financial and building physics aspects, as well as the comparison of an innovative cross laminated timber technology with conventional materials to explore whether offsetting the embodied emissions with exported solar energy is feasible. As a clear definition for carbon neutrality is missing in the literature, first we analyse the existing terminology and issues of zero carbon concepts to define the objectives of our research.

1.2. Terminology of zero carbon concepts

In the terminology, the prefixes climate/CO₂/GHG/carbon are mostly used as analogous formulations. Often the term “emission” is also added to make clear that it is more than just energy savings. In our view, the GHG prefix is the most scientific. This can be expressed with the Global Warming Potential (GWP) in CO₂-equivalents (kg CO₂-eq) (Liu et al., 2022; Krarti and Aldubyan, 2021; Satola et al., 2021; Deutscher Bundestag, 2010). However, for simplicity, the prefix “carbon” can also be used.

The concepts use the terms “nearly zero/zero/neutral”. Each term indicates that the building does not emit GHGs within the system boundary under consideration. In our opinion, the clearest term in this context is “zero”.

The terminology “net/absolute”, often defined only in brackets, refers to whether a period-based – typically annual – accounting (net) or real zero emission (absolute) is the requirement. In the case of a “net” balance, some emissions are associated with the process (e.g. construction or operation), but there are offsets over the lifetime that result in zero emissions by the end of the period. Offsets are classified in the literature into three categories (Lützkendorf and Frischknecht, 2020; Satola et al., 2021):

- (1) Net balance approach (e.g. electricity generated from solar energy)
- (2) Economic compensation (e.g. emission trading)
- (3) Technical reduction (e.g. CO₂ removal from the atmosphere).

Another question is the definition of the system boundary (Zhao et al., 2016; Lützkendorf et al., 2015). While most methods still only consider the operation phase, assessing the whole life cycle and including embodied emissions from material production would be important to achieve the climate goals (Lützkendorf and Frischknecht, 2020; Satola et al., 2021; Habert et al., 2020). The manufacturing process and transport of construction products currently represents 11% of human-related GHG emissions (Anon., 2017a). Significant CO₂ reductions have been achieved in the manufacturing process of several construction materials. However, there are still some materials used in large quantities (e.g. concrete, steel) that have a significant impact on the CO₂ balance of buildings (Alig et al., 2020; Pan and Pan, 2021). Their use could make the concept of a “net zero carbon balance” difficult to achieve.

1.3. Issues related to the definition of carbon neutrality

An important issue related to carbon neutrality is the environmental impact of the energy, typically electricity, that is produced and consumed. The level of emissions is strongly influenced by the electricity mix, the share of renewable energy in electricity production and the source of electricity in a given country (Mosteiro-Romero et al., 2014; Papachristos, 2015; Lützkendorf, 2020). Reducing CO₂ emissions from buildings can be achieved (a) by reducing the operational energy demand of buildings; (b) by reducing the CO₂ content of the energy used to operate buildings (Ahmed et al., 2022); (c) by reducing the CO₂ emissions from the manufacturing of the building materials. Parkin concluded that energy savings and the CO₂ savings from buildings are often not proportional to each other, depending on the national electricity mix and the primary energy source of operational energy (Parkin et al., 2020).

In a net balance approach, the matching between on-site generation and direct consumption can cause significant differences in the emission balance. Energy purchased from the grid typically has higher CO₂ emissions than locally produced solar energy with close to zero operational CO₂ emissions. In the calculations, the potentially avoided impact depends on the length of the accounting period, as the amount of exported energy is different if a yearly, monthly, hourly or sub-hourly balance is established.

A potential weakness of the net balance approach is the risk of double counting. The emission reduction may be attributed to both the building that produces the energy and the customer that purchases the exported energy. That is why LCA standards require the potential benefits to be reported separately as additional information (EN 15978, 2011). There is also uncertainty in the typical assumption that exported energy avoids the present grid

mix emissions, as in reality these may change in the long term with the transformation of the electricity sector and the benefits may decrease.

Another question is which energy uses are considered in the operational phase when targeting carbon neutrality. Most energy regulations only assess a part of the total energy consumption. For example, appliances and elevators are not considered (EC 2012/27/EU, 2012), while other schemes include building-induced mobility as well. Similarly, in a life cycle approach the question arises which building elements to take into account in the production. Lighting fixtures, user-related appliances (washing machine, TV, household appliances, etc.) and furniture are typically not included in building assessments, nor are the electric and plumbing systems. Heating, ventilation and air conditioning (HVAC) systems are usually also not considered with a detailed inventory. This issue is further complicated by the limited availability of data on these elements. Also, there are no or incomplete standards for the replacement and life expectancy of building structures and mechanical systems (EN 15459-1, 2018).

Low-carbon products with bio-based materials have a large potential in reducing embodied emissions. A fundamental property of bio building materials is that the material removes CO₂ from the atmosphere as it grows. When incorporated into buildings, these materials act as a temporary CO₂ storage. However, the environmental assessment results vary widely depending on the calculation and the accounting of the release of CO₂ at the end of life (Hoxha et al., 2020).

1.4. Objectives

The main objective of this paper is to explore whether carbon neutrality, defined as net zero greenhouse gas emissions, can be achieved over the whole life cycle of a building with a net balance approach where the avoided grid impacts due to exported solar electricity offset the emissions from production and end-of-life of the building. A cross laminated timber prefabricated system is compared with conventional materials to assess the feasibility of the concept when materials with and without carbon storage potential are applied. The effect of different system boundaries is considered on the balance, such as including or excluding user-related energy consumption and the potential benefits due to future recycling and reuse of materials. Also, the effect of a dynamically decarbonizing grid electricity mix is assessed, which means that the future benefits from the avoided impacts decrease.

The paper presents a market-driven product development process of a carbon neutral compact house with prefabricated building elements. That entails developing a new product for a manufacturing company, from the initial idea to completed construction. The building has approximately 75 m² built-up area, designed with three rooms. The building had to meet two main criteria: (a) it had to be realized as a compact house, with factory prefabrication and fast on-site installation; (b) it had to achieve carbon neutrality. Several options have been compared in a comprehensive analysis, including Building Information Modelling (BIM), dynamic energy simulation, heat and moisture simulation (HAM), life cycle assessment (LCA) and life cycle costing (LCC).

The paper is structured as follows: in Section 2 the materials and methods used for the design process are described. After a general outline of the process, the methods used for the specific subtasks are explained. In Section 3, the main results obtained from the optimization process are presented along with the discussion of the results. System boundaries for reaching net zero GHG emission are analysed and the sensitivity of the results to a dynamically decarbonizing electricity mix is explored. Finally, the main conclusions of the research are summarized in Section 4.

2. Material and methods

2.1. Design process

In the research initiated by the manufacturing company based on market needs, we followed the process shown in Fig. 1. The definition of the main objectives (Step 1) was followed by a brainstorming (Step 2) with the participation of the manufacturer, the architects and the building experts to define the scope and the first variants for the analysis (Step 3). In Step 4: Pre-analysis, a BIM model of the building was created in ArchiCAD software to quantify the amounts of building materials. Energy demand was calculated with DesignBuilder, which was the input for the environmental (LCA) and economic assessment (LCC). Due to space limitations, this step is not presented in detail. However, we consider the pre-analysis a very useful methodological element. The basic aim was to examine three extreme variants: (1) the presumed cost optimum version; (2) the presumed LCA-LCC optimum version; and (3) a version with the building materials preferred by the customer. We wanted to find out the rough boundaries of the basic concept and give a quick feedback to the customer. This step also provided an opportunity to test the research method. Based on the lessons learnt, a new geometric model was created, and the material composition of the “competing” versions were defined (Step 5).

In Step 6: “Alternative and competitor analysis” eight versions were compared (Tables 1 and 2). Alternatives have been defined to answer the main questions raised during the research (e.g. Can the concept be realized with conventional insulation materials such as expanded polystyrene or mineral wool? Does the two-storey option offer advantages? Is it possible to quantify the benefits of the concept compared to conventional construction? etc.)

One variant (CC-V03_Pitched-C), selected as a result of the comparative tests, was subject to detailed tests (CC-V03_Pitched-D) (Step 7). In addition to the previous assessments, a heat and moisture transfer (HAM) study was performed to (a) quantify the differences between the HAM-based energy calculation and the standard energy calculation, which does not consider the effects of moisture and (b) to identify potential moisture problems within the structure. Step 8, the implementation of the prototype and the subsequent monitoring of the building have not been completed yet and they are out of the scope of this paper.

The following sections present the methodology and results of the Alternative, Competitor and Detailed analyses (Step 6–7). The geometry of the studied variants are presented in Fig. 2. The geometry was based on the customer's market needs and the transportability requirements of a mobile home. The design brief stated that the building should have a living room and two bedrooms for three persons, with an approximate floor area of 75 m². Transportability was a main limitation as the buildings are completely prefabricated and need to be transported to the site in large, container-size 3D blocks. The building consists of three blocks and the maximum width of one block was limited to 3,45 m. The external dimensions were maximized and this resulted in minor differences in the net floor area of the model. The architecturally preferred option was a one-storey building, but a two-storey version (CC-V02_2S_CLT) was also provided by the manufacturer and architects to be tested in the research project. This has the same useful interior spaces as the single-storey versions. However, it differs significantly from the other buildings under study in terms of the total floor area because of the increased area for corridors and staircases. In addition to the client's request, this building was also investigated in order to assess the effect of a more favourable building geometry in terms of building surface to volume.

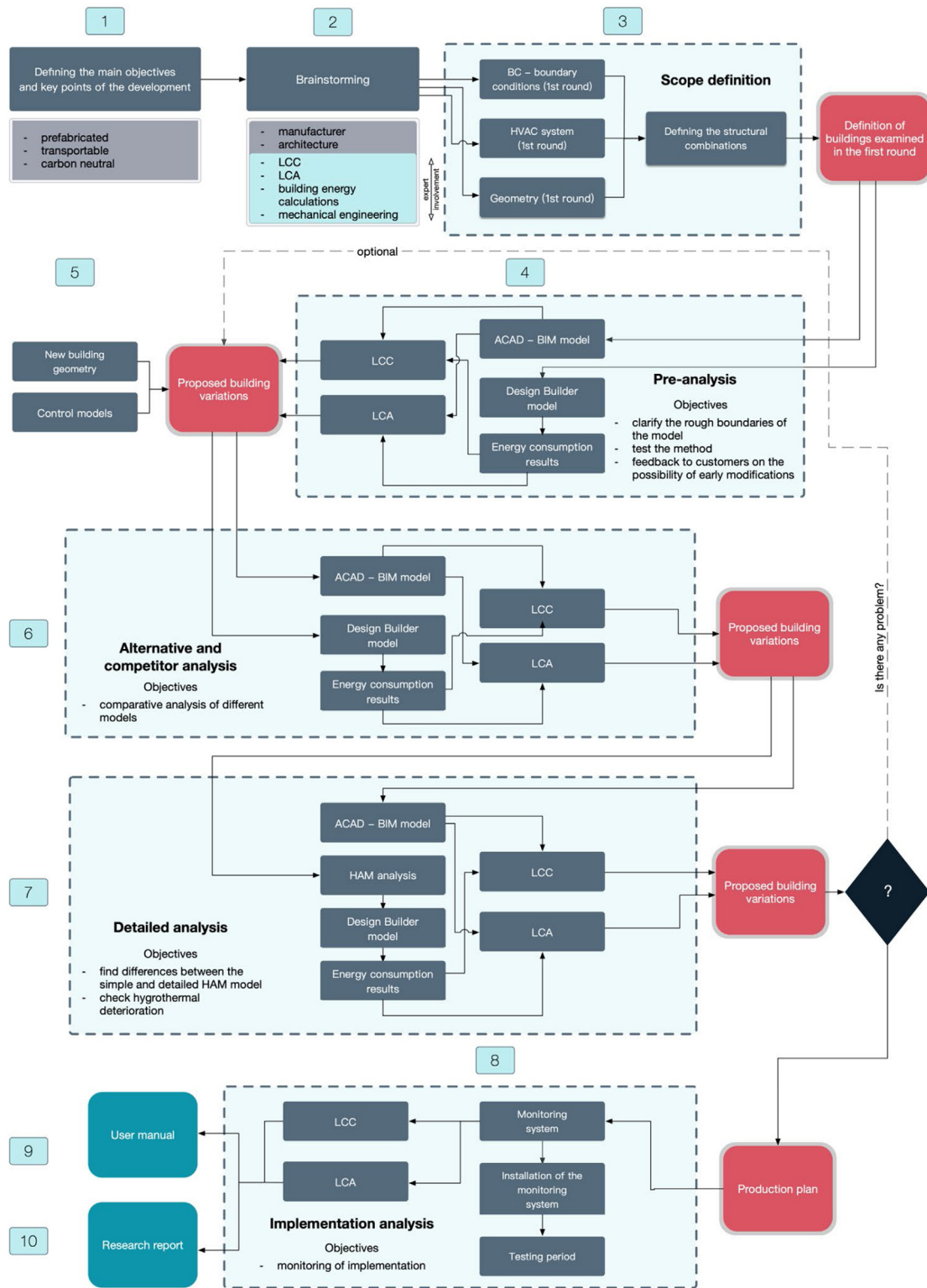


Fig. 1. Flow chart of the research project.

In the assessments, the building envelope and the internal constructions were taken into account, as well as the heat generator, the buffer storage tanks and the floor heating pipes. However, water pipes and electric network were not included due to lack of data, and neither were furniture and sanitaryware which would be chosen by the homeowner. The material composition of the building elements is described in [Annex A](#) and visualized in [Annex B](#). The main variants have a cross laminated timber (CLT)

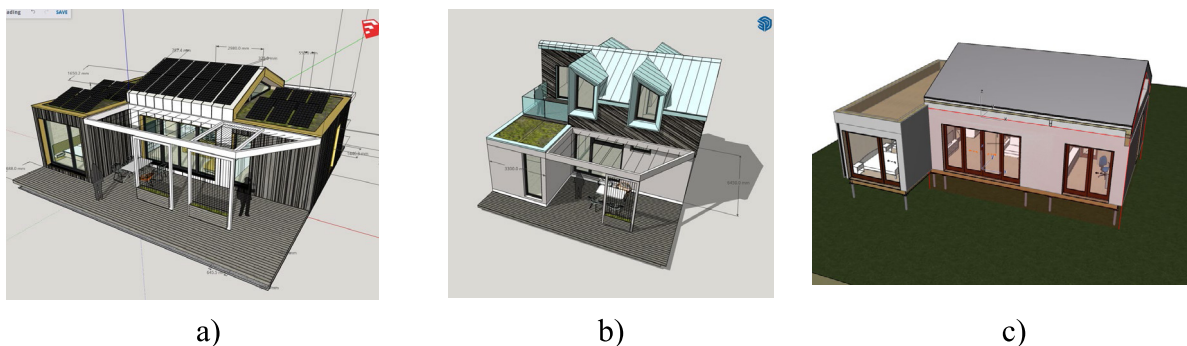
loadbearing structure, which is compared to a post and beam type structure from laminated veneer lumber (LVL) and a conventional brick structure with load-bearing walls. CLT panels consisting of layers stacked crosswise at 90 degrees serve as load-bearing elements in walls and floors, without the need for additional columns or beams. The one-storey timber versions have ground screws as foundation, while concrete foundation is necessary for the hollow brick and for the two-storey versions.

Table 1
Main parameters of the examined variants.

Aim of investigation	Building height	Material of main loadbearing structures	Type of geometry	Code of investigated variant	Area (m ²)
Alternative analysis	One storey	CLT	V02	CC-V02_wood	75
		CLT		CC-V02_rockwool	75
		CLT		CC-V02_polystyrene	75
		LVL		CC-V02_1S_LVL	75
	Two storeys	CLT	V03	CC-V03_Pitched-C	76
Competitor analysis	One storey	Brick/concrete	2S	CC-V02_2S_CLT	96
Detailed analysis	One storey	Brick/concrete	V02	Brick-V02_same	75
		Brick/concrete		Brick-V02_NzB	75
	One storey	CLT	V03	CC-V03_Pitched-D	76

Table 2
Description of the examined variants.

Code	Description
CC-V02_wood	Building variant with wood fibre thermal insulation and cross laminated timber (CLT) structure based on the lessons learned from pre-analysis.
CC-V02_rockwool	Variant created from CC-V02_wood with rockwool insulation of the same thickness.
CC-V02_polystyrene	Variant created from CC-V02_wood with polystyrene thermal insulation of the same thickness.
CC-V02_1S_LVL	Variant created from CC-V02_wood with wood fibre thermal insulation but with laminated veneer lumber (LVL) loadbearing structure instead of CLT.
CC-V02_2S_CLT	Two-storey variant with different geometry, with the constructions of CC-V02_wood but with strip foundation for structural reasons.
Brick-V02_same	Variant created from CC-V02_wood, with the same internal volume. The external constructions have the same thermal transmittance as CC-V02_wood but with brick walls and strip foundation.
Brick-V02_NzB	Variant created from CC-V02_wood, with the same internal volume. The thermal transmittance of the external constructions comply with the nearly zero energy (nZEB) requirements in Hungary, with brick walls and strip foundation.
CC-V03_Pitched-C and CC-V03_Pitched-D	Variant created from CC-V02_wood, identical in all constructions but with a slightly modified new geometry with a larger pitched-roof structure due to customer's needs.

**Fig. 2.** (a) V02 type, one-storey geometry (SketchUp-model); (b) 2S, two-storey geometry (SketchUp-model); (c) V03 type, one-storey geometry (ArchiCAD model).

A number of HVAC system alternatives have been investigated for the operation of the building. An air-to-water heat pump for space and water heating and cooling (SCOP = 3), building-mounted photovoltaic (PV) systems for local energy production, and natural ventilation were designed. The maximum capacity of the PV system was limited by the available space on the roof (6.2 kWp). During the use phase, heating, cooling, hot water production, lighting and the consumption of appliances were calculated. Carbon neutrality was assessed with and without appliances. The calculation period (Reference Study Period – RSP) was 30 years based on LCC calculation method (EC 244/2012, 2012). In LCA calculations we used the same study period. During this period no major renovation was assumed, but the necessary replacements were considered. The lifespan of the building and certain structures may be longer than 30 years, but only the first 30 years were considered as a reference study period in this study. While in building LCA the most common assumption is an RSP of 50 or 60 years (Röck et al., 2020), the goal in this study was to achieve carbon neutrality in a shorter period of 30 years.

2.2. Building Information Modelling (BIM)

Developments in Building Information Modelling (BIM) make it possible to integrate dynamic energy simulation and LCA in the building design workflow (Röck et al., 2018; Santos et al., 2019). Wastiels and Decuyper identified five different strategies for the application of LCA using BIM (Wastiels and Decuyper, 2019). Even though a deep integration is desirable, it is recognized that this is not the current practice yet, and manual steps are required in the workflow (Soust-Verdaguer et al., 2017). Several studies applied LCA on case studies, most of them facilitated some features of BIM (e.g. extraction of material quantities, visualization of 3D building models, etc.), but they either use some self-developed tools (e.g. Excel spreadsheet) (Soust-verdaguer et al., 2018) or apply commercial plug-ins (Mora et al., 2019) to evaluate the environmental impacts. The use of BIM models in building energy modelling is possible, although it poses several problems. Generally, IFC and gbXML file formats are used to interchange the two procedures, but the interoperability is rarely perfect.

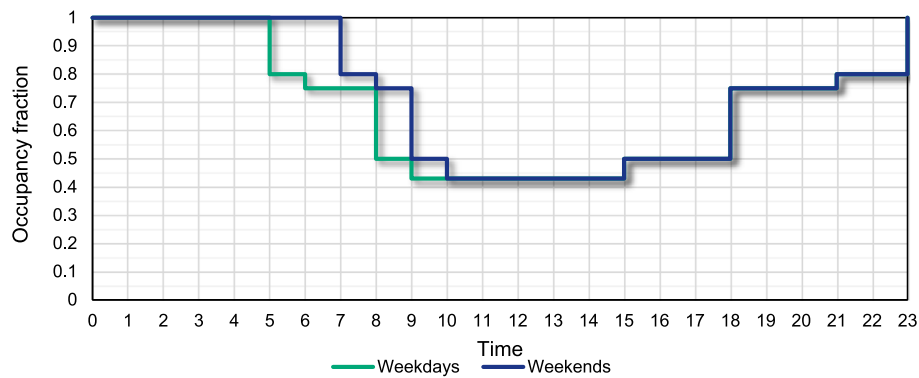


Fig. 3. Applied occupancy schedules.

Some information is lost during the translation from the BIM tool to the simulation software, and even the geometry can be deficient, which is the basic information for the Building Energy Model (Baamer et al., 2020; Prada-Hernandez et al., 2015). But of course, the main goal is to be able to transfer not only building geometry but also construction materials, schedules, and thermal zones. From this point of view, importing from Revit to DesignBuilder using the gbXML format is currently not entirely reliable, and often time-consuming manual work is needed to set up properly (Sušnik et al., 2021).

This research applied a hybrid design workflow including automated tasks and manual modelling work in several design tools. The goal was twofold. First, the workflow had to be flexible enough to adapt to the usual workflow of the architecture team. Second, it had to be suitable for various levels of detailed calculations, including hygrothermal simulation of construction details or the dynamic energy simulation of the building. The workflow included automated tasks to derive the bill of quantities using ArchiCAD 23 and Sketchup for Web software. The data was reused in several design steps such as the definition of construction assemblies, and the calculation of LCA and LCC results in self-developed Excel tools. However, manual steps were required to rebuild the model for energy simulation with DesignBuilder software and for HAM simulations using Comsol Multiphysics software because geometry information from the initial model was not sufficient for these analyses.

2.3. Dynamic energy simulation

Hourly dynamic energy simulations were carried out to define the building's energy performance. The DesignBuilder v6.1.5.2 software was used, which is a 3D modeller tool for the EnergyPlus 8.9 simulation engine. In the modelling of the building, the Conduction Transfer Function (CTF) solution algorithm was used, which is a sensible heat only solution and does not consider the moisture storage or diffusion in the elements. These were, however, considered in the HAM analysis. The BIM models provided the basis of the geometrical modelling in the software. The building was created primarily with building blocks; some parts, like the canopy, were made with component blocks to consider their shading effect. The thermal zones were located according to the building plan with each room representing one thermal zone. A generated weather file was applied where measurement data were interpolated to the desired location (Hungary, Budapest). The structural layers were assigned according to Annex A, where the thermal properties of the construction materials were set according to the software's built-in database and the available product datasheets. In the detailed analysis, the effective design thermal conductivities of the materials were used based on the HAM simulations. These thermal conductivities were averaged

for the heating season and included the effects of different temperature and relative humidity values across the layers including inhomogeneities, respectively. Therefore, the calculated thermal transmittances using the effective, HAM based thermal conductivities are representative for the exact design conditions. The windows have a 3-layer glass structure with Argon filling and a Low-E layer with painted wooden frames and are fitted with external shutters. Shutters were assumed to be open during the winter period (1st November–31st March). During other periods, they shade the window above a 120 W/m^2 setpoint. A domestic hot water demand of $2 \text{ l/(m}^2\text{day)}$ was assumed. The building's HVAC system was modelled in a simplified way, equipped with heating (setpoint of 20°C and 18°C setback), cooling (26°C and 28°C setback) and natural ventilation. For the household electricity consumption, we set an average of 2.5 W/m^2 value. The Hungarian energy calculation regulation assumes an internal gain of 5 W/m^2 for residential buildings. We divided this value into two parts: gains from electrical appliances and gains from people using the building. The heat gain from people using the building was based on the weekly schedule of 3 people according to the ASHRAE 90.1-2007 residential profile (Fig. 3). The infiltration in the building was assumed to be 0.3 ACH; when the outside temperature was between 10°C and 26°C , ventilation was increased by 0.3 ACH. During the overheating risk period (1st May–15th September), if the outside temperature was between 10°C and 26°C , the building was cooled down by intensive night ventilation (2 ACH) between 7 p.m. and 7 a.m. if needed. The simulations provided sufficient information on the performance of the building and helped to compare and optimize the models and structural variations; these results were used for further analysis.

2.4. Heat and moisture transfer (HAM)

Building constructions' performance is affected by moisture. To evaluate the realistic performance, therefore, we performed 3D conjugated heat and moisture transfer (HAM) simulations on the selected building envelope components. The objective of these simulations was to obtain an effective thermal conductivity of the used materials as well as to include the effect of inhomogeneities in the thermal transmittance of the constructions, such as the hygrothermal effects of the mechanical fasteners or the CLT supporting structures.

The solved partial differential equations (PDE) shown in Eqs. (1) and (2) were implemented into Comsol Multiphysics v5.5 (Comsol Inc., 2021). Eq. (1) shows the heat transfer, in which the left side describes the heat storage terms. The right side shows the transport, especially the first member represents heat fluxes from

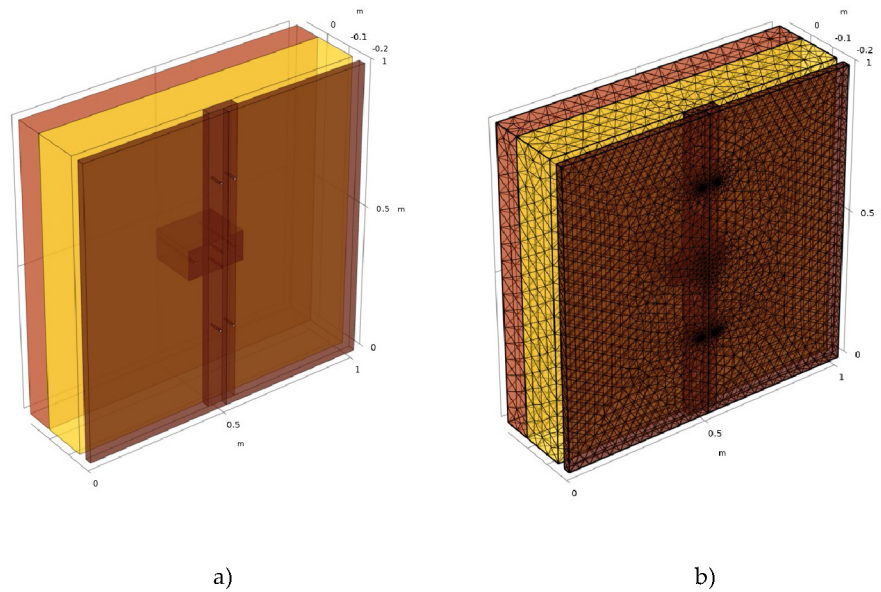


Fig. 4. (a) Semi transparent 3D geometry model of a HAM simulated wall construction including inhomogeneities (b) finite element mesh created for HAM simulation using mesh refinement around inhomogeneities.

heat conduction and the second part shows heat fluxes from evaporation fluxes:

$$(\rho C_p)_{eff} \frac{\partial T}{\partial t} = \nabla [\lambda_{eff} \nabla T + L_v \delta_p \nabla (\varphi p_{sat}(T))] \quad (1)$$

The PDE of steady-state moisture transfer is defined in Eq. (2). The left side of the equation shows the moisture storage terms, while the first member of the right side of the equation represents the liquid transport of the moisture fluxes, while the second is responsible for moisture fluxes from vapour transport:

$$\frac{\partial w}{\partial \varphi} \frac{\partial \varphi}{\partial t} = \nabla [\xi D_w \nabla \varphi + \delta_p \nabla (\varphi p_{sat}(T))] \quad (2)$$

For the HAM simulations average external data sets of Budapest were obtained from Meteonorm 7 (Meteotest, 2021) for the standard heating season as boundary conditions, however, only temperature, relative humidity and wind speed were used during the simulations. The effects of solar radiation, precipitation and wind direction were neglected in the model, because the building components' location and orientation is not known. Omitting these effects from the model, however, does not affect the reliability of the calculated results, as mostly ventilated structures were modelled, where the outer shell of the constructions protects the structure from solar radiation and precipitation.

The 3D models of the floor, external wall, pitched and flat roofs were created within Comsol Multiphysics using geometric dimensions as parameters. The geometry model and finite element mesh of a wall element with CLT and wood fibre insulation are shown in Fig. 4, where the timber brackets and planks as well as the steel mechanical fasteners are visible.

Heat transfer coefficients and the equivalent vapour diffusion thicknesses of the boundary layers were set according to EN 15026 (EN 15026, 2007), as well as the internal conditions of air were modelled according to the standard's Annex C using normal occupancy. Vapour barrier layers or the effects of technological separation foils were also modelled using boundary layers.

Effective, design thermal transmittances were obtained for all the construction layers after the simulations averaged for the heating season, containing the effects of temperature and moisture changes as well as the inhomogeneities in each layer. Using this method, the effective, equivalent thermal conductivities of

the layers could be included in the dynamic energy performance simulations.

The temperature factor at internal surface point (f_{rsi}) was also obtained from the simulations according to ISO 10211 (Anon., 2017b) and checked if it meets the durability and hygrothermal requirements to avoid the deterioration of the construction (Nagy, 2019).

Thermal transmittances (U value) were also obtained for the heating season calculated on the basis of heat flow results on the internal surface of the constructions using Eq. (3) and then compared to the simplified calculations and checked their conformity to regulations:

$$U = \frac{Q}{A \cdot \Delta T} \quad (3)$$

2.5. Life cycle assessment (LCA)

Life Cycle Assessment (LCA) is a scientific method for the environmental evaluation of products (ISO 14040, 2006; EN 15978, 2011). This method can also be applied to assess the whole life cycle of buildings from material production through building operation to the end-of-life processes. The goal of this assessment was to compare the environmental impact of the alternatives and assist the design process by providing environmental data to achieve carbon neutrality. The functional equivalent is the full compact house as defined in Section 2.1.

In Hungary, the availability of Environmental Product Declarations is limited. Although the house is realized in Hungary, a lot of imported materials are applied in the constructions. Hence, we decided to use the German Ökobaudat database as the main source of environmental data (BBSR, 2020). In the case of items produced in Hungary, there may be small deviations from the German data primarily due to the differences in the electricity mix. The database includes generic, average and specific datasets. The choice of the data was based on the following considerations:

- A specific dataset was selected if it was available for a certain product of a manufacturer as these Environmental Product Declarations (EPD) can be regarded as the most accurate.
- If a specific EPD was not available, an average dataset referring to the market average was chosen.

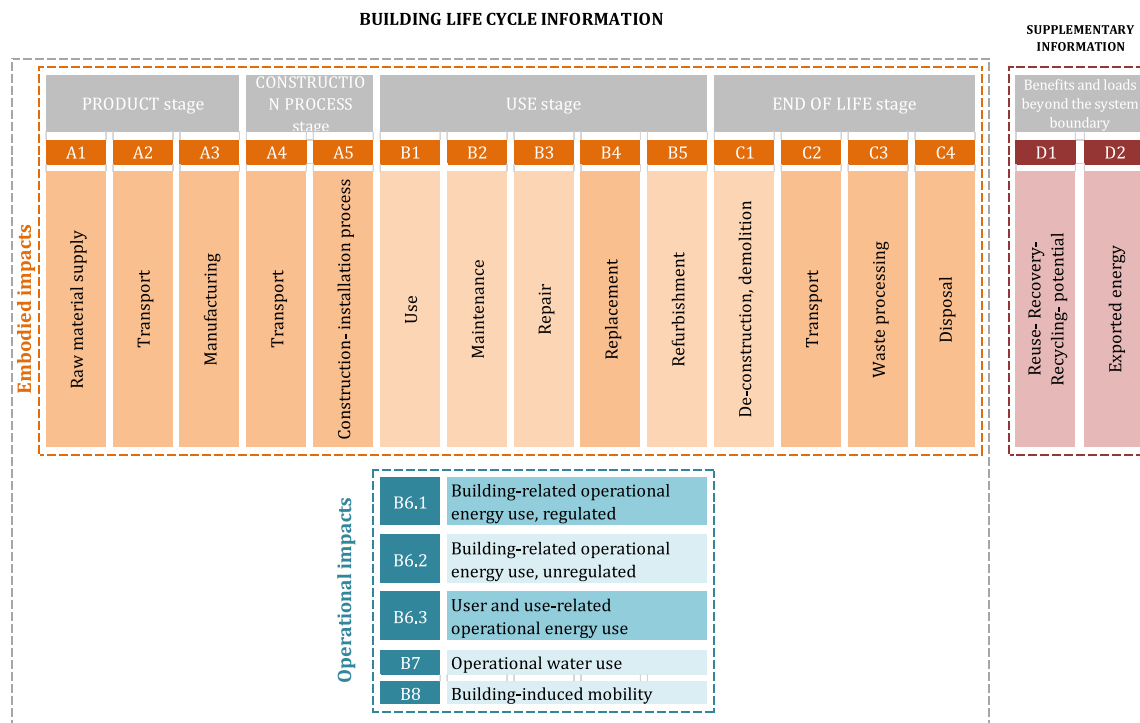


Fig. 5. Life cycle stages of a building based on EN 15978, with module B6 modified according to Lützkendorf and Frischknecht (2020) and module D divided into two parts. Considered life cycle stages are highlighted with a darker background.

- Otherwise a generic dataset from the background database was selected.

For insulation products, the environmental impact was proportionated to the density of the specific type. The selected datasets and main assumptions are presented in Annex C.

In the assessment, the following life cycle stages were considered applying the naming convention of EN 15978: product stage (A1–A3), construction process stage (A4–A5), replacement (B4), operational energy use (B6) and end of life (C2–C4) (see Fig. 5). Data for stages A1–A3 were taken from the Ökobaudat database as described above. The database includes standard values for the transportation to the construction site (stage A4) but instead of these our values representative for the Hungarian conditions were used. Materials were classified into eight groups depending on whether the product is imported or not and how many production factories exist in the country. In stage A5 (construction process) only cutting waste was considered (wooden products 10%, insulation materials 3%, membranes 5% and finishes, claddings 2%) (Kellenberger and Althaus, 2009) as no specific energy use values were yet available for the installation process.

In the operation phase, the replacement (B4) was calculated based on the expected lifetime of materials (Annex C), which was adjusted to the position of the material in the building element. Operational energy use (B6) was divided into three parts according to Lützkendorf and Frischknecht (2020): B6.1 regulated, B6.2 unregulated building-related and B6.3 user-related operational energy use. In this case, regulated energy use includes space and water heating, cooling and lighting, while user-related energy is due to appliances. These were determined with the dynamic building simulation and the Hungarian electricity mix (data from ecoinvent v3.6) (Anon., 2020). Onsite photovoltaic electricity generation was reported separately. B5 was not considered as no major refurbishment is planned over the calculation period. B7 water use is not relevant in this study.

At the end-of-life, a uniform transport distance of 20 km was assumed in C2 and C3 waste processing or C4 disposal were considered based on the Ökobaudat data (Annex C). C1 stage was neglected due to the lack of data. For wooden products, the –1/+1 approach was adopted (Hoxha et al., 2020) that considers carbon sequestration in the growth phase with a negative value in A1, which is released at the end-of-life in stage C.

Reuse/recycling potential and the exported energy from the photovoltaic systems were reported in module D as requested by the standard. However, as the level of uncertainty is different for energy that is exported during the calculation period and for reuse/recycling occurring beyond the lifetime of the building, we recommend dividing module D into two parts: D1 for reuse/recycling potential and D2 for exported energy. The exported energy avoids the impacts of grid electricity and in our interpretation, this is assumed to offset the emissions from the production and end-of-life stages to achieve a (net) zero GHG building.

Several impact categories were included in the LCA but as the main focus of this study is zero GHG balance, only the results for GWP (CML 2001) are presented. Calculations were carried out in a self-developed excel based tool.

2.6. Life cycle costing (LCC)

In the course of the research, a full life cycle cost analysis (LCC) was also carried out to compare the different variants. LCC is an approach that assesses the total cost of a building over its life cycle, including initial investment costs, maintenance costs, operating costs and the residual value of the asset at the end of its life (Sesana and Salvalai, 2013; Gluch and Baumann, 2004; Luo et al., 2021). The most frequently used method of LCC calculation for building investments is defined by the European Commission Regulation (EU) No. 244/2012 and the Guidelines and methodological annex of this regulation (EC 244/2012, 2012). The essence of the method is to sum up all the costs over the calculation

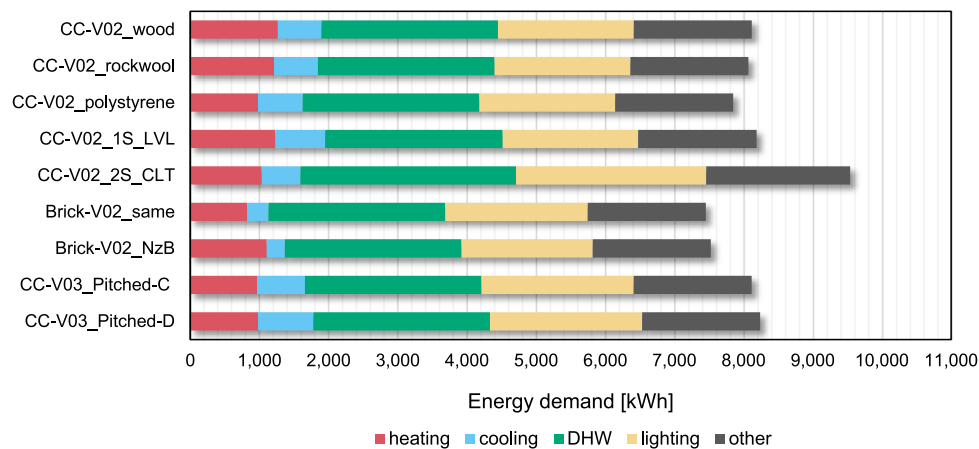


Fig. 6. Net energy demand of the different models.

period in net present value to find the best solution from the economic point of view. The total cost over the entire life cycle is called the “global cost”. All costs must be taken into account in real value, i.e. inflation is excluded. Costs can be classified into three different cost categories:

- Initial investment cost (production, construction): This is the relatively easiest cost element to calculate because it occurs today and it is not necessary to consider price changes. In our case, the investment is realized in a few months, so a present value calculation does not need to be performed.
- Costs incurring during the use phase (operation, maintenance, etc.): These costs are the most difficult to calculate and involve significant uncertainty. Annual operating costs can be calculated with energy calculation methods with different accuracy. In this research, the final energy demand from DesignBuilder simulations was the basis of the LCC calculations. There is a standard for maintenance costs of technical equipment (EN 15459-1, 2018), but there are no standards regarding the building elements, only the recommendations of various institutions are available (BBSR, 2017).

Residual value at the end of life cycle: In financial investigations, usually much shorter lifetimes are considered than the typical lifetime of buildings. General financial audits usually examine 7 year periods. The lifespan of construction investments is much longer than this time. Regulation (EU) No 244/2012 does not recommend the expected lifetime, but rather a calculation period of 20 or 30 years. As the regulation proposes a linear depreciation, most investments still have a financial value at the end of the calculation period. This residual value can be considered by discounting it to the beginning of the calculation period. It is important to emphasize that the lifetime of technical equipment is typically shorter than the most frequently examined 30 year period and replacement also needs to be considered.

The cost of the materials and products and the related labour costs came from the following sources:

- TERC Etalon online cost estimation database based on the Consolidated Construction Standards System (“ÖN” data warehouse) 2020 data (TERC, 2020);
- manufacturer and supplier prices.

The values are net amounts, in EUR, and based on the Hungarian market prices. The assumed discount rate (R_R) is 4% and the annual energy price increase rate is 2%. Costs are aggregated for the main building elements and then for the whole building for the proposed alternatives.

3. Results and discussion

3.1. Dynamic energy simulation

The results of the dynamic building simulation are shown in Fig. 6, where the different energy consumptions are indicated for the analysed models. The variants include different load-bearing structures (CLT, LVL, Brick), different thermal insulation materials (wood fibre, mineral wool, polystyrene) and geometrically modified versions. The Hungarian climate is dominated by heating demand (heating season lasts from 15th October to 15th April), but the extreme heat of the summer season also requires mechanical cooling. From the insulation options, the highest heating energy demand occurred in case of wood fibre insulation but the difference was small; polystyrene showed slightly better results, since it has lower thermal conductivity compared to wood fibre. An important difference between the CLT and LVL structures is the design of the insulation and the thermal mass, which resulted in a slight difference in the heating energy demand. In terms of cooling energy demand, there was no significant difference between the different variants, only the LVL construction had about 10% higher value due to the lower thermal mass. The development also included a two-storey building model, which, thanks to its compact design, achieved good results in terms of both the heating and cooling energy demand, with an 18% reduction in the former and an 11% reduction in the latter, compared to the CC-V02_wood design. However, since the area of the two-storey building was larger than that of the one-storey version, the area-dependent domestic hot water (DHW), lighting and occupant-dependent consumption and the total energy demand was higher than for the other variants.

For the brick versions, the external constructions of the Brick-V02_same model have the same thermal transmittance values as the CC-V02_wood version, while the Brick-V02_NzB model fulfils the current nZEB requirements of the Hungarian regulation. Based on this, the Brick-V02_same model has the lowest heating energy consumption, and its cooling energy consumption is also very low. The building, in this case, has a high heat storage capacity due to the heavy structure, which has a positive impact on its performance, especially in cooling.

The second comparison includes the CC-V03_Pitched-C and CC-V03_Pitched-D models. These were designed with a slightly modified pitched roof, and the latter model already included the effects of moisture transport and the effect of different structural connections; equivalent thermal conductivity values accounted for these. The HAM analysis in the model resulted in an increase of ~1% in heating energy demand and ~15% in cooling energy

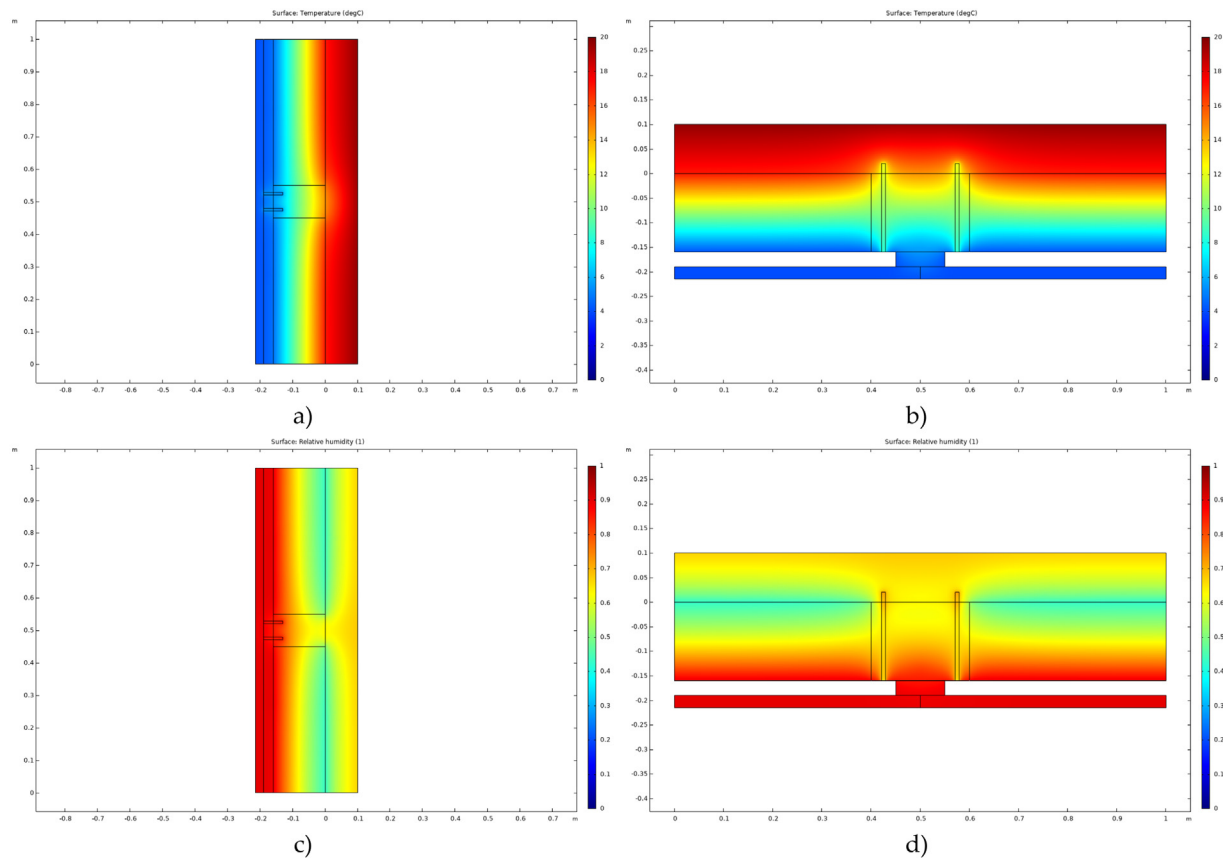


Fig. 7. (a) temperature distribution in vertical section of CC_Wall_CLTVW1-T_16cmSteico; (b) temperature distribution in horizontal section of CC_Wall_CLTVW1-T_16cmSteico; (c) relative humidity distribution in vertical section of CC_Wall_CLTVW1-T_16cmSteico; (d) relative humidity distribution in horizontal section of CC_Wall_CLTVW1-T_16cmSteico.

demand. It did not significantly change the overall building energy demand results, but it has provided useful information on the adequacy of the structural design.

Hot water, lighting and appliances dominate the total energy demand. Heating and cooling only account for 10%–12% of the demand in terms of final energy in the wooden variants and 7%–9% in the brick buildings, while hot water, lighting and appliances for 88%–90% and 91%–93%, respectively.

3.2. Heat and moisture transfer (HAM)

The results of the HAM simulations showed that the temperature factor of all examined constructions at internal surface is above $f_{Rsi} = 0.95$, therefore no hygrothermal deteriorations are expected during the service life of the simulated constructions. Observing the results of the examined building constructions (CC_Wall_CLTVW1-T_16cmSteico shown in Fig. 7) as 2D horizontal and vertical sections with CLT and wood fibre insulation, there were also no critical surface or internal temperatures between layers or moisture buffering in the constructions, therefore we can state that the tested materials and the building constructions are safe to use together and cause no hygrothermal issues. It is also visible that no freezing can occur in the ventilated façade, as well as no relative humidity in layers are above 90%. However, it is also notable that the point thermal and moisture bridges caused by the mechanical fasteners are significantly changing the temperature and relative humidity distribution in the building constructions.

One of the most important results in light of the HAM simulations, however, are the effective design thermal conductivities

obtained. The results showed that if we consider the inhomogeneities in the model of constructions and the effect of design temperature and relative humidity, some layers' or elements thermal conductivity could increase significantly (see Annex D). The 10/20 cm spruce brackets that we used to mount the wall increased from 0.09 W/mK (dry spruce without fasteners) to 0.41 W/mK (moist spruce with steel fasteners included), which is more than 350%. We can state that the effective thermal conductivity of wood elements and layers increased significantly, CLT is usually between 20%–30%, while spruce structural elements are between 78%–356%. On the other hand, Steico thermal insulation mostly kept its thermal conductivity, the difference was only 1%–2%. Therefore, since most of the thermal resistance of the construction are coming from the thermal insulation itself, the overall thermal performance did not change significantly.

The thermal transmittances of the constructions calculated using DesignBuilder and declared thermal conductivities of materials as well as the effective, design thermal conductivity based thermal U values from the HAM simulations are shown in Table 3. The U values with the HAM simulation are between 10.6%–16.5% higher depending on the building construction. The wall construction suffered the largest increase in its thermal transmittance due to the large amount of inhomogeneities caused by the brackets and steel mechanical fasteners. However, we can state that all of the constructions still meet the requirements of the Hungarian legislation, which requires maximum 0.24 W/m²K U value for walls and 0.17 W/m²K for the non-ground contacting floor and roof constructions, respectively. If any of the building constructions does not meet the hygrothermal requirements to avoid the deterioration, or the energy performance requirements by the legislation, the constructions needs to be redesigned. These

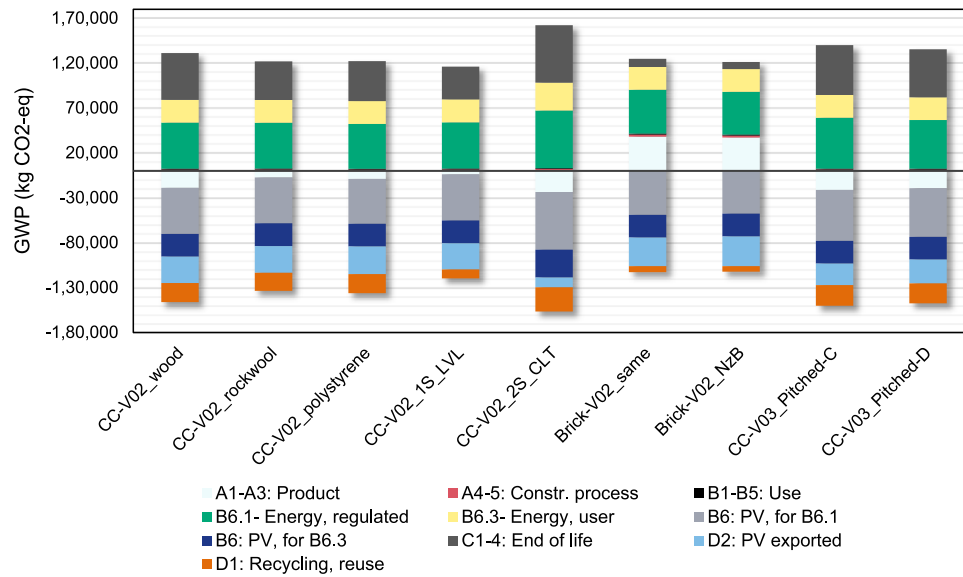


Fig. 8. Global Warming Potential of the variants according to the life cycle stages.

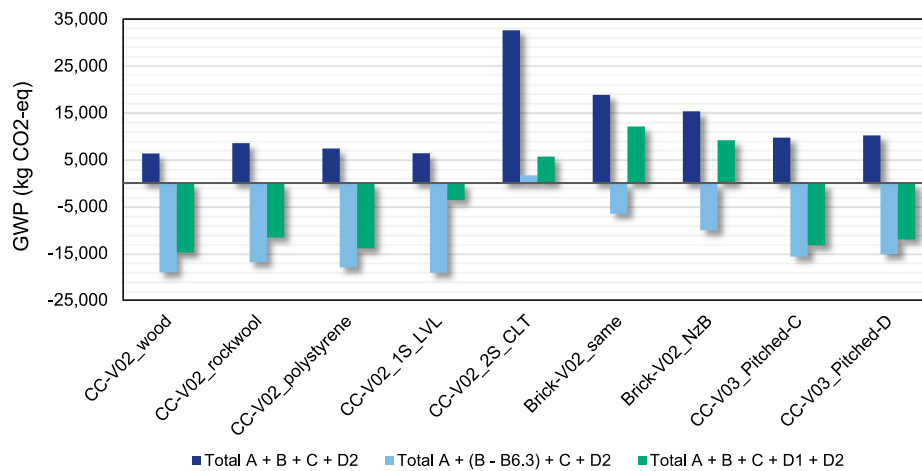


Fig. 9. Global Warming Potential of the variants over the life cycle plus the benefits from D2 exported energy, with different system boundaries.

Table 3

Difference between the U vales depending on the calculation method.

Construction	U value using declared thermal conductivities (W/m ² K)	U value using effective thermal conductivities from HAM (W/m ² K)	Increase (%)
CC_Floor_CLTF1_18cmSteico	0.141	0.156	10.6
CC_Wall_CLTVW1-T_16cmSteico	0.176	0.205	16.5
CC_Roof_CLTR2_21cmSteico	0.138	0.154	11.6
CC_Roof_CLTR1_20cmSteico (pitched)	0.147	0.167	13.6

examined constructions are proven to be adequate in all respects, therefore these HAM based U values were used in the detailed dynamic simulations.

3.3. Life cycle assessment (LCA)

Figs. 8 and 9 show the life cycle assessment results for the full life cycle, for the Global Warming Potential (GWP) indicator. The Product stage had a negative value in all the wooden variants, as the carbon sequestration during the growth phase of the wooden products was accounted for in stage A. However, this carbon will be emitted in stage C at the end-of-life when the wood is burnt or landfilled. The brick houses, on the other hand, had a positive GWP at the production stage but little CO₂ was emitted at the

end-of-life. From the wooden houses, the LVL system had the lowest carbon storage capacity, as this is a frame structure with infill insulation hence with a lower amount of timber. The highest carbon storage was observed in the CLT structures with wood fibre insulation material. The brick buildings used a large amount of concrete, as well as the two-storey version due to the need for a concrete foundation.

The impact of the use stage was low: over the 30 year study period, only the bituminous roof waterproofing and the heat pump are replaced (B5). The sum of the operational energy use (B6) was zero, as in a yearly balance the photovoltaic system produced enough energy to supply the space and water heating, cooling, lighting and appliances. The two-storey variant had higher floor area which lead to higher lighting and appliance energy demand, while the brick houses had lower space heating

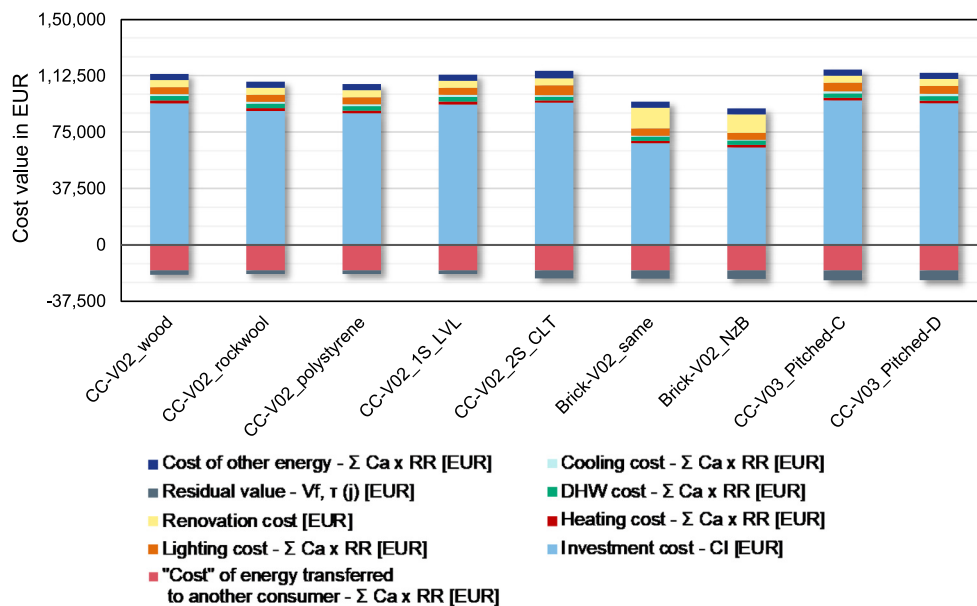


Fig. 10. Life cycle cost of the variants.

and cooling energy demand because of the larger thermal mass as explained in Section 3.1.

The surplus PV energy that is exported to the grid is depicted in stage D2. In the analysis, all variants had the same sized PV system (6.2 kWp) generating the same amount of energy. As the operational energy need of the variants differed, the amount of exported PV energy also differed: the CC-V02_2S_CLT version had the highest operational energy demand, hence the lowest amount of exported PV electricity. The reuse/recycling potential beyond the life cycle is shown in D1, which was again higher for the wooden buildings.

Carbon neutrality was targeted by including the avoided grid impacts of the exported energy in module D. Different system boundaries were considered: with and without user-related energy use and with and without including the reuse/recycling potential in module D1. According to the client's original brief, carbon neutrality should be achieved without the user-related operational energy (appliances). The reason for this was that the carbon compact house manufacturer only considered the building and building-related operation as part of its system. User-related energy can be so diverse that it was not considered as part of a guaranteed carbon-neutral system/product. As seen in Fig. 9, all variants achieve carbon neutrality except for the two-storey version with the planned PV capacity if user-related energy is not included. However, if appliances are also included in the operational energy demand, the buildings are not completely GHG neutral: the highest GWP (32 602 kg CO₂-eq) belongs to the two-storey version, followed by the brick buildings. The CC-V02_wood and the LVL variants are the closest to carbon neutrality with a GWP of 6299 and 6355 kg CO₂-eq, respectively. If reuse/recycling potential (D1) is considered, all wooden buildings comply with the goals except for the two-storey version and the brick buildings are also not GHG neutral.

3.4. Life cycle costing (LCC)

Fig. 10 shows the LCC results for 30 years (see also Annex E). When comparing the different insulations, the result showed that the solution with wood fibre had the highest investment costs due to the significantly higher cost of the building material: wood fibre unit price is 263% higher than polystyrene, and 220% higher than rockwool.

The versions CC-V03_Pitched-C, CC-V02_1S_LVL, CC-V02_2S_CLT present the cost of the geometries updated during the research and the cost of the alternative buildings of the same or similar mass as the planned building, but designed in a different system. The differences between the CC-V02_1S_LVL and CC-V02_2S_CLT come from the different geometry. The versions CC-V03_Pitched-C and CC-V03_Pitched-D have similar prices to the CC-V02_1S_LVL.

The brick variants Brick-V02_same and Brick-V02_NzB have the lowest global costs and investment cost among all versions. In terms of global costs, the result is more nuanced, but from an economic point of view, wood-based structures are at a disadvantage compared to conventional brick structures. The main difference lies in the investment costs: conventional brick buildings are much cheaper than the wood based construction versions. Even if the renovation cost is on average three times higher, the global cost is still the lowest of these two versions. The difference in operating costs is mainly due to heating and lighting costs, but it is not significant compared to global costs. Revenue from the sale of surplus energy from the solar system was considered in operating cost as a negative cost. In practice, the surplus energy generated can be used locally e.g. to charge electric cars, so the equality of the selling and buying prices is justified.

Overall, it can be stated that the wood-based structure's cost significantly increases the global cost. Brick structures are almost 30% cheaper in terms of investment. Over the studied 30 year life cycle, the global cost difference decreases, but even it is still more than 20%.

3.5. Sensitivity analysis

Carbon neutrality was achieved in almost all wooden variants with the planned PV capacity, depending on the system boundary. In the sensitivity analysis, first the minimum necessary size of the PV system was determined with an iterative process, also considering the manufacturing impact of the panels. Table 4 shows that a capacity of 6.6–8.2 kWp would be needed, depending on the variant if the reuse/recycling potential (D1) is not considered. Brick buildings and the two-storey variant require the largest capacity. If module D1 were included, lower sizes between 5.26–6.97 kWp would be sufficient, but the future reuse/recycling potential has large uncertainty.

Table 4

Photovoltaic sizes (kWp) required for a net zero GHG balance without and with considering the benefits in module D1.

	CC-V02_wood	CC-V02_rockwool	CC-V02_polystyrene	CC-V02_1S_LVL	CC-V02_2S_CLT	Brick-V02_same	Brick-V02_NzB	CC-V03_Pitched-C	CC-V03_Pitched-D
A+B+C+D2	6.60	6.74	6.67	6.60	8.21	7.40	7.17	7.01	6.85
A+B+C+D1+D2	5.26	5.46	5.32	5.97	6.50	6.97	6.78	5.36	5.44

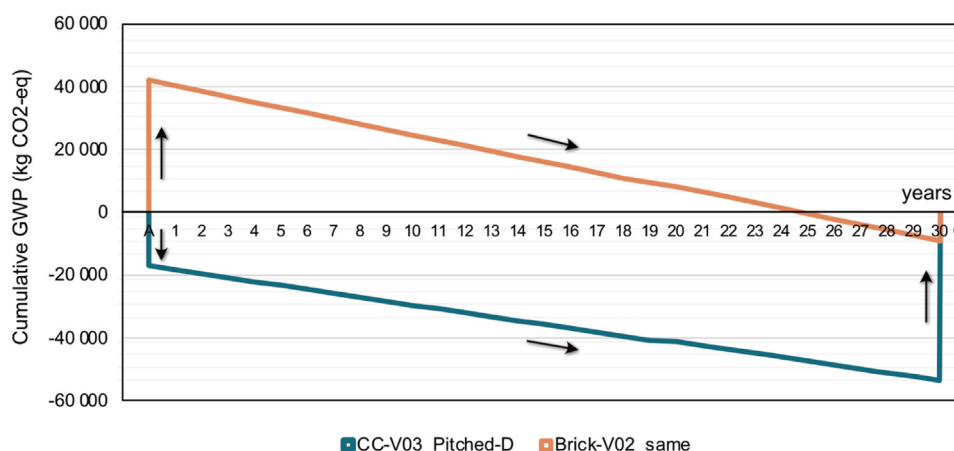


Fig. 11. Cumulative GWP of the CC-V03_Pitched-D and the Brick-V02_same variants over the 30 year calculation period, with a PV capacity sufficient for a net zero GHG balance (PV sizes 6.85 and 7.40 kWp).

The results presented are suitable for comparing the variants but do lack a very important aspect of carbon neutrality: the time factor. Building materials are manufactured and the building is built today, the operation of the building and the PV generation are continuous during the use phase and the end-of-life occurs when the building is demolished. The systems are dimensioned so that they have a net zero balance at 30 years but for reaching the climate targets (Delbeke et al., 2019), the temporal dynamics are also relevant. The cumulative GWP of two variants is visualized in Fig. 11 as a function of time, assuming a PV capacity sufficient for a net zero GHG balance. The balance of the brick building is positive (emitting GHG) until year 25 when it becomes negative and then zero at the end-of-life. On the contrary, the timber building store carbon over 30 years and the cumulative GWP is in a steadily decreasing negative range and only becoming zero when the carbon is released at the end-of-life. The end-of-life is included in our calculations but in reality it has a high probability that the building is not demolished after 30 years and the carbon is stored over a much longer period.

In these assessments, it was assumed that the avoided impacts of the PV generated electricity are constant and correspond to the present electricity mix, which is not the case in reality (González-Prieto et al., 2021). To study the sensitivity of the results to a dynamically decarbonizing electricity mix, two additional scenarios were considered. The scenarios were developed in the South East Europe Electricity Roadmap (SEERMAP) project (Szabó et al., 2017). The projection was carried out by the interaction of the European Electricity Market Model (EEMM) and the Green-X model (Capros et al., 2014; Mezősi and Szabó, 2016) and life cycle based emission factors were calculated until 2050 (Kiss et al., 2020). Based on the previous studies the scenarios are described as follows:

- The “No target” scenario sets no long-term goal for carbon-dioxide emission reduction, neither for the SEERMAP region, nor for the rest of the EU. In line with this, it involves the realization of all fossil-based investments indicated in national plans, and support for renewable energy is phased out after 2025.
- The “Decarbon” scenario targets an emission reduction of 94% for 2050 – compared to 1990 emission levels – in line with the long-term indicative EU emission reduction goals for the electricity sector as a whole (European Commission, 2011).

The required PV sizes are much larger in these scenarios than with the static electricity mix: with the No target scenario 8.2

Table 5
Photovoltaic sizes (kWp) required for a net zero GHG balance depending on the future electricity decarbonization scenario (A+B+C+D2).

	Brick-V02_same	CC-V03_Pitched-D
Static, present mix	7.4	6.9
Dynamic, No target scenario	9.3	8.2
Dynamic, Decarbon scenario	12.7	10.6

and 9.3 kWp and with the Decarbon scenario 10.6 and 12.7 kWp are necessary for the Pitched-D and brick houses, respectively (Table 5). This is due to the diminishing benefit from the avoided impact as the electricity mix becomes cleaner. The differences between the scenarios are also visible in Fig. 12 where the shape of the Static and No target functions are similar (although with different PV sizes) but in the Decarbon scenario the gradual reduction in the avoided impact is clearly visible. Similar results were achieved by Grinham et al. who showed that achieving zero carbon balance depends on the grid carbon intensity (Grinham et al., 2022). In a mediterranean climate, a 6.5 kWp photovoltaic array was sufficient in an optimized design to achieve net zero life cycle GHG emissions in an apartment unit, but cleaner grid makes it harder to offset the embodied emissions (Stephan and Stephan, 2020). In Norway, life cycle energy and material balance was not met with 78 m² of photovoltaics in a single-family house due to the low grid carbon intensity (Kristjansdottir et al., 2018).

4. Conclusions

This paper described the development of a carbon neutral compact house concept through a combination of dynamic energy simulation, heat and moisture simulation, life cycle assessment and life cycle costing. Our comprehensive analysis provides experience for the practical implementation of net zero carbon buildings.

The basic hypothesis of our research was that the concept of a life-cycle (net) zero carbon compact house is feasible with solar energy offset, which was proved by the analysis. However, the system boundaries largely influence the amount of necessary panels and need to be exactly defined. User-related energy was particularly crucial, which depends widely on consumer habits. According to the concept of the manufacturing company the building system covers some of the user-related energy but does not guarantee carbon neutrality if user energy consumption is high. It is easier to reach carbon neutrality if potential benefits

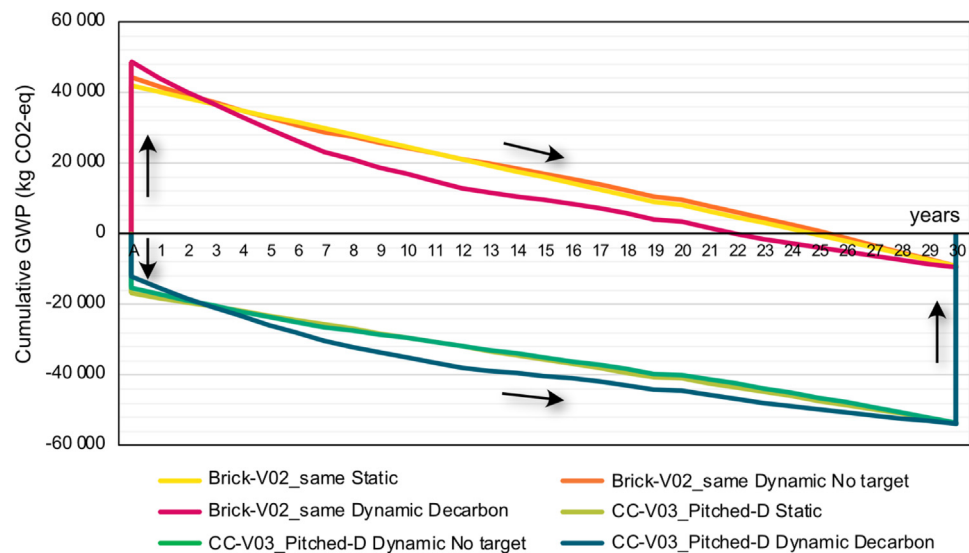


Fig. 12. Cumulative GWP of the CC-V03_Pitched-D and the Brick-V02_same variants over the 30 year calculation period with different electricity scenarios, with a PV capacity sufficient for a net zero GHG balance (PV sizes according to Table 5).

from reuse/recycling at the end-of-life are included in the balance, which are very significant in case of timber buildings but have a high uncertainty. There is also a level of uncertainty in the potentially avoided impacts when excess solar energy is fed into the electricity grid. If the foreseen dynamic decarbonization of the electricity mix was considered, about 1.5 times larger photovoltaic sizes were required to offset the environmental load of the construction due to the diminishing benefits.

The environmental assessment showed that the ratio of the embodied impacts (A1–5 + B1–5 + C1–4) and the operational impacts without solar energy (B6) are about 1:2 for wooden buildings and 1:1.5 for brick buildings. This is a significant difference, but smaller than previously expected. However, a main difference between timber and brick buildings is the time factor: while the initial emissions from the production of the brick buildings are gradually offset with the excess solar energy, the timber buildings act as a carbon storage with negative emissions over the study period and carbon is only released at the eventual end-of-life stage, with the final balance becoming zero in both cases. If demolition was delayed and the material was recycled/reused, the difference would become more significant. In the embodied impacts, there is a significant difference between the building foundation solutions. The CO₂ emissions of the concrete foundations required for brick and two-storey buildings were significantly higher than those of the ground floor versions with ground-screw. However, it is important to stress that the net zero requirement for the whole life cycle can be achieved both for the timber and for brick buildings by installing a realistic amount of additional solar panels.

Our energy studies have shown that for a well insulated building with slightly better than nZEB rated boundary structures and heat pump heating/cooling, uses which are independent from the building, namely hot water, lighting and other user-related energy dominate the total energy demand. Higher thermal mass of brick buildings resulted in lower heating-cooling energy demand, but the final difference was less significant due to the importance of other uses. As heating and cooling energy demand represents a relatively small fraction of the total energy consumption, the additional insulation has only minimally reduced the overall energy demand of the building. However, the additional material requirement of the increased insulation has also resulted in a slight increase in CO₂ emissions in the installation and global costs of buildings. The strategic way to achieve decarbonization

is presumably to improve the technical systems of nZEB buildings rather than to increase the amount of insulation above a certain level.

The heat and moisture transfer investigations showed 10%–16% higher thermal transmittances for the building elements. The final results were slightly higher than without HAM calculations but still complying with the carbon neutrality requirement. The analysis is recommended in product development to detect any potential hygrothermal issues and avoid deterioration.

The experience of the research workflow showed that a comprehensive analysis was only possible by using several different software tools. The transfer of data between the software tools required considerable time and manual labour and sometimes resulted in data loss. To achieve a widespread implementation of the approach and to find solutions that can be applied at different scales and functions, it would be important to create a platform that combines several aspects (modelling, energy, environment and economics).

Further work is planned to refine the results, for example to investigate the impact of expected climate change on the concept of a carbon neutrality, and monitor the production and real-life operation of the realized carbon compact building.

5. Nomenclature

Abbreviations	
2S	Two stories examined building
3D	Three dimension (modelling)
ACH	Air changes per hour
BIM	Building Information Modelling
CC	Carbon compact building (mobile building, main structural materials based on wood)
CLT	Cross-laminated timber
CTF	Conduction Transfer Function
DHW	Domestic hot water
EPD	Environmental Product Declarations
GHG	greenhouse gas emissions
GWP	Global Warming Potential
HAM	heat and moisture simulation
HVAC	Heating, ventilation and air conditioning
LCA	Life Cycle Assessment

(continued on next page)

LCC	Life Cycle Cost
LVL	Laminated veneer lumber
nZEB	nearly zero energy building
PDE	partial differential equations
PV	Photovoltaic system
V02	Examined building with smaller pitched roof (mainly ground floor)
V03	Examined building with larger pitched roof (ground floor)
Units	
U	Thermal transmittance (W/m ² K)
λ	Thermal conductivity (W/mK)
ρ	Density (kg/m ³)
C_p	Heat capacity at constant pressure (J/kg · K)
T	Temperature (K)
t	Time (s)
∇	Nabla vectorial differential operator
∂	Partial derivative
L_v	Latent heat of evaporation of water (J/kg)
δ_p	Vapour permeability (kg/m · s · Pa)
φ	Relative Humidity (1)
p_{sat}	Saturation pressure of water vapour (Pa)
w	moisture content (kg/m ³)
ξ	Differential moisture capacity (kg/m ³)
D_w	Liquid transport coefficient (m ² /s)
f_{Rsi}	Temperature factor at internal surface point (1)
Q	Heat flow (W)
ΔT	Temperature difference (K)
A	Internal surface (m ²)

CRedit authorship contribution statement

Zsuzsa Szalay: Conceptualization, Methodology, Investigation, Supervision, Writing – original draft, Writing – review & editing. **Dóra Szagri:** Methodology, Investigation, Software, Visualisation, Writing – original draft. **Ádám Bihari:** Methodology, Investigation, Writing – original draft. **Balázs Nagy:** Methodology, Investigation, Software, Visualisation, Writing – original draft. **Benedek**

Table A.1

Material compositions of the examined buildings.

	CC-V02_wood	CC-V02_rockwool	CC-V02_polystyrene	CC-V02_1S_LVL
Foundation	Ground screws	Ground screws	Ground screws	Ground screws
Slab-on-ground floor	–	–	–	–
Suspended floor	CC_Floor_CLTF1_18cmSteico - 1 cm ceramic/parquet - 2 × 1 cm Betonyp (cement fibreboard) - 2,5 cm Siccus board (polystyrene-metal layer for dry underfloor heating system) - 12 cm CLT (Cross Laminated Timber load-bearing structure) - foil: Rothoblaas BARRIER ALU 200 (vapour barrier layer) - 18 cm Steico Protect (wood fibre insulation) - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 2,1 cm laminated board - modified bituminous sheet	CC_Floor_CLTF1_18cmAirRock - 1 cm ceramic/parquet - 2 × 1 cm Betonyp (cement fibreboard) - 2,5 cm Siccus board (polystyrene-metal layer for dry underfloor heating system) - 12 cm CLT (Cross Laminated Timber load-bearing structure) - foil: Rothoblaas BARRIER ALU 200 (vapour barrier layer) - 18 cm rockwool insulation (Air Rock HD) - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 2,1 cm laminated board - modified bituminous sheet	CC_Floor_CLTF1_18cmGEPS - 1 cm ceramic/parquet - 2 × 1 cm Betonyp (cement fibreboard) - 2,5 cm Siccus board (polystyrene-metal layer for dry underfloor heating system) - 12 cm CLT (Cross Laminated Timber load-bearing structure) - foil: Rothoblaas BARRIER ALU 200 (vapour barrier layer) - 18 cm Grafit EPS Bachl - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 2,1 cm laminated board - modified bituminous sheet	CC_Floor_LVL2_25_steico - 1 cm ceramic/parquet - 2 × 1 cm Betonyp (cement fibreboard) - 2,5 cm Siccus board (polystyrene-metal layer for dry underfloor heating system) - 2,5 cm laminated board - foil: Rothoblaas BARRIER ALU 200 (vapour barrier layer) - 25 cm LVL (Laminated Veneer Lumber) structure filled with 25 cm Steico Flex wood fibre insulation - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 2,1 cm laminated board - modified bituminous sheet

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Kiss: Methodology, Writing – review & editing. **Miklós Horváth:** Methodology, Writing – review & editing. **Péter Medgyasszay:** Conceptualization, Methodology, Investigation, Data curation, Supervision, Writing – original draft, Project administration.

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

No data was used for the research described in the article.

Acknowledgements

The research was supported by Project FK 128663 implemented with the support provided from the National Research, Development and Innovation Fund of Hungary, financed under the FK_18 funding scheme.

The research is part of project no. BME-NVA-02, implemented with the support provided by the Ministry of Innovation and Technology of Hungary from NRDI, financed under the TKP2021 funding scheme.

The fourth author was supported by the ÚNKP-21-4 New National Excellence Program of the Ministry for Innovation and Technology from the source of the National Research, Development and Innovation Fund.

The sixth author was supported by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences and by the ÚNKP-21-5 New National Excellence Program of the Ministry for Innovation and Technology from the source of the National Research, Development and Innovation Fund.

Annex A

See [Table A.1](#).

Table A.1 (continued).

	CC-V02_wood	CC-V02_rockwool	CC-V02_polystyrene	CC-V02_1S_LVL
External wall	CC_Wall_CLTVW1-T_16cmSteico - 10 cm CLT (Cross Laminated Timber load-bearing structure) - 16 cm Steico Protect (wood fibre insulation) - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 3 cm airgap - 2,5 cm Thermowood cladding	CC_Wall_CLTVW1-T_16cmAirRock - 10 cm CLT (Cross Laminated Timber load-bearing structure) - 16 cm rockwool insulation (Air Rock HD) - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 3 cm airgap - 2,5 cm Thermowood cladding	CC_Wall_CLTVW1-T_16cmSteicoGEPS - 10 cm CLT (Cross Laminated Timber load-bearing structure) - 16 cm Graphite EPS Bachl insulation - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 3 cm airgap - 2,5 cm Thermowood cladding	CC_LVLVW2_20_4Steico - 1,2 cm laminated board - foil: Rothoblaas BARRIER ALU 200 (vapour barrier layer) - 20 cm LVL (Laminated Veneer Lumber) structure filled with 20 cm Steico Flex wood fibre insulation - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 3 cm airgap - 2,5 cm Thermowood cladding
Partition wall	CC_Wall_CLT10 - 10 cm CLT (Cross Laminated Timber structure)	CC_Wall_CLT10 - 10 cm CLT (Cross Laminated Timber structure)	CC_Wall_CLT10 - 10 cm CLT (Cross Laminated Timber structure)	CC_Wall_CLT10 - 10 cm CLT (Cross Laminated Timber structure)
Internal floor	–	–	–	–
Flat roof	CC_Roof_CLTR2_21cmSteico - 12 cm CLT (Cross Laminated Timber load-bearing structure) - foil: Rothoblaas BARRIER ALU 200 (vapour barrier layer) - 21 cm Steico Protect L (wood fibre insulation) - 0,9 cm laminated board - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 2 layers BAUDER Thermoplan membrane (waterproofing layer) - Sedum green roof	CC_Roof_CLTR2_21cmAirRock - 12 cm CLT (Cross Laminated Timber load-bearing structure) - foil: Rothoblaas BARRIER ALU 200 (vapour barrier layer) - 20 cm rockwool insulation (Air Rock HD) - 0,9 cm laminated board - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 2 layers BAUDER Thermoplan membrane (waterproofing layer) - Sedum green roof	CC_Roof_CLTR2_21cmGEPS - 12 cm CLT (Cross Laminated Timber load-bearing structure) - foil: Rothoblaas BARRIER ALU 200 (vapour barrier layer) - 21 cm Graphite EPS Bachl insulation - 0,9 cm laminated board - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 2 layers BAUDER Thermoplan membrane (waterproofing layer) - Sedum green roof	CC_Roof_LVLR4_25+6-Steico - 1,2 cm laminated board - foil: Rothoblaas BARRIER ALU 200 (vapour barrier layer) - 25 cm LVL (Laminated Veneer Lumber) structure filled with 25 cm Steico Flex wood fibre insulation - 4 cm Steico Universal wood fibre insulation - 0,9 cm laminated board - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 2 layers BAUDER Thermoplan membrane (waterproofing layer) - Sedum green roof
Pitched roof	CC_Roof_CLTR1_20cmSteico (pitched) - 12 cm CLT (Cross Laminated Timber load-bearing structure) - foil: Rothoblaas BARRIER ALU 200 (vapour barrier layer) - 20 cm Steico Protect L (wood fibre insulation) - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 3+3 cm airgap/LVL - 2,5 cm planking - TRASPIR 3D coat - 0,05 cm Lindab SRP Click (metal sheet cover)	CC_Roof_CLTR1_20cmAirRock (pitched) - 12 cm CLT (Cross Laminated Timber load-bearing structure) - foil: Rothoblaas BARRIER ALU 200 (vapour barrier layer) - 20 cm rockwool insulation (Air Rock HD) - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 3+3 cm airgap/LVL - 2,5 cm planking - TRASPIR 3D coat - 0,05 cm Lindab SRP Click (sheet metal cover)	CC_Roof_CLTR1_20cmGEPS (pitched) - 12 cm CLT (Cross Laminated Timber load-bearing structure) - foil: Rothoblaas BARRIER ALU 200 (vapour barrier layer) - 20 cm Graphite EPS Bachl insulation - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 3+3 cm airgap/LVL - 2,5 cm planking - TRASPIR 3D coat - 0,05 cm Lindab SRP Click (sheet metal cover)	CC_Roof_LVLR3 (pitched) - 1,2 cm laminated board - foil: Rothoblaas BARRIER ALU 200 (vapour barrier layer) - 20 cm LVL (Laminated Veneer Lumber) structure filled with 20 cm Steico Flex - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 3+3 cm airgap/LVL - 2,5 cm planking - TRASPIR 3D coat - 0,05 cm Lindab SRP Click (sheet metal cover)
Windows	Wood, Triple Glazed	Wood, Triple Glazed	Wood, Triple Glazed	Wood, Triple Glazed

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Annex B

See Fig. A.1.

Annex C

See Table A.2.

Table A.1 (continued).

	CC-V02_wood	CC-V02_rockwool	CC-V02_polystyrene	CC-V02_1S_LVL
External doors	Wood	Wood	Wood	Wood
Internal doors	Wood	Wood	Wood	Wood
Shading	Outside, Blind with high reflective slats	Outside, Blind with high reflective slats	Outside, Blind with high reflective slats	Outside, Blind with high reflective slats
	CC-V02_2S_CLT	Brick-V02_same	Brick-V02_NzB	CC-V03_Pitched-C and CC-V03_Pitched-D
Foundation	Concrete foundation	Concrete foundation	Concrete foundation	Ground screws
Slab-on-ground floor	CC_Floor_CLTF1_18cmSteico-on-the-floor - 1 cm ceramic/parquet - 2*1 cm Betonyp (cement fibreboard) - 2,5 cm Siccus board (polystyrene-metal layer for dry underfloor heating system) - 12 cm CLT (Cross Laminated Timber load-bearing structure) - foil: Rothoblaas BARRIER ALU 200 (vapour barrier layer) - 18 cm Steico Protect (wood fibre insulation) - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 2,1 cm laminated board - modified bituminous sheet (VILLAS-ICOPAL E-G 4 F/K) - 10 cm reinforced concrete (ø10/15 steel-net, concrete: C25/30-XC2-8-F2) - 25 cm gravel	CC_Floor-Brick-20-EPS-G - 1 cm ceramic/parquet - 6 cm concrete - polyethylene sheet - 20 cm Austrotherm Graphite 100 insulation - modified bituminous sheet (VILLAS-ICOPAL E-G 4 F/K) - 12 cm reinforced concrete (ø10/15 steel-net, concrete: C25/30-XC2-8-F2) - 25 cm gravel	CC_Floor-Brick-10-EPS-G - 1 cm ceramic/parquet - 6 cm concrete - polyethylene sheet - 10 cm Austrotherm Graphite 100 insulation - modified bituminous sheet (VILLAS-ICOPAL E-G 4 F/K) - 12 cm reinforced concrete (ø10/15 steel-net, concrete: C25/30-XC2-8-F2) - 25 cm gravel	–
Suspended floor	–	–	–	CC_Floor_CLTF1_18cmSteico - 1 cm ceramic/parquet - 2 × 1 cm Betonyp (cement fibreboard) - 2,5 cm Siccus board (polystyrene-metal layer for dry underfloor heating system) - 12 cm CLT (Cross Laminated Timber load-bearing structure) - foil: Rothoblaas BARRIER ALU 200 (vapour barrier layer) - 18 cm Steico Protect (wood fibre insulation) - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 2,1 cm laminated board - modified bituminous sheet
External wall	CC_Wall_CLTVW1-T_16cmSteico - 10 cm CLT (Cross Laminated Timber load-bearing structure) - 16 cm Steico Protect (wood fibre insulation) - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 3 cm airgap - 2,5 cm Thermowood cladding	CC-Wall-Brick-38_8cmEPS - 0,5 cm thin-layer finish render - 8 cm EPS Bachl expanded polystyrene insulation - 1,5 cm plaster (UniPutz) - 38 cm brick (Porotherm Klíma) - 1,5 cm plaster (UniPutz)	CC-Wall-Brick-38 - 3 cm perlite plaster - 38 cm brick (Porotherm Klíma) - 1,5 cm plaster (UniPutz)	CC_Wall_CLTVW1-T_16cmSteico - 10 cm CLT (load-bearing wood) - 16 cm Steico Protect (wood fibre insulation) - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 3 cm airgap - 2,5 cm Thermowood cladding
Partition wall	CC_Wall_CLT10 - 10 cm CLT (Cross Laminated Timber load-bearing structure)	CC-Wall_Brick-10 - 1,5 cm plaster (UniPutz) - 10 cm brick (Porotherm 10 N+F) - 1,5 cm plaster (UniPutz)	CC-Wall_Brick-10 - 1,5 cm plaster - 10 cm brick (Porotherm 10 N+F) - 1,5 cm plaster (UniPutz)	CC_Wall_CLT10 - 10 cm CLT (Cross Laminated Timber structure)

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Table A.1 (continued).

	CC-V02_2S_CLT	Brick-V02_same	Brick-V02_NzB	CC-V03_Pitched-C and CC-V03_Pitched-D
Internal floor	CC_Floor_CLTF1_AGF - 1 cm ceramic/parquet - 2 × 1 cm Betonyp (cement fibreboard) - 2,5 cm Siccus board (polystyrene-metal layer for dry underfloor heating system) - 12 cm CLT (Cross Laminated Timber load-bearing structure) - 15 cm airgap - 12 cm CLT (Cross Laminated Timber load-bearing structure)	–	–	–
Flat roof	CC_Roof_CLTR2_21cmSteico - 12 cm CLT (Cross Laminated Timber load-bearing structure) - foil: Rothoblaas BARRIER ALU 200 (vapour barrier layer) - 21 cm Steico Protect L (wood fibre insulation) - 0,9 cm laminated board - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 2 layers BAUDER Thermoplan membrane - Sedum green roof	CC_Roof_RC_18cmEPS-G - 1,5 cm plaster (UniPutz) - 17 cm PoroTherm beam and block slab with 5 cm reinforced concrete - foil: Rothoblaas BARRIER ALU 200 (vapour barrier layer) - 18 cm Austrotherm Graphite 100 expanded polystyrene insulation - 0,9 cm laminated board - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 2 layers BAUDER Thermoplan membrane - Sedum green roof	CC_Roof_RC_15cmEPS-G - 1,5 cm plaster (UniPutz) - 17 cm PoroTherm beam and block slab with 5 cm reinforced concrete - foil: Rothoblaas BARRIER ALU 200 (vapour barrier layer) - 15 cm Austrotherm Graphite 100 expanded polystyrene insulation - 0,9 cm laminated board - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 2 layers BAUDER Thermoplan membrane - Sedum green roof	CC_Roof_CLTR2_21cmSteico - 12 cm CLT (Cross Laminated Timber load-bearing structure) - foil: Rothoblaas BARRIER ALU 200 (vapour barrier layer) - 21 cm Steico Protect L (wood fibre insulation) - 0,9 cm laminated board - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 2 layers BAUDER Thermoplan membrane - Sedum green roof
Pitched roof	CC_Roof_CLTR1_20cmSteico (pitched) - 12 cm CLT (Cross Laminated Timber load-bearing structure) - foil: Rothoblaas BARRIER ALU 200 (vapour barrier layer) - 20 cm Steico Protect L (wood fibre insulation) - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 3+3 cm air gap/LVL - 2,5 cm planking - TRASPIR 3D coat - 0,05 cm Lindab SRP Click (metal sheet cover)	CC_Roof_ConW_15+10cm Rockwool (pitched) - 1,2 cm gypsum board - 3 cm air gap - foil: Rothoblaas BARRIER ALU 200 (vapour barrier layer) - 10 cm wood structure filled with rockwool insulation (Deltarock) - 15 cm wood structure filled with rockwool insulation (Deltarock) - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 3+3 cm air gap/LVL - 2,5 cm planking - TRASPIR 3D coat - 0,05 cm Lindab SRP Click (metal sheet cover)	CC_Roof_ConW_15+7_5cmRockwool (pitched) - 1,2 cm gypsum board - 3 cm air gap - foil: Rothoblaas BARRIER ALU 200 (vapour barrier layer) - 7,5 cm wood structure filled with rockwool insulation (Deltarock) - 15 cm wood structure filled with rockwool insulation (Deltarock) - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 3+3 cm air gap/LVL - 2,5 cm planking - TRASPIR 3D coat - 0,05 cm Lindab SRP Click (metal sheet cover)	CC_Roof_CLTR1_21cmSteico (pitched) - 12 cm CLT (Cross Laminated Timber load-bearing structure) - foil: Rothoblaas BARRIER ALU 200 (vapour barrier layer) - 21 cm Steico Protect L (wood fibre insulation) - foil: Rothoblaas TRASPIR 115 (vapour permeable air barrier layer) - 3+3 cm air gap/LVL - 2,5 cm planking - TRASPIR 3D coat - 0,05 cm Lindab SRP Click (metal sheet cover)
Windows	Wood, Triple Glazed	Wood, Triple Glazed	Wood, Triple Glazed	Wood, Triple Glazed
External doors	Wood	Wood	Wood	Wood
Internal doors	Wood	Wood	Wood	Wood
Shading	Outside, Blind with high reflective slats	Outside, Blind with high reflective slats	Outside, Blind with high reflective slats	Outside, Blind with high reflective slats

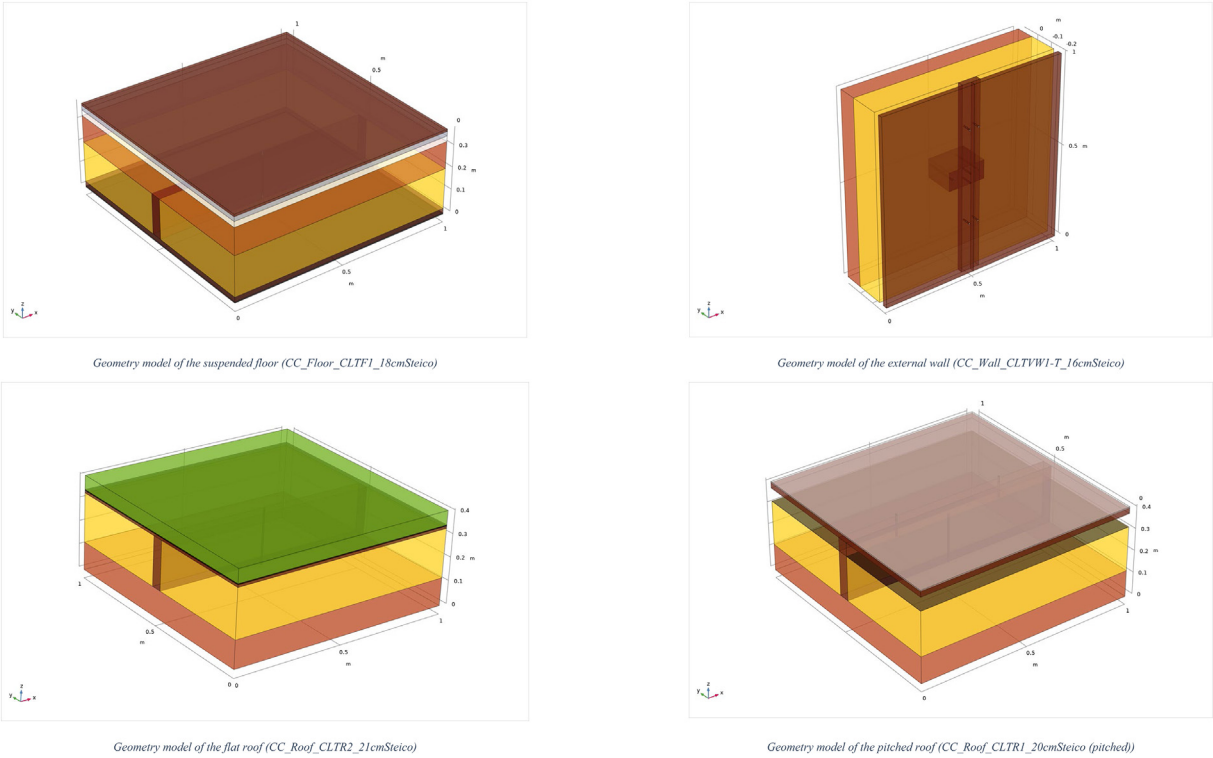


Fig. A.1. Geometry models of the main building elements.

Table A.2

LCIA datasets and main assumptions assigned to the materials and technical building systems.

	Wooden buildings	Ökobaudat dataset	Data type	Transport scenario	Cutting waste	Life time (yr)	Ref unit	Density (kg/m ³)	Surface weight (kg/m ²)	GWP (A1–A3) kg CO ₂ -eq	GWP (C3) kg CO ₂ -eq	GWP (C4) kg CO ₂ -eq	GWP (D1)
Wood	Cross Laminated Timber (CLT)	Brettspertholz (Durchschnitt DE)	Representative	3	0.02	50	m ³	489		−633.37	792.82		−357.56
	Plywood	Sperrholzplatte	Generic	3	0.1	50	m ³	491		−733.76	1030.49		−32.45
	LVL frame	Furnierschichtholz	Generic	3	0.1	50	m ³	466		−465.42	896.18		−30.48
	Wooden board	Nadelschnittholz-getrocknet (Durchschnitt DE)	Representative	7	0.1	50	m ³	485		−734.69	797.14		−358.22
Insulation	Graphite EPS	Dämmplatte mit Neopor [®] Plus	Specific	2	0.03	50	m ³	15		47.59		49.98	−24.27
	Mineral wool, low density, AIR ROCK ND	ROCKWOOL Steinwolle-Dämmstoff im niedrigen Rohdichtebereich	Average	7	0.03	50	m ³	50		63.44		0.79	−1.74
	Mineral wool, medium density, AIR ROCK HD	ROCKWOOL Steinwolle-Dämmstoff im mittleren Rohdichtebereich	Average	7	0.03	50	m ³	70		88.81		1.11	−2.45
	Wood fibre, Steico average	Holzfaserdämmstoff	Average	3	0.03	50	m ³	157		−172.83	239.54		−30.30
	Wood fibre, Steico Protect L	Holzfaserdämmstoff	Average	3	0.03	50	m ³	110		−121.09	167.83		−21.23
	Wood fibre, Steico Universal board	Holzfaserdämmstoff	Average	3	0.03	50	m ³	271		−297.22	411.94		−52.11
	Wood fibre, Steico Flex	Holzfaserdämmstoff	Average	3	0.03	50	m ³	60		−66.05	91.54		−11.58
	Cellulose blown-in, Steico	Zellulosefaser Einblas-Dämmstoff	Generic	3	0.03	50	m ³	45		−73.37	99.08		−30.51
Membranes	Vapour barrier Rothoblaas BARRIER ALU 200	Dampfbremse PA	Generic	3	0.05	50	m ²		0.1	0.71	0.22		−0.09
	Vapour open Rothoblaas TRASPIR 115	Dampfbremse PET gitterverstärkt (Dicke 0.0001 m)	Generic	3	0.05	50	m ²		0.1	0.74	0.33		−0.10
	Waterproofing Rothoblaas Klima Control	Dampfbremse PE (Dicke 0.0002 m)	Generic	3	0.05	50	m ²		0.2	0.40	0.56		−0.27
	Bituminous waterproofing	Bitumenbahnen V 60 (Dicke 0.005 m)	Generic	3	0.05	50	m ²		5.0	2.04		0.40	
	Waterproofing BAUDER Thermoplan	BauderTHERMOPLAN	Average	3	0.05	15	m ²		2.2	3.11	0.01		−1.77
	3D vapour pressure equalizing membrane. TRASPIR 3D coat	PE/PP Vlies	Generic	3	0.05	50	m ²		0.5	1.26	1.88		−0.85

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Table A.2 (continued).

	Wooden buildings	Ökobaudat dataset	Data type	Transport scenario	Cutting waste	Life time (yr)	Ref unit	Density (kg/m ³)	Surface weight (kg/m ²)	GWP (A1–A3) kg CO ₂ -eq	GWP (C3) kg CO ₂ -eq	GWP (C4) kg CO ₂ -eq	GWP (D1)
Plaster	Thin plaster	WDVS Verklebung und Beschichtung Kunstharzputz	Generic	2	0.05	30	m ²		12	6.70		0.19	
Roofing, cladding	HPL Resopal 6 mm	HPL-Platte	Generic	3	0.02	30	m ³	1400		−385.54	1978.67		12.13
	Metal sheet	Feuerverzinktes Stahlblech	Generic	3	0.02	50	m ²		5.7	16.39			−9.00
	Ceramic tile	Dachziegel1	Generic	2	0.02	50	m ²		45	15.88	0.30		−0.09
	Eternit	Faserzementplatte	Generic	7	0.02	50	m ²	1300		6.99		0.20	
	Ceramic floor tile	Keramische Fliesen und Platten	Average	2	0.02	50	m ²		19	12.94	4.04		−0.10
	Betonyp	Zementgebundene Spanplatte	Generic	2	0.02	50	m ³	1200		1694.15	279.38		−84.65
Openings	Glazing, 3 layers	Dreifachverglasung (Dicke: 0.036 m)	Generic	2	0	30	m ²		30	57.77	3.03	0.49	−1.41
	Wooden window frame	Holz-Blendrahmen	Generic	2	0	30	m			−0.37	4.04		−1.62
	Aluminium window frame	Aluminium-Rahmenprofil, thermisch getrennt, pulverbeschichtet	Generic	2	0	30	m			15.77	0.69		−9.52
	Wooden door	Tür - Hörmann KG Eckelhausen-Haustür	Generic	2	0	30	m ²		47	163.38	10.52	0.12	−92.51
	Shading	Sonnenschutzlamellen Metall	Generic	3	0	30	m ²		2	23.64			−14.88
Ground	Ground screw	Befestigungsmit-tel/Schrauben verzinkt	Generic	4	0	50	kg			3.56			−1.58
	Brick building	Ökobaudat dataset	Data type	Transport scenario	Cutting waste	Life time (yr)	Ref unit	Density (kg/m ³)	Surface weight (kg/m ²)	GWP (A1–A3) kg CO ₂ -eq	GWP (C3) kg CO ₂ -eq	GWP (C4) kg CO ₂ -eq	GWP (D1)
Brick	38 cm brick Porotherm K	Mauerziegel	Average	1	0.02	100	m ³	740		177.98	−12.94	0.46	−7.03
	10 cm partition (Porotherm 10 N+F)	Mauerziegel	Average	1	0.02	100	m ³	820		197.22	−14.34	0.32	−7.03
Cladding	Internal plaster	Kalk-Gips-Innenputz	Generic	2	0.05	50	m ³	1283		283.58		13.51	
	Insulation plaster	Putzmörtel-Wärmedämmputz	Average	2	0.05	50	kg	600		0.97		0.02	−0.02
	Mortar	Mauermörtel-Dünnbettmörtel/Mörtel mit besonderen Eigenschaften	Average	2	0.05	100	kg	1300		0.51		0.02	−0.03
	Gypsum board	Gipskartonplatte (Feuerschutz)(Dicke 0.0125 m)	Generic	7	0.05	50	m ²		10	1.54		0.15	

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Table A.2 (continued).

	Brick building	Ökobaudat dataset	Data type	Transport scenario	Cutting waste	Life time (yr)	Ref unit	Density (kg/m ³)	Surface weight (kg/m ²)	GWP (A1–A3) kg CO ₂ -eq	GWP (C3) kg CO ₂ -eq	GWP (C4) kg CO ₂ -eq	GWP (D1)
Concrete	Concrete floor C25/30-XC2-8-F2	Beton der Druckfestigkeitsklasse C 25/30	Average	1	0.03	100	m ³	2400		197.00	6.01		−21.40
	Reinforcing steel	Bewehrungsstahl	Generic	1	0.03	100	kg	7850		0.68			
	Concrete beams	Beton der Druckfestigkeitsklasse C 30/37	Average	1	0.03	100	m ³	2400		219.00	6.01		−21.40
	Concrete foundation	Beton der Druckfestigkeitsklasse C 20/25	Average	1	0.03	100	m ³	2400		178.00	6.01		−21.40
	Cement screed	Zementestrich	Generic	1	0.03	100	kg	2400		0.18		0.02	
	Gravel	Kies 2/32 getrocknet	Generic	1	0.03	100	kg	1850		0.03	0.01		0.00
Insulation	Mineral wool Deltarock	ROCKWOOL Steinwolle-Dämmstoff im niedrigen Rohdichtebereich	Average	7	0.03	50	m ³	39		49.48		0.62	−1.36
	Austrotherm expert insulation	EPS-Hartschaum (Styropor®) für Decken/Böden und als Perimeterdämmung B/P-035	Average	2	0.03	100	m ³	26		75.40		85.90	−45.20
Technical systems	Ökobaudat dataset		Data type	Transport scenario		Life time (yr)	Ref unit	GWP (A1–A3) kg CO ₂ -eq		GWP (C3) kg CO ₂ -eq	GWP (C4) kg CO ₂ -eq		GWP (D)
Photovoltaics	Photovoltaiksystem 1200 kWh/m, *a (ohne Stromgutschrift)		Generic	4		30	m ²	296.69			12.14		−36.20
Heat pump	Strom Wärmepumpe (Luft–Wasser) 7 kW		Generic	4		20	pcs.	321.29		21.06	3.00		−169.07
Floor heating	Fu"zbodenheizung PEX (100 mm Abstand)		Generic	4		50	m ²	7.75		6.68			−2.78
Buffer storage	Pufferspeicher (Stahl)		Generic	4		20	kg	3.17		0.66			−1.43

Transport scenarios:

- 1: 50 km lorry.
- 2: 150 km lorry + 30 km van.
- 3: 800 km freight rail + 30 km van.
- 4: 800 km lorry + 30 km van.
- 5: 20 km lorry.
- 6: 30 km van.
- 7: 350 km transport lorry + 30 km van.
- 8: 1300 km transport lorry + 30 km van.

Annex D

Annex E

See Table A.4.

See Table A.3.

Table A.3

HAM simulation based effective thermal conductivity of the examined layers.

Construction	Layers	Declared thermal conductivity, 10 °C, dry (W/mK)	HAM simulation based effective thermal conductivity (W/mK)	Increase (%)
CC_Wall_CLTVW1-T_16cmSteico	10 cm CLT	0.1	0.12	20
	16 cm Steico Protect	0.037	0.0379	2
	10/20 cm spruce brackets, 0.5 m distance mounted w. steel fasteners	0.09	0.41	356
	1 lyr Rothoblaas Traspir	0.3	0.3	–
	3 cm air gap	–	–	–
	3/10 cm spruce supporting structure mounted w. steel fasteners	0.09	0.24	167
	2.5 cm Thermowood façade cladding mounted to wood plank using steel fasteners	0.13	0.18	38
CC_Floor_CLTF1_18cmSteico	1 cm parquet	0.13	0.15	15
	2 × 1 cm Betonyp (cement fibreboard)	0.26	0.31	19
	2.5 cm Siccus board (polystyrene)	0.035	0.0362	3
	12 cm CLT	0.1	0.13	30
	1 lyr Rothoblaas Barrier Alu 200	0.4	0.4	–
	18 cm Steico Protect	0.037	0.0376	2
	5/18 spruce supporting structure mounted w. steel fasteners	0.09	0.16	78
	1 lyr Rothoblaas Traspir	0.3	0.3	–
	2.1 cm laminated board modified bituminous waterproofing	0.13 0.5	0.18 0.5	38 –
CC_Roof_CLTR2_21cmSteico	12 cm CLT	0.1	0.12	20
	1 lyr Rothoblaas Barrier Alu 200	0.4	0.4	–
	21 cm Steico Protect	0.037	0.0377	2
	5/18–5/25 spruce supporting structure mounted w. steel fasteners	0.09	0.16	78
	0.9 cm laminated board	0.13	0.18	38
	1 lyr Rothoblaas Traspir	0.3	0.3	–
	2 lyr Bauder Thermoplan	0.5	0.5	–
CC_Roof_CLTR1_20cmSteico (pitched)	Sedum green roof	0.8	0.8	–
	12 cm CLT	0.1	0.13	30
	1 lyr Rothoblaas Barrier Alu 200	0.4	0.4	–
	20 cm Steico Protect	0.037	0.0375	1
	5/20 spruce supporting structure mounted w. steel fasteners	0.09	0.16	78
	6 cm airgap	–	–	–
	2 × 5/3 cm spruce supporting structure mounted w. steel fasteners	0.09	0.2	122
	2.5 cm wood plank	0.13	0.2	54
	1 lyr Rhotoblaas Traspir 3D coat	0.2	0.2	–
	0.05 cm Lindab SRP click	50	50	–

Table A.4

Life cycle cost results of the variants.

	CC- V02_wood	CC- V02_rockwool	CC- V02_polystyrene	CC- V02_1S_LVL	CC- V02_2S_CLT	Brick- V02_same	Brick- V02_NzB	CC- V03_Pitched-C	CC- V03_Pitched-D
Examined life cycle – [a]	30	30	30	30	30	30	30	30	30
Real discount rate – RR	4	4	4	4	4	4	4	4	4
Discount Factor – Rd (i)	0.3083	0.3083	0.3083	0.3083	0.3083	0.3083	0.3083	0.3083	0.3083
Investment cost – CI [EUR]	94 294.27	89 220.27	87 734.66	93 503.31	94 747.22	67 748.93	64 897.47	96 283.48	94 377.83
Operating cost – $\Sigma Ca \times RR$ [EUR]	–2 102.29	–2 130.94	–2 271.55	–1 740.12	–432.09	–2 999.15	–3 190.57	–1 128.22	–1 404.03
Heating cost – $\Sigma Ca \times RR$ [EUR]	1 923.21	1 884.65	1 718.26	1 975.01	1 541.62	1 544.48	1 773.07	1 708.26	1 719.69
DHW cost – $\Sigma Ca \times RR$ [EUR]	2 965.45	2 965.45	2 965.45	3 081.83	2 392.42	2 853.60	2 912.06	2 965.45	2 965.45
Ventilation cost – $\Sigma Ca \times RR$ [EUR]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cooling cost – $\Sigma Ca \times RR$ [EUR]	1 247.75	1 257.67	1 283.45	1 432.23	1 108.89	612.96	517.75	1 372.72	1 582.99
Lighting cost – $\Sigma Ca \times RR$ [EUR]	4 675.19	4 675.19	4 675.19	4 663.29	6 541.45	4 898.95	4 515.70	5 739.25	5 236.97
“Cost” of energy transferred to another consumer – $\Sigma Ca \times RR$ [EUR]	–16 972.55	–16 972.55	–16 972.55	–16 972.55	–16 972.55	–16 972.55	–16 972.55	–16 972.55	–16 972.55
Cost of other energy – $\Sigma Ca \times RR$ [EUR]	4 058.65	4 058.65	4 058.65	4 080.08	4 956.08	4 063.41	4 063.41	4 058.65	4 063.41
Renovation cost [EUR]	4 677.01	4 677.01	4 677.01	4 677.01	4 677.01	13 735.69	12 305.48	4 677.01	4 677.01
Residual value – $\nabla f. \tau$ (j) [EUR]	2 918.72	2 400.48	2 400.48	5 316.49	5 316.49	5 450.60	5 637.97	6 513.83	6 482.89
Global cost (average value) – $C_g(\tau)$ [EUR]	93 950.26	89 365.85	87 739.65	94 039.72	93 675.65	73 034.87	68 374.41	93 318.45	91 167.92

References

- Ahmed, A., Ge, T., Peng, J., Yan, W.-C., Tee, B.T., You, S., 2022. Assessment of the renewable energy generation towards net-zero energy buildings: A review. *Energy Build.* 256, 111755. <http://dx.doi.org/10.1016/j.enbuild.2021.111755>.
- Alig, M., Frischknecht, R., Krebs, L., Ramseier, L., Commissioners, P., 2020. LCA of climate friendly construction materials. <http://dx.doi.org/10.13140/RG.2.2.27488.51209>.
- Amoruso, F.M., Sonn, M.H., Schuetze, T., 2022. Carbon-neutral building renovation potential with passive house-certified components: Applications for an exemplary apartment building in the Republic of Korea. *Build. Environ.* 215, 108986. <http://dx.doi.org/10.1016/j.buildenv.2022.108986>.
- Anon., 2017a. International Energy Agency. Global Status Report 2017.
- Anon., 2017b. MSZ EN ISO 10211:2017, Thermal bridges in building construction. Heat flows and surface temperatures. Detailed calculations (ISO 10211:2017), Hungarian Standard Institute.
- Anon., 2020. Ecoinvent Association, ecoinvent, <https://www.ecoinvent.org/> v3.6.
- Ansah, M.K., Chen, X., Yang, H., 2022. A holistic environmental and economic design optimization of low carbon buildings considering climate change and confounding factors. *Sci. Total Environ.* 821, 153442. <http://dx.doi.org/10.1016/j.scitotenv.2022.153442>.
- Baamer, A.S., Bruton, K., O'Sullivan, D., 2020. A comparative analysis of energy simulation tools for architectural research : A case study of a typical house in Saudi Arabia intelligent efficiency research group, civil and environmental engineering department, school of engineering, university coll. In: 5th Building Simulation and Optimization Virtual Conference.
- BBSR, 2017. BBSR Nutzungsdauern von Bauteilen für Lebenszyklusanalysen nach Bewertungssystem nachhaltiges Bauen (BNB) Nutzungsdauern von Bauteilen für Lebenszyklusanalysen nach Bewertungssystem nachhaltiges Bauen (BNB).
- BBSR, 2020. ÖKOBAUDAT <https://www.oekobaudat.de/> version ÖKOBAUDAT 2020-I.
- Capros, P., Paroussos, L., Fragkos, P., Tsani, S., Boitier, B., Wagner, F., Busch, S., Resch, G., Blesl, M., Bollen, J., 2014. Description of models and scenarios used to assess European decarbonisation pathways. *Energy Strategy Rev.* 2, 220–230. <http://dx.doi.org/10.1016/j.esr.2013.12.008>.
- Chandrakumar, C., McLaren, S.J., Dowdell, D., Jaques, R., 2020. A science-based approach to setting climate targets for buildings: The case of a New Zealand detached house. *Build. Environ.* 169, 106560. <http://dx.doi.org/10.1016/j.buildenv.2019.106560>.
- Comsol Inc., 2021. Contact COMSOL - Official site of COMSOL multiphysics.
- De Masi, R.F., Gigante, A., Vanoli, G.P., 2021. Are nZEB design solutions environmentally sustainable? Sensitive analysis for building envelope configurations and photovoltaic integration in different climates. *J. Build. Eng.* 39, 102292. <http://dx.doi.org/10.1016/j.job.2021.102292>.
- Delbeke, J., Runge-Metzger, A., Slingenberg, Y., Werksman, J., 2019. The paris agreement. In: Towards a Climate-Neutral Europe: Curbing the Trend. pp. 24–45. <http://dx.doi.org/10.4324/9789276082569-2>.
- Deutscher Bundestag, 2010. Das Energiekonzept - Beschluss des Bundeskabinetts. Bundesministerium Für Wirtschaft Und Energie (BMWi), p. 32.
- EC 2012/27/EU, 2012. Directive 2012/27/EU of The European parliament And Of The Council of 25 2012 on energy efficiency, amending directives 2009/125/EC and 2010/30/EU and repealing directives 2004/8/EC and 2006/32/EC. Off. J. Eur. Union 1–56.
- EC 244/2012, 2012. Commission delegated regulation (EU) No 244/2012 of 16 January 2012. Off. J. Eur. Union 18–36.
- EN 15026, 2007. Hygrothermal performance of building components and building elements - Assessment of moisture transfer by numerical simulation.
- EN 15459-1, 2018. Energy performance of buildings. Economic evaluation procedure for energy systems in buildings. Part 1: Calculation procedures, Module M1–14.
- EN 15978, 2011. Sustainability of construction works - assessment of environmental performance of buildings - calculation method.
- European Commission, 2002. Directive 2002/65/EC of The European parliament and of the council. In: Fundamental Texts on European Private Law. pp. 65–71. <http://dx.doi.org/10.5040/9781782258674.0021>.
- European Commission, 2011. Communication from the commission: A Roadmap for moving to a competitive low carbon economy in 2050, COM(2011) 112 Final. 34, 1–34. <http://dx.doi.org/10.1002/jsc.572>.
- Forde, J., Osmani, M., Morton, C., 2021. An investigation into zero-carbon planning policy for new-build housing. *Energy Policy* 159, 112656. <http://dx.doi.org/10.1016/j.enpol.2021.112656>.
- Galvin, R., 2022. Net-zero-energy buildings or zero-carbon energy systems? How best to decarbonize Germany's thermally inefficient 1950s-1970s-era apartments. *J. Build. Eng.* 54, 104671. <http://dx.doi.org/10.1016/j.job.2022.104671>.
- Gluch, P., Baumann, H., 2004. The life cycle costing (LCC) approach: A conceptual discussion of its usefulness for environmental decision-making. *Build. Environ.* 39, 571–580. <http://dx.doi.org/10.1016/j.buildenv.2003.10.008>.
- González-Prieto, D., Fernández-Nava, Y., Marañón, E., Prieto, M.M., 2021. Environmental life cycle assessment based on the retrofitting of a twentieth-century heritage building in Spain, with electricity decarbonization scenarios. *Build. Res. Inf.* 49, 859–877. <http://dx.doi.org/10.1080/09613218.2021.1952400>.
- Grinham, J., Fjeldheim, H., Yan, B., Helge, T.D., Edwards, K., Hegli, T., Malkawi, A., 2022. Zero-carbon balance: The case of HouseZero. *Build. Environ.* 207, 108511. <http://dx.doi.org/10.1016/j.buildenv.2021.108511>.
- Habert, G., Röck, M., Steininger, K., Lupisek, A., Birgisdottir, H., Desing, H., Chandrakumar, C., Pittau, F., Passer, A., Rovers, R., Slavkovic, K., Hollberg, A., Hoxha, E., Jusselme, T., Nault, E., Allacker, K., Lützkendorf, T., 2020. Carbon budgets for buildings: Harmonising temporal, spatial and sectoral dimensions. *Build. Cities* 1, 429–452. <http://dx.doi.org/10.5334/bc.47>.
- Hoxha, E., Passer, A., Saade, M.R.M., Trigaux, D., Shuttleworth, A., Pittau, F., Allacker, K., Habert, G., 2020. Biogenic carbon in buildings: A critical overview of LCA methods. *Build. Cities* 1, 504–524. <http://dx.doi.org/10.5334/bc.46>.
- IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.
- ISO 14040, 2006. Environmental management—Life cycle assessment—Principles and framework. <http://dx.doi.org/10.5594/j09750>.
- Jabari, F., Ghaebi, H., Mohammadi-Ivatloo, B., Mohammadpourfard, M., Bannae-Sharifian, M.B., 2020. Design, worst case study, and sensitivity analysis of a net-zero energy building for sustainable urban development. *Sustainable Cities Soc.* 54, <http://dx.doi.org/10.1016/j.scs.2019.101991>.
- Kellenberger, D., Althaus, H.J., 2009. Relevance of simplifications in LCA of building components. *Build. Environ.* 44, 818–825. <http://dx.doi.org/10.1016/j.buildenv.2008.06.002>.
- Kiss, B., Kácsor, E., Szalay, Z., 2020. Environmental assessment of future electricity mix—Linking an hourly economic model with LCA. *J. Clean. Prod.* 264, <http://dx.doi.org/10.1016/j.jclepro.2020.121536>.
- Krarti, M., Aldubyan, M., 2021. Role of energy efficiency and distributed renewable energy in designing carbon neutral residential buildings and communities: Case study of Saudi Arabia. *Energy Build.* 250, 111309. <http://dx.doi.org/10.1016/j.enbuild.2021.111309>.
- Kristjansdottir, T.F., Houlihan-Wiberg, A., Andresen, I., Georges, L., Heeren, N., Good, C.S., Brattebø, H., 2018. Is a net life cycle balance for energy and materials achievable for a zero emission single-family building in Norway? *Energy Build.* 168, 457–469. <http://dx.doi.org/10.1016/j.enbuild.2018.02.046>.
- Lan, L., Wood, K.L., Yuen, C., 2019. A holistic design approach for residential net-zero energy buildings: A case study in Singapore. *Sustainable Cities Soc.* 50, 101672. <http://dx.doi.org/10.1016/j.scs.2019.101672>.
- Liu, H.Y., 2019. Building a dwelling that remains carbon-neutral over its lifetime – A case study in Kinmen. *J. Clean. Prod.* 208, 522–529. <http://dx.doi.org/10.1016/j.jclepro.2018.10.101>.
- Liu, C., Zhang, S., Chen, X., Xu, W., Wang, K., 2022. A comprehensive study of the potential and applicability of photovoltaic systems for zero carbon buildings in hainan province, China. *Sol. Energy* 238, 371–380. <http://dx.doi.org/10.1016/j.solener.2022.04.057>.
- Luo, W., Zhang, Y., Gao, Y., Liu, Y., Shi, C., Wang, Y., 2021. Life cycle carbon cost of buildings under carbon trading and carbon tax system in China. *Sustainable Cities Soc.* 66, 102509. <http://dx.doi.org/10.1016/j.scs.2020.102509>.
- Lützkendorf, T., 2020. The role of carbon metrics in supporting built-environment professionals. *Build. Cities* 1, 676–686. <http://dx.doi.org/10.5334/bc.73>.
- Lützkendorf, T., Foliente, G., Balouktsi, M., Wiberg, A.H., 2015. Net-zero buildings: Incorporating embodied impacts. *Build. Res. Inf.* 43, 62–81. <http://dx.doi.org/10.1080/09613218.2014.935575>.
- Lützkendorf, T., Frischknecht, R., 2020. (Net-) zero-emission buildings: A typology of terms and definitions. *Build. Cities* 1, 662–675. <http://dx.doi.org/10.5334/bc.66>.
- Maierhofer, D., Röck, M., Ruschi Mendes Saade, M., Hoxha, E., Passer, A., 2022. Critical life cycle assessment of the innovative passive nZEB building concept 2226 in view of net-zero carbon targets. *Build. Environ.* <http://dx.doi.org/10.1016/j.buildenv.2022.109476>, Under Rev.
- Meteotest, A.G., 2021. Meteotest.
- Mezősi, A., Szabó, L., 2016. Model based evaluation of electricity network investments in central Eastern Europe. *Energy Strategy Rev.* 13–14, 53–66. <http://dx.doi.org/10.1016/j.esr.2016.08.001>.
- Mora, T.D., Bolzonello, E., Peron, F., Carbonari, A., 2019. PLEA 2018 Hong Kong integration of LCA tools in BIM toward a regenerative design.
- Mosteiro-Romero, M., Krogmann, U., Wallbaum, H., Ostermeyer, Y., Senick, J.S., Andrews, C.J., 2014. Relative importance of electricity sources and construction practices in residential buildings: A Swiss-US comparison of energy related life-cycle impacts. *Energy Build.* 68, 620–631. <http://dx.doi.org/10.1016/j.enbuild.2013.09.046>.
- Nagy, B., 2019. Designing insulation filled masonry blocks against hygrothermal deterioration. *Eng. Fail. Anal.* 103, 144–157. <http://dx.doi.org/10.1016/j.engfailanal.2019.05.005>.
- Nematchoua, M.K., Sadeghi, M., Reiter, S., 2021. Strategies and scenarios to reduce energy consumption and CO₂ emission in the urban, rural and sustainable neighbourhoods. *Sustainable Cities Soc.* 72, 103053. <http://dx.doi.org/10.1016/j.scs.2021.103053>.

- Pan, W., Pan, M., 2021. Drivers, barriers and strategies for zero carbon buildings in high-rise high-density cities. *Energy Build.* 242, 110970. <http://dx.doi.org/10.1016/j.enbuild.2021.110970>.
- Papachristos, G., 2015. Household electricity consumption and CO₂ emissions in the Netherlands: A model-based analysis. *Energy Build.* 86, 403–414. <http://dx.doi.org/10.1016/j.enbuild.2014.09.077>.
- Parkin, A., Herrera, M., Coley, D.A., 2020. Net-zero buildings: When carbon and energy metrics diverge. *Build. Cities* 1, 86–99. <http://dx.doi.org/10.5334/bc.27>.
- Prada-Hernandez, A.V., Rojas-quintero, J.S., Vallejo-Borda, J.A., Ponz-Tienda, J.L., 2015. Interoperability of building energy modeling (bem) with building information modeling (bim). In: *Sibragec Elagec* 2015. pp. 519–526. <http://dx.doi.org/10.13140/RG.2.1.3807.3042>.
- Röck, M., Hollberg, A., Habert, G., Passer, A., 2018. LCA and BIM: Visualization of environmental potentials in building construction at early design stages. *Build. Environ.* 140, 153–161. <http://dx.doi.org/10.1016/j.buildenv.2018.05.006>.
- Röck, M., Ruschi Mendes Saade, M., Balouktsi, M., Nygaard, F., Birgisdottir, H., Frischknecht, R., Habert, G., Lützkendorf, T., 2019. Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. *Appl. Energy* 114107. <http://dx.doi.org/10.1016/j.apenergy.2019.114107>.
- Röck, M., Saade, M.R.M., Balouktsi, M., Rasmussen, F.N., Birgisdottir, H., Frischknecht, R., Habert, G., Lützkendorf, T., Passer, A., 2020. Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. *Appl. Energy* 258, 114107. <http://dx.doi.org/10.1016/j.apenergy.2019.114107>.
- Santos, R., Costa, A.A., Silvestre, J.D., Pyl, L., 2019. Integration of LCA and LCC analysis within a BIM-based environment. *Autom. Constr.* 103, 127–149. <http://dx.doi.org/10.1016/j.autcon.2019.02.011>.
- Satola, D., Balouktsi, M., Lützkendorf, T., Wiberg, A.H., Gustavsen, A., 2021. How to define (net) zero greenhouse gas emissions buildings: The results of an international survey as part of IEA EBC annex 72. *Build. Environ.* 192, 107619. <http://dx.doi.org/10.1016/j.buildenv.2021.107619>.
- Sesana, M.M., Salvalai, G., 2013. Overview on life cycle methodologies and economic feasibility for nZEBs. *Build. Environ.* 67, 211–216. <http://dx.doi.org/10.1016/j.buildenv.2013.05.022>.
- Shirinbakhsh, M., Harvey, L.D.D., 2021. Net-zero energy buildings: The influence of definition on greenhouse gas emissions. *Energy Build.* 247, 111118. <http://dx.doi.org/10.1016/j.enbuild.2021.111118>.
- Soust-Verdaguer, B., Llatas, C., García-Martínez, A., 2017. Critical review of bim-based LCA method to buildings. *Energy Build.* 136, 110–120. <http://dx.doi.org/10.1016/j.enbuild.2016.12.009>.
- Soust-verdaguer, B., Llatas, C., García-martínez, A., Carlos, J., De Cózar, G., 2018. BIM-based LCA method to analyze envelope alternatives of single-family houses : Case study in Uruguay. *J. Archit. Eng.* 24, 1–15. [http://dx.doi.org/10.1061/\(ASCE\)AE.1943-5568.0000303](http://dx.doi.org/10.1061/(ASCE)AE.1943-5568.0000303).
- Stephan, A., Stephan, L., 2020. Achieving net zero life cycle primary energy and greenhouse gas emissions apartment buildings in a Mediterranean climate. *Appl. Energy* 280, <http://dx.doi.org/10.1016/j.apenergy.2020.115932>.
- Sušnik, M., Tagliabue, L.C., Cairoli, M., 2021. BIM-based energy and acoustic analysis through CVE tools. *Energy Rep.* <http://dx.doi.org/10.1016/j.egy.2021.06.013>.
- Szabó, L., Mezősi, A., Pató, Z., Kelemen, Á., Beöthy, Á., Kácsor, E., Kaderják, P., Resch, G., Liebmann, L., Hiesl, A., Kovács, M., Köber, C., Marković, S., Todorović, D., 2017. *SEERMAP: South East Europe Electricity Roadmap South East Europe Regional Report* 2017.
- TERC, 2020. *TERC ETALON online budgeting softerwer.* (in Hungarian).
- Wastiels, L., Decuyper, R., 2019. Identification and comparison of {LCA}–{BIM} integration strategies. *IOP Conf. Ser. Earth Environ. Sci.* 323, 12101. <http://dx.doi.org/10.1088/1755-1315/323/1/012101>.
- Zhang, S.C., Yang, X.Y., Xu, W., Fu, Y.J., 2021. Contribution of nearly-zero energy buildings standards enforcement to achieve carbon neutral in urban area by 2060. *Adv. Clim. Change Res.* 12, 734–743. <http://dx.doi.org/10.1016/j.accres.2021.07.004>.
- Zhao, X., Pan, W., Lu, W., 2016. Business model innovation for delivering zero carbon buildings. *Sustainable Cities Soc.* 27, 253–262. <http://dx.doi.org/10.1016/j.scs.2016.03.013>.