Renovated or replaced? Finding the optimal solution for an existing building considering cumulative CO_2 emissions, energy consumption and costs – A case study

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ABSTRACT

The buildings sector is responsible for 37 % of global final energy consumption and nearly 40 % of total direct and indirect CO_2 emissions. This has led to promoting renovation efforts to decrease operational emissions of the existing building stock. With decreasing operational emissions, embodied emissions are becoming more important. In new buildings, embodied emissions account for about half of total emissions through the life cycle of a building. If both embodied and operational emissions are considered, renovation often outperforms new constructions, due to high embodied emissions of the structure - especially solid construction with a basement. Based on this, the decision if a building should be renovated or replaced is often not straight forward and depends on various factors. In this paper, a typical German building was considered as a case study, for which both renovation and replacement scenarios were considered, to identify the optimal solutions in terms of overall energy consumption and CO_2 emissions of the building in the use phase, the environmental impacts of the building along its entire life cycle, and related costs. Results show that the lowest CO_2 emissions during the lifetime of the analyzed building can be achieved with a sustainable replacement building (-2.05 kg CO_2/m^2/ year) by using a heat pump with ground collector coupled with PV. This allows, compared to the existing reference building, reductions of 97 % and 101 % in terms of energy consumption and CO_2 emissions, respectively; while natural gas-based technologies are the least targeted and the most volatile to fuels' prices changes over the years.

1. Introduction

Climate change has become one of the most prevalent challenges that humanity is facing, and its consequences are increasingly noticed every day. The Paris Agreement [41] serves as a step towards addressing this challenge, since most of the nations have committed to achieving net-zero greenhouse gas (GHG) emissions by restricting the temperature increase to 1.5 °C above pre-industrial levels. One of the most important contributors to global warming is the building sector, as only in the European Union (EU) it is responsible for 35 % of the GHG emissions, 42

% of the total energy consumption, 50 % of extracted resources and 30 % of water consumption [15]. In view of these environmental issues, the building sector must adapt and demonstrate larger commitment, by transitioning towards a carbon-free built environment.

Countries have undertaken initiatives to enable the transition to net-zero as early as possible. The EU's efforts for achieving the ambitious transition to net-zero are embodied in the European Green Deal [16], where it is proposed that all new buildings must be zero emissions from 2030. Specifically for Germany, buildings play a central role in achieving the country's energy and climate protection policy goals, as

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around 40 % of national CO_2 emissions are generated by this sector. For this, the government set targets that aim at significantly reducing the primary energy demand of existing buildings by 2050.

Different laws and regulations have been proposed to reach the CO_2 emissions reduction targets of the building sector in Germany. One of the newest is the Building Energy Act [18] which defines maximum U-values for retrofitting and a reduction of primary energy non-renewable factors for gaseous biomass when using a highly efficient combined heat and power (CHP) plant and applied to district heating networks (DHN). Also, new installations of oil-based heating systems will be banned as of 2026.

The focus of these measures are primarily on reducing carbon emissions during operation of a building. However, the more energy efficient a building becomes, the more relevant the construction (and the supply chain for all materials) becomes, hence a life cycle perspective is crucial to really optimize CO_2 emissions of a building [24], Galimshina et al. 2021.

This means that, besides accounting for the operational emissions, embodied emissions in the buildings' construction process and materials must be considered when quantifying the overall emissions of the building sector. There are studies that have contributed to the general knowledge of pathways for reducing these emissions. For example, Sebi et al. [33] identifies that retrofitting measures can lead to large long-term savings for the building sector. The authors compare the focus and effectiveness of retrofitting strategies in USA, Germany and France, concluding that for these countries to reach their climate and emissions targets, a high up-front investment is required so their strategies reach all sectors (residential and non-residential) with proper financial and technical support. Also, these strategies should not only focus on single-measure retrofit, but on more comprehensive retrofit packages, and must include solutions to the owner-tenant dilemma. Other authors argue that measures must be taken from the early planning phase of new buildings. For example, Hollberg et al. [20] propose a parametric real-time approach to introduce energy performance analysis in early design stages to increase energy efficiency while reducing the cost impact. Schlegl et al. [32] discuss that the integration of life cycle assessment (LCA) benchmarks in this phase can contribute to reducing the use of resources and environmental impacts over the entire life cycle of a building. Kakkos et al. [23] examined the potential environmental benefits of a new, circular, construction technology by applying such a life cycle perspective - showing a high reduction potential on the level of the building materials. Other studies have focused on comparing the emissions impact from renovated and a new building. In Umweltbundesamt [40], the energy expenditure was evaluated over the life cycle (operating and grey energy) for renovated and new single/multi-family buildings under different classifications and standards. Based on the cost-benefit ratio between a renovated and a new single-family house, the study found that replacing it would be a better solution if it is done with lightweight and sustainable construction methods, finding the opposite for a multi-family house, for which the best option would be to renovate. More recently, Mayer et al. [25] investigated the financial benefits for energy retrofits of owner-occupied single-family houses in Germany, considering current incentive schemes, standards and regulations. Authors formulated different retrofitting measures packages, finding that the cost-benefit ratio for heating system retrofits is better than for measures on the building envelope.

While all above listed studies provide significant contributions to the question on whether renovation or replacement measures would bring the greatest benefits for achieving the emissions targets; there are still information gaps that have to be considered. For example, these studies make general assumptions on the building's geometry, construction methods, and technical parameters due to lack of information, especially when considering the replacement options. Studies evaluating retrofitting measures assume that homeowners have the possibility to adopt entire retrofitting packages at once. But in reality, different combinations of retrofitting measures can be adopted over time; however, it is

then difficult to decide cost, energy and emissions-wise which intervention should be implemented first and which could be adopted after.

This paper introduces a bottom-up simulation approach for the evaluation of the energy consumption, overall life cycle impacts (expressed with operational and embodied CO_2 emissions), and economic perspectives, allowing the combination of different strategies over time, quantifying more realistic benefits of a renovated and a new building. The method and material section of this paper starts by introducing the existing reference building. In a next step the selection of renovation and replacement scenarios including underlying assumptions are defined. This is followed by a description of the building energy simulation approach. For the overall life cycle impacts, a detailed explanation of the applied life cycle assessment model to renovation and replacement cases is presented, indicating the various steps considered and assumptions taken. The cost analysis is then introduced, where all the cost specifications and proposed sensitivity scenarios based on the fuels' prices are described. Finally, the results are presented and discussed, with a conclusion and further discussion on the limitations of the study and outlook.

2. Method and materials

In the on-hand paper, the performance of a renovated building is compared to a newly built replacement building in terms of overall energy consumption and CO_2 emissions during their use phase, their environmental impacts along their entire life cycle, and related costs. The approach consists of a detailed analysis of the energy performance during operation using a building energy simulation tool, a lifecycle emission evaluation, and finally a cost analysis (Fig. 1). To compare the performance of these two buildings various scenarios in terms of building materials, energy systems and time of renovation are defined and analyzed. The following sections explain the applied methods in detail.

2.1. Existing reference building

A typical brick based single-family housing type has been selected as reference building which can be found in many mid-European countries. The building was selected from the TABULA database (EFH type E, Germany), and was built between 1958 and 1968 (Fig. 2, left) [36]. This building type and age class was selected, due to its representativeness in the German building stock (54 %), its potential of CO_2 emissions reduction, measured by its relatively large share of the total heating consumption (40 %) of the building stock [40], and because its age is reasonable to perform renovation measures, and it is not subject to historic preservation requirements. The geographic location defined for this study is the city of Potsdam, Germany.

TABULA's dataset contains general information regarding each main building component such as the total surface area and total thermal transmittance (U-value), and the building's energy system used to meet the space heating and domestic hot water demand. However, since the goal of this study is to account for the CO_2 emissions embodied in the construction materials as well as for the operating energy system, more details on the technical specifications were needed for performing the quantifications and simulations more reliably. Therefore, specifications on the building's geometry were defined through 3D modeling and the technical parameters needed for performing the energy simulations were also gathered from a variety of sources.

To match the selected building from TABULA with a defined geometry and construction material an existing 3D model from SketchUp 3D Warehouse [38] was used and adapted.

For defining the building envelope thermal parameters, the specified total U-values for each main building component were taken from TABULA's database. As this database only provides the total thermal transmittance and not material layer specific information, more detailed information on materials was taken from Ubakus [39], while their
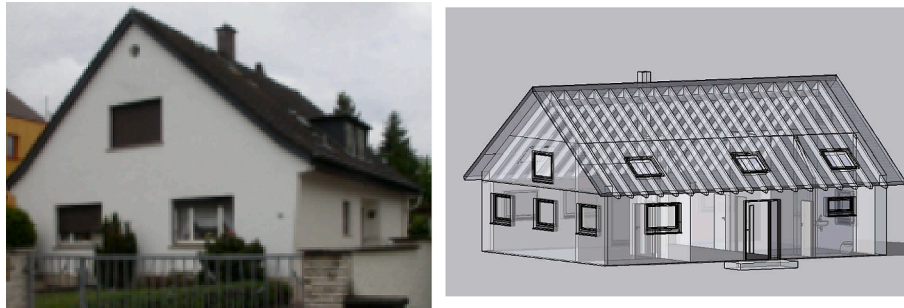
Fig. 1. Overview on the method.

Fig. 2. Left, TABULA's representation of EFH E [36]. Right, view of the created 3D model.

thermal properties were defined by the pre-defined building constructions in Designbuilder from construction years before 1978 [7], and other sources in the literature. The summary list of materials and their properties are defined in Tables A1 and A2 in the Appendix. The thermal properties used for these materials and their sources are presented in Table A2. The total calculated U-value of each main building component is compared to the ones specified in TABULA in Table 1.

The energy system used for both space heating and domestic hot water are centralized single units. Both systems are low temperature non-condensing boilers from 1987 to 1994 using natural gas as energy carrier. These are used as reference for the energy systems that are modeled for the base case building in this study. The assumptions on the specifications for both systems are presented in Table 2.

2.2. Renovation and replacement scenarios of selected building

To compare the performance of the existing retrofitted building to a newly built replacement building over a time horizon of the next 25 years, 7 renovation scenarios and 2 replacement building scenarios are considered which consist of a set of envelope renovation and energy

Table 1
Comparison of calculated U-values against the U-values provided in TABULA.

Building Element	U-values (W/m²-K) Calculated	TABULA
External wall	1.18	1.2
Interior wall (type 1)	1.86	–
Interior floor	1.17	1.08
Roof	0.76	0.8
Interior wall (type 2)	2.58	–
Window	2.81	2.8

Note: No values are provided in TABULA for the interior walls. Interior walls type 1 represent those with more structural function and are thicker than those of type 2.

Table 2
Assumptions on specifications for the domestic hot water and space heating equipment.

Equipment	Energy source	Volume (m3)	Design Flow Rate (m3/s)	Standard Efficiency	Standard Rated Energy Factor
Low temperature non-condensing boiler for domestic hot water	Natural gas	0.189	0.000117	0.705	0.521
Central heating – single unit for space heating	Natural gas	–	1.707	0.705	–

system options distributed over the time horizon. The combination of individual measures are based on commonly applied renovation measures in Germany. The proposed options in this study are:

- OP1: Replacement of heating system (8 options)
- OP2: Partial renovation of the building envelope, including replacement of windows and doors, and replacement of heating system (8 combinations)
- OP3: Renovation of the building envelope, including insulation of walls and roof, and replacement of windows and doors (4 combinations)
- OP4: Full renovation, including OP1 and OP3 and the insulation of floors (32 combinations)
- OP5: Replacement with a new building (2 combinations)

These options are then placed into different scenarios considering time constraints (Fig. 3), these are relevant for the options containing the replacement of heating systems – that will incur into reinvestments, and for the combinations of options 1 and 3, differing in the uptake of following renovation measures. For example, for scenario 3, it is assumed that option 3 is followed by the slow uptake (10 years) of option 1, while for scenario 4, a fast uptake (5 years) of option 1 is considered. Fig. 3 also includes 2 scenarios for the replacement building.

2.2.1. Renovation measures

The proposed renovation options were selected based on existing literature [25,34,40]. However, to analyze their potential application, assumptions need to be made regarding the building-level decision making, available infrastructure, useful life of interventions, etc. First, it is assumed that the existing base case building is occupied by the owners, hence they have the availability and willingness to pay for different renovation measures.

For the energy systems, the main assumptions are that the existing systems need to be replaced after a useful life between 15 and 25 years (depending on the technology) with one or two investment cycles (depending on the scenario analyzed over time). The gas heating infrastructure is locally available, and the building infrastructure allows it to be connected to a district heating system. Also, the soil allows deep drilling, and it is large enough to consider ground collectors for heat pumps, and owners account for the authorization for drilling works. Finally, it is also assumed that there is enough space for installing a solar thermal system and solar photovoltaic (PV) systems at the property.

As for the envelope, the main assumptions are that the useful life of individual measures ranges between 40 and 50 years, and some combinations of funding mechanisms are allowed for the owner to cover the renovation costs (e.g. grants, credits).

Individual renovation measures were selected considering their compliance with GEG's maximum allowed U-values. Two options are presented for the renovation of roof and walls, option 1 presents the limit U-values allowed in GEG [18]; and option 2 presents a more significant reduction that aligns to current subsidies mechanisms. Due to their final impact on the energy consumption and slight difference in

costs, the most efficient options are assumed for the windows, door, and floor; this means that the selected U-values overfullfill the GEG and meet the criteria for subsidies. All measures and options are presented in Table 3. As for the energy systems, the one with the greatest potential of

Table 3
Individual measures to consider for further analysis.

Building envelope		
Building Element	**Description**	**U-Value (W/m²K)**
Roof	Insulation of rafter gap (mineral wool) and additional insulation layers using vapor barriers and bitumen membranes. Total insulation thickness: OP1: 150 mm OP2: 300 mm	OP1: 0.24 OP2: 0.14
Walls	Insulation with mineral wool, plastering (composite system) and cellulose or breather membrane. Total insulation thickness: OP1: 120 mm OP2: 240 mm	OP1: 0.24 OP2: 0.12
Windows	Triple glazing, argon filled, low-E, insulated frame	0.8
Door	Insulation layer	1.3
Floor	12 cm insulation layer below/on top/ combination	0.25

Energy system

- Gas condensing boiler (annual efficiency rate: 0.99)
- Electric heat pump (air/water)
- District heating (annual efficiency rate: 1)
- District heating system coupled with PV
- Heat pump with ground collector (annual performing factor: 3.8)
- Heat pump with ground collector coupled with PV
- Solar thermal system for domestic hot water (DHW) and heating
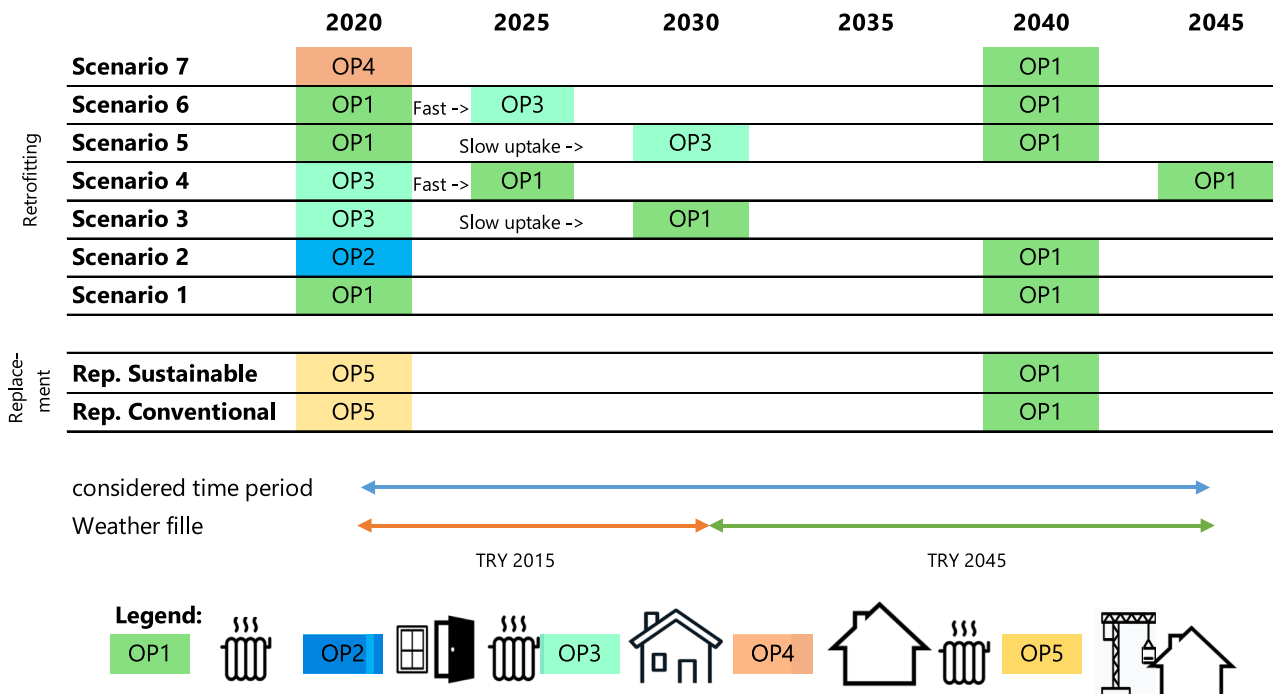- Gas condensing boiler coupled with solar thermal system

Fig. 3. Structure of different renovation and replacement scenarios over time.

CO_2 reductions were selected from the literature. No oil-based equipment is further considered because these will be banned for new installations and renovation measures in the following years. However, gas-based boilers with improved efficiency are considered only for the renovation scenarios and not for the replacement building, this is to account for the uncertainties involved in the role of gas as a supportive fuel to enable a clean energy transition. No hydrogen options are considered as it is assumed that the infrastructure needed for implementing them will not become available in the short term.

2.2.2. Replacement scenario

To guarantee a comparable performance of both the replacement and the renovated building the reference floor area is kept the same (121 m2) for both the existing and the replacement building. For defining the geometry of the replacement building, a building was taken as reference from Fertighaus [17] and adapted as required. The plans and 3D model created are presented in Fig. A1 of the Appendix. The building has one floor with an attic that is not considered as a living space (as indicated for the existing building) and as a result it remains unheated (Fig. A2).

Two different construction options are analyzed for the replacement building. In a first case, the building will be built using conventional materials and construction techniques (solid construction). In the second case, a more sustainable solution is considered based on a lightweight structure mostly made of timber. This is due to the carbon capture capability of this material, which has a positive impact in relation to the reduction of the embodied emissions of the building.

A selected set of systems from Table 3 are selected as the energy systems to analyze for the replacement building, these are identified from the results from the renovation scenario 1 (Fig. 3). In addition, due to the ban imposed on mono-oil and gas systems from 2024 in Germany, these systems are not considered. The lifespan of the replacement building is assumed to be 50 years, according to BNB [29].

2.2.3. Conventional option

In Germany, most newly built houses follow the principles of solid construction, with a typical house consisting of brick masonry. The main construction elements of this building need to be in alignment with the maximum allowed U-values provided in the [18] for newly built houses [30] as this is the minimum standard that has to be satisfied for the construction of new buildings in 2023. The technical parameters for the building components were taken from Ubakus [39]. For this option, concrete was considered only for the floors and intermediate ceilings. The choice of aerated concrete blocks was made because a typical aerated concrete wall has lower impact than a concrete one [3]. Details of the building components are presented in Table A3 in the Appendix.

According to BNB (2022), the primary structure of such a building is meant to last for more than 50 years, which means that no replacement will be done for the primary structure. As the building has one floor with an unheated attic (non-living area), the external element that serves as an insulation barrier is the ceiling, not the roof. For this, the ceiling has to satisfy the maximum permitted value (i.e., 0.24 W/m²K), while the roof was assigned as a cold roof.

2.2.4. Sustainable option

To achieve a radical swift from the conventional materials and construction principle to a more carbon–neutral solution, a lightweight and modular primary structure is investigated, allowing an increase of the materials recovery after the end-of-life of the building (design-for-disassembly). This building is made out of wood – a primary material that can be easily recovered and recycled, and that is contributing to the mitigation of the building's grey energy due to its CO_2-absorption ability. Such a building is expected to have lower environmental impact than a conventional one [23].

As previously mentioned, U-values of all these building components must satisfy the GEG standard. However, no subsidies can be received for new buildings that satisfy this standard, as these are allowed only for

the KFW efficiency house 40, which needs only 40 % of the reference building according to GEG. Hence, the sustainable building components (presented in detail in Table A4 in the Appendix) are designed to meet the requirements of the KfW 40 standard [30]. The ceiling must satisfy the KFW 40 maximum permitted value, as the roof is also assigned as a cold roof. The walls, roof and ceiling components were taken from Dataholz [6], which provides wooden construction elements that are approved for use in Germany. Minor modifications were made to those elements to facilitate the modeling with the support of the Ökobaudat database [31]. Those changes are provided in Table A5 in the appendix.

2.3. Building energy simulation analysis

Both the existing and the replacement building were modelled in the building energy simulation software EnergyPlus [9]. This software is a whole building simulation software that allows to dynamically model heating and cooling energy consumption. It requires a weather file and an IDF (Input Data File) that stores all the energy systems' technical specifications and the building's geometry and construction parameters.

The weather data files used for the building's energy simulation are extracted from the Test Reference Years (TRY) created by the German Departmental Research [4] for the years 2015 and 2045. Using Potsdam as geographic location, the grid corresponding to the WG S84 coordinates 52.3938C N, 13.0651 C E was used. As the TRY weather files are available for two different calculated synthetically years, the present climate conditions (2015) are used for the years between 2020 and 2030, and the file with a calculated climate upheating for the year 2045 is used for the years between 2031 and 2045. Statistical weather data for the two years are presented in Table 4. The simulations are then performed for 8760 time-steps, resulting in the hourly profiles for both climate conditions, which are then extrapolated to the 30 year time span based on equation (1). Where Q denotes the total energy consumed over the whole 30 years and $\dot{Q}_{TRY2015}$ and $\dot{Q}_{TRY2035}$ is the energy consumed with the respective weather file over the indicated time period.

$$\dot{Q} = \sum_{2020}^{2030} \dot{Q}_{TRY2015} + \sum_{2031}^{2050} \dot{Q}_{TR} \tag{1}$$

One thermal zone is considered per conditioned room in the building. The electricity usage within a thermal zone is based on standard data and is 3.88 W/m² for lighting and 2.5 W/m² for all other electrical equipment (based on ASHRAE standards); and the area per occupant was defined as 53 m²/person, typical values for a German single family house [13]. Additional information on relevant schedules can be found in the Appendix. The set point temperature for both thermal zones is set as 18C for heating during the night hours (18:00 – 06:00) and 20 C during the day hours (07:00 – 17:00).

The simulation process presented in Fig. 4 was applied to the reference building to obtain the current energy consumption, which is used as a baseline for comparison when renovation and replacement measures are applied. This simulation process is also applied for the renovation measures, in which the same building geometry as the base case is used and only the constructions and energy systems are changed accordingly. For the replacement buildings, the same process is carried out, but using the new geometry and technical parameters.

2.4. Life cycle assessment

Life cycle assessment (LCA) is a standardized and established framework that allows the quantification of environmental impacts and benefits associated with a product or service throughout their entire life cycle (i.e., from raw material extraction till the end-of-life treatment). Here, such a LCA was performed in order to assess embodied and operational emissions for all here examined renovation and replacement cases. The ISO 14040 [21] and 14044 [22] global standards ensure that the LCA framework is applied in a transparent and consistent manner

Table 4
Statistical information on weather parameter (dry bulb temperature, solar radiation, heating degree (HDD) and cooling degree days (CDD).

|	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann. Avg/*Sum
Daily Avg Dry bulb temp (°C)	2015	0.5	2	4.8	10.2	14.5	17.5	19.5	19.3	15	9.9	4.7	1	9.9
	2045	2.3	3	6.5	10.2	15.1	17.8	20	20.3	15.9	11.2	6.5	3.6	11.0
Daily Avg Global radiation (Wh/m^2)	2015	619	1192	2300	3560	4258	4442	4191	3988	2936	1503	718	485	2516
	2045	707	1152	2240	3506	4094	4144	4461	4283	3308	1693	839	453	2573
HDD (base 18 °C)	2015	543	448	409	235	120	46	20	20	93	251	399	528	3112*
	2045	486	419	357	234	100	37	18	13	70	213	346	446	2739*
CDD (base 18 °C)	2015	0	0	0	0	11	31	65	59	2	0	0	0	168*
	2045	0	0	0	1	12	33	81	84	8	1	0	0	220*
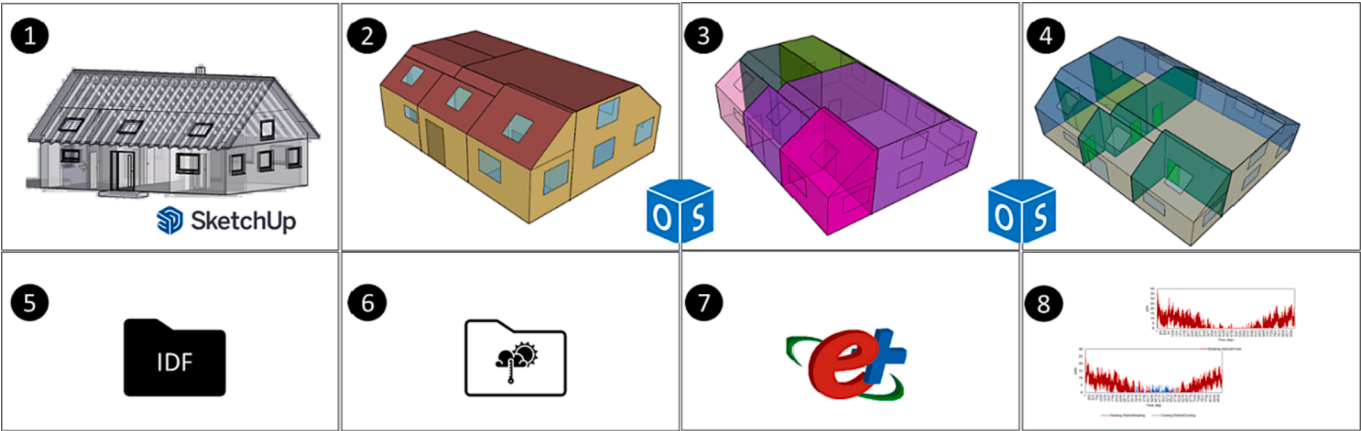
Fig. 4. Building energy simulation process. 1. Creation of 3D model. 2. Creation of OpenStudio model using a simplified version of the 3D model; designation of building constructions and energy systems parameters. 3. Definition of thermal zones. 4. Definition of thermal boundary conditions. 5. Export OpenStudio model into IDF. 6. Selection of weather file to use in the simulation. 7. Simulation in EnergyPlus using IDF and weather file. 8. Obtention of results from the simulation.

across various sectors. In addition, the EN 15978 [12] standard builds upon the ISO standards and provides further information regarding LCA in the context of buildings, hence it was selected for the purpose of this study. According to these standards, within an LCA four basic steps are distinguished – i.e. (i) Goal and scope definition, (ii) Life Cycle Inventory (LCI) analysis, (iii) Life Cycle Impact Assessment (LCIA), and (iv) results interpretation.

2.4.1. Goal and scope definition

Objective of the LCA calculations is it to assess the environmental impacts and benefits of various renovation options of the base case building and compare them with those of a newly constructed replacement building (using conventional or sustainable construction principles). The reference unit for all calculations is "1 m2 of net living area per one-year lifetime during the reference period of analysis". Fig. 5 presents the LCA stages considered for the renovation (orange-colored boxes) and replacement (green-colored boxes) cases, based on the granularity distinguished within the EN 15978 standard.

2.4.2. Life cycle inventory analysis

The second step of the LCA framework according to the ISO 14040 series consists of the collection of all necessary input and output flows of the included life cycle stages (shown in Fig. 5) for each of the analyzed building scenarios. For the transport stages A4 and C2, it was assumed
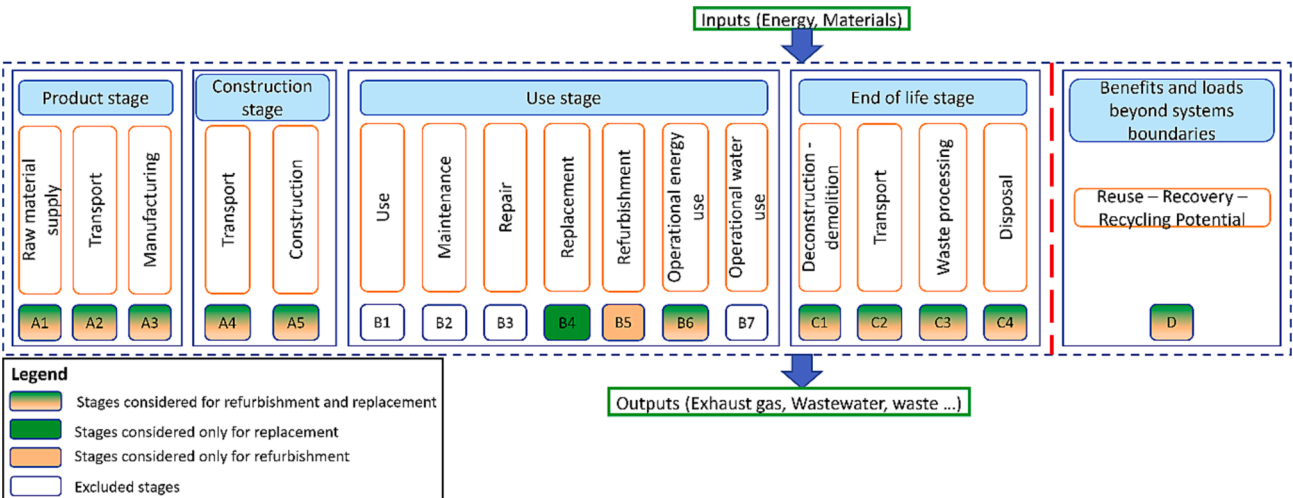

Fig. 5. LCA stages for renovation and replacement scenarios, according to EN 15978.

that the average distance covered for material transport is 350 km [1]. The impact of the construction stage A5 was taken from the same source and was adjusted to reflect the net living area of the here modelled building – i.e. the values have been adjusted from a net living area of 143 m^2 (timber house in [1] to an area of 121 m^2 in this study. It is important to note that the stages B4 and B5 do not only include the production of replacement and refurbishment components, but include also their transportation to the building site and the EoL stage of the replaced building components.

The data included in the LCA stages were matched with respective datasets from the Ökobaudat database. In situations, where a specific material could not be properly represented by any dataset from Ökobaudat, a respective dataset from the Ecoinvent database [11] was used. For determining the emissions from the electricity consumption over the analyzed timeframe 2020 to 2045, respective datasets representing the electricity mixes in 2020, 2030, 2040 and 2050 – contained in Ökobaudat – were used, instead of using over the entire period the dataset for the current electricity mix. This takes into account the decarbonization plans for the German electricity mix over the investigated period. In the renovation scenarios it is assumed that the building was constructed 50 years prior to the considered timeframe and no renovation has been performed so far. Since this building will stay for another 25 years (reaching 75 years of lifespan in total), 1/3 of the building construction impacts were allocated to the renovation scenarios. For the two replacement cases, as the building has a lifespan of 50 years, only half of the construction impacts of the building are considered for the analyzed timeframe.

2.4.3. Life cycle impact assessment

In this stage, all emissions arising in the life cycle are then assigned to the environmental effects under consideration (classification) and presented based on their contributions in the corresponding impact categories (see e.g. ISO 14044 2006). From a mathematical point of view, this is done by multiplying the (cumulative) emission (m_{total}) with the corresponding characterisation factor, CF, for each of the substances contributing to the respective impact category (Equation (2).

$$EI_{total} = \sum_{sub} \left(CF_{sub} * m_{total,sub} \right) \tag{2}$$

Since the goal of this study is to develop pathways to reach net-zero carbon emissions, the global warming potential (GWP) indicator was chosen for the results. This indicator is used for the estimation of the carbon footprint for a product or service by assessing various GHG emissions throughout their lifetime and reports the results in kg of CO_2 equivalents.

2.5. Cost analysis

For further analysis and comparison, the costs involved during the renovation and replacement of the building are analyzed. These are classified into investment and operational costs (Equation (3). The investment costs incur when the renovation and replacement actions take place, as well as when the technologies or envelope components have reached their useful life and need to be replaced. These are further classified into energy technology costs and building element costs, both including the labor costs required for installation. The energy technology costs are calculated based on the required system capacity to supply the energy demand of the building, a result obtained from the simulations for each renovation and replacement scenario.

$$C_{total} = Cbuild_{inv} + Ctech_{inv} + \sum_{i}^{lifetime} C_{Op} \tag{3}$$

Where C_{total} are the total costs, $Cbuild_{inv}$ are the investment costs related to building elements, $Ctech_{inv}$ are the investment costs related to energy technology, and C_{Op} are the annual operational costs from the current

year to the last building's operational year.

The underlying cost data are obtained from BDEW [5], DVGW [10], and through consultation with experts, whereby energy technology and building element costs were determined for each renovation scenario. Please note that cost data are based on current market prices during conducting the study. The technology costs include the dismantling of the current heating system (gas non-condensing boiler) and the installation of the new one. In addition, the energy consumption of a heating system has an annual base cost. This remains constant for all heating systems independently from their capacities, except for the district heating, which are estimated based on Destatis [8]. Based on the insulation measure's thickness, length, and U-values (specifically from the windows) extracted from the base case building geometry and Table 1, the building elements included in the different renovation scenarios were calculated. The same references were used for estimating the energy technology costs for the replacement building scenarios, considering their resulting capacity requirements after the simulations. As there is no existing infrastructure, the dismantling labor costs are not considered. The construction costs for both cases of the replacement building are extracted from the most updated database of BKI (2022), specifying values from April 2022 for both construction types considered in this study. The construction and labor costs for the replacement building cases are calculated as the average per unit costs for each cost group, according to DIN 276 BKI (2022). These costs amount to 441,561 EUR for the conventional case, and 516,770 EUR for the sustainable case. Further details on the final investment costs considered in all scenarios are found in Tables A6–A11 of the Appendix.

The operational costs represent those that are incurred during the operational years of the building; in this study, these are estimated only for the analyzed timeframe (2020–2045). These costs are subject to the fuels' sources that the technologies utilize to supply the energy demand of the building. The fuels' sources considered in this study are natural gas, electricity, and district heating. After calculating the annual energy consumption (for heating and electrical devices) for every year in the timeframe, this was multiplied by each fuels' source price at the specific year. For estimating the fuels' source prices in the coming years, a *business-as-usual (BAU)* scenario is proposed, using historical prices data for the last 10 years from Germany to compute an average annual inflation rate. Considered data were extracted from different sources, such as Statista [35], and Global Petrol Prices [19]. The current prices (in 2020, the initial year) and the average annual growth rate are found in Table 5.

The annual operational costs (C_{Op}) are estimated based on Equation (4), where $Enprice_i$ is the current price of energy (depending on the fuel source of the heating system), HS the heating system energy consumption, $Elec\,price_i$ the current price of electricity, $Elecdev$ the electric devices consumption, and $inf^{y_i-y_c}$ the inflation rate between the initial year y_i and the current year y_c.

$$C_{Op} = Enprice_i \bullet HS \bullet inf^{y_i-y_c} + \text{Elec}\,price_i \bullet Elecdev \bullet inf^{y_i-y_c} \tag{4}$$

To account for uncertainties of input assumptions, a small sensitivity analysis on the volatility of fuels' prices is performed here, replacing the annual inflation rate in Equation (4). Based on the literature (i.e. ENTSOs [14] and the historical data previously analyzed, it was found that natural gas tends to be more volatile than district heating, and the latter tends to be more volatile than electricity. Therefore, the sensitivity ranges assumed are +/-30 % for natural gas, +/-20 % for district

Table 5
Current prices and average annual inflation rate for each fuel source.

Fuel source	Current price (EUR/kWh)	Average annual inflation rate
Natural gas	0.0612	1.052
District heating	0.073	1.0471
Electricity	0.3116	1.027

heating, and +/-10 % for electricity. These are translated into the sensitivity scenarios presented in Table 6.

3. Results and discussion

3.1. Base case simulation

The existing reference building was simulated to have a reference baseline to which all proposed renovation and replacement building scenarios could be compared to. Using the TRY weather files 2015 and 2045, the building's energy demand was calculated under the assumption that all loads are met with an efficiency of 100 %. Then, considering the current energy system installed in the building (gas non-condensing boiler) the actual energy consumption was calculated. The aggregated annual results obtained for both energy demand and actual consumption were compared to the calculated values from TABULA. The values compared are only for the year 2015, aligning with the date specified in the TABULA database; these values are only compared for heating, as TABULA does not include results for electrical appliances nor cooling. In the case of energy consumption, TABULA also includes empirical values, which are also used for comparison. The simulated energy demands and consumptions are presented in Table 7 for 2015 and 2045, and Fig. 6 includes the hourly heating and cooling demands for both reference years.

When comparing the simulations of years 2015 and 2045, the main difference is observed in the decrease of heating demand by 19 % and the increase of cooling demand by 23.5 %, this reflects the impact of climate change in the future. Regarding the energy consumption comparison, a difference of 4.2 % was obtained when comparing the simulated space heating consumption to the calculated value from TABULA, and −15.3 % for the DHW values. However, the largest difference is found when the simulated values are compared with the empirical values provided by TABULA, with 75.6 % and 42.9 % for space heating and DHW respectively. It is important to note that even the calculated values from TABULA reach a difference of up to 69 % more than what these empirical values present. Also, that there is no further reference of where the empirical data was obtained in terms of location in Germany and timeframe, nor reference about the sample size taken, which is likely to influence these values.

3.2. Energy consumption and life cycle analysis

The aggregated results for the analyzed timeframe (2020–2045) obtained from the building energy simulations for each proposed scenario were compared to the energy consumption that the existing building would have if no measures were implemented during this timeframe. With this, the impact that each renovation and replacement scenario will have in terms of reduction of energy consumption is quantified. Similarly, the overall impact perceived with the implementation of each scenario in terms of reductions of total GHG emissions (embodied and operational) during the analyzed timeframe is calculated with the LCA method. The results for each renovation and replacement scenario in function of the different heating systems are presented in Fig. 7. Here it can be seen that the largest reductions of both energy

Table 6
Annual inflation rates considered for each fuel source per sensitivity scenario.

Sensitivity scenarios	Natural gas	District heating	Electricity
Increase Natural gas	1.3	1.0471	1.027
Increase District heating	1.052	1.2	1.027
Increase Electricity	1.052	1.0471	1.1
Decrease Natural gas	0.7	1.0471	1.027
Decrease District heating	1.052	0.8	1.027
Decrease Electricity	1.052	1.0471	0.9
Increase all	1.3	1.2	1.1
Decrease all	0.7	0.8	0.9

Table 7
Simulated space heating (SH) demand and consumption, domestic hot water (DHW) consumption, and cooling demand for the years 2015 and 2045.

	2015			2045		
	SH	DHW	Cooling	SH	DHW	Cooling
Annual demand (kWh)	34,406	–	840	28,883	–	1,097
Normalized annual demand (kWh/m²)	284	–	6.94	239	–	9.06
Annual cons. (kWh)	47,972	2,772		40,126	2,750	–
Normalized annual cons. (kWh/m²)	397	23	–	332	23	

consumption and GHG emissions are obtained with the replacement buildings – mainly with the sustainable case – for all heating systems considered. This scenario reaches reductions of 97 % and 96 % for energy consumption and GHG emissions respectively with the heat pump with ground collector coupled with solar PV panels (HP + GC + PV). However, even if this scenario brings large reductions, it is still not able to achieve the zero emissions target, emitting a yearly amount of 5.5 kg CO_2-eq/m².

The HP + GC + PV results as the most efficient heating system for all other scenarios too. However, energy consumption and emissions reductions in scenario 3 are the lowest ones, even when considering this system. This scenario represents the case where envelope renovations take place first, and then there is a slow uptake (10 years) of a more efficient heating system. This is followed by scenario 4, which is similar to scenario 3 with the exception of replacing the heating system at a faster rate (5 years). These results suggest that if envelope renovations happen and the heating system is not replaced by a more efficient one at that time, the energy consumption will not be significantly reduced.

In the cases where the heating system is first replaced and then there is either a slow (scenario 5) or fast (scenario 6) uptake of envelope renovations, it is found that it would bring up to 14 % more reductions than scenarios 3 or 4. Scenario 7 (full envelope renovation and replacement of heating system), on the other hand, presents small differences in energy consumption when compared to both replacement building cases (conventional and sustainable), with the same reduction profile being observed for the GHG emissions, when using the HPGC + PV system. However, for the other energy systems this difference is even smaller when looking at the GHG emissions reduction obtained by this renovation scenario and the replacement sustainable case. This is due to the embodied emissions from the existing building (counted for the renovation scenarios) which are higher than the ones from the conventional replacement building. However, it should be noted that although the reductions may seem small, in absolute value these are not negligible because these reductions have been calculated based on the base case building. For instance, for the HPGC + PV system the difference in reduction between the conventional replacement and the renovation scenario 7 is approximately 9.8 % compared to the base case. The baseline building's emissions are 434487 kg CO_2-eq, meaning that the absolute difference is 42580 kg CO_2-eq, which is non-negligible. Directly comparing the total emissions from scenario 7 (75416 kg CO_2-eq) and conventional building (32838 kg CO_2-eq), the percentage reduction is 58.4 %, which is significant.

It is interesting to note a relatively effective impact in reduction of energy consumption and GHG emissions from scenario 2, implying only the replacement of windows, doors, and heating system. The reductions obtained are very similar to the ones from scenarios 5 and 6; hence, this suggests that simple and economic renovation measures combined with heating system replacement (both implemented at the same time), can be more effective consumption- and emissions-wise than any of the scenarios implying adopting envelope renovation and heating system
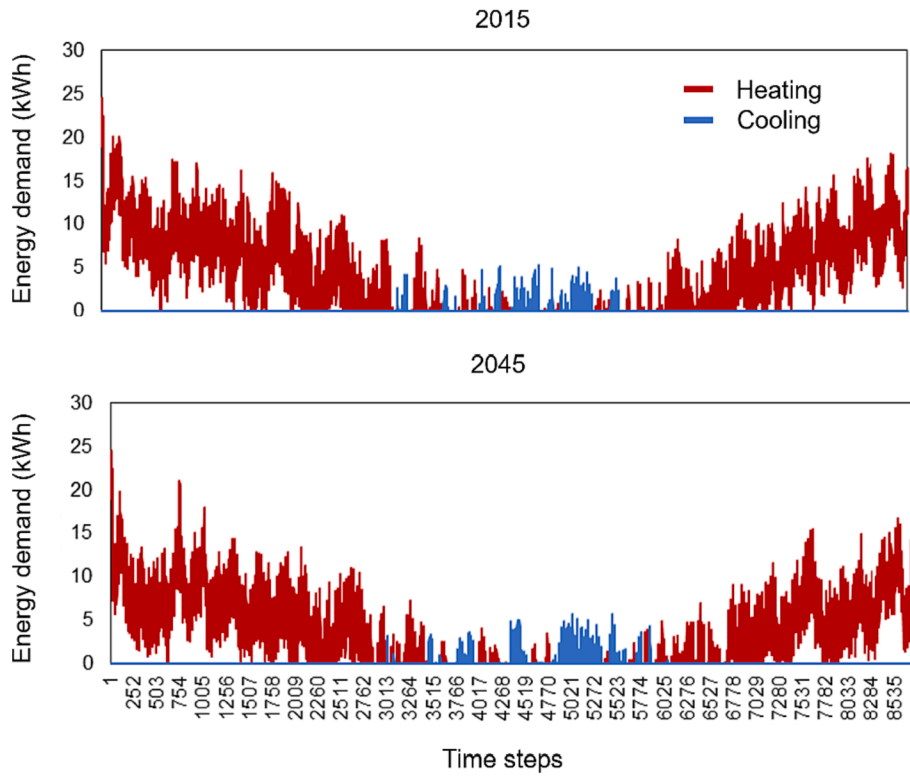
Fig. 6. Results from hourly heating and cooling demands for the years 2015 and 2045.

Fig. 7. Left, reductions of energy consumption by scenario and by heating system over the timeframe. Right, reductions of total GHG emissions (expressed as CO2-eq) by scenario and by heating system over the timeframe.

replacement with a lag between them. By analyzing the impact of scenario 1 and all other scenarios, it is determined that replacing the heating system as fast as possible will bring the most benefits from the energy consumption reductions perspective, reducing the operating GHG emissions as well.

As expected, when analyzing the impact of the different roof and walls renovation options proposed in Table 3 on the energy consumption, the combination with the lowest U-values reached more savings in energy consumption. However, there is not a significant difference when compared to other combinations. What can be noted from these results is that the greatest energy consumption savings are obtained with the walls' lowest U-values, rather than with the roof's.

Fig. 8 presents the embodied and operational emissions (heating and electricity consumption) of the various renovation and replacement building cases based on the worst and the best performing energy system. In terms of emissions, the gas condensing boiler (GCB) and the district heating (DH) system are the worst performing energy systems for the renovation & and the replacement cases respectively. When a less environmentally friendly energy system is chosen, the operational emissions dominate the total impact of each case, being responsible for over 90 % of the total impact for all renovation options, 72 % for the replacement conventional case and 84 % for the sustainable one. Since gas-based technologies are the worst operating systems, these are not analyzed for the replacement building cases. Therefore, the DH results as the least performing operating system for these cases.

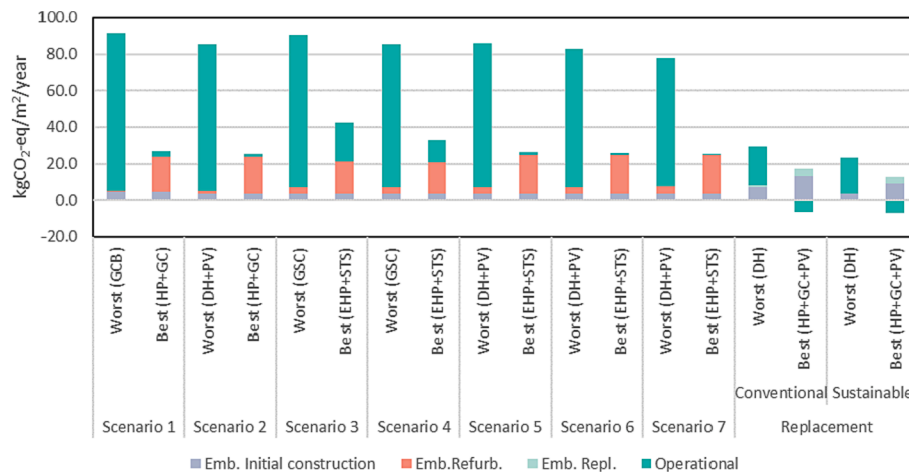On the other hand, the HP + GC + PV is the best operating energy

Fig. 8. Normalized embodied & operational emissions per m2 and year for each renovation and replacement option based on the worst and best performing energy system.

system for both replacement cases. In most of the renovation scenarios, the operational emissions are negligible (less than 11 %) compared to the embodied impact from the existing building (except for scenarios 3 and 4, where the operational emissions contribute roughly 48 % and 35 % to the total impact of the building), and the replacement cases. This occurs because in those renovation cases, the heating consumption of the building has been minimized due to the envelope retrofit, leading to minimize operational GHG emissions. Also, because CO_2-emission free electricity is produced by the PVs, which covers approximately 88 % of the total electricity demand. The electricity consumption is a priori independent of the renovation measures and has been assumed the same for all renovation and replacement cases, thereby this reduces the overall energy consumption of the building and the resulting operational emissions. In addition, by using this CO_2-emission free electricity, the use of electricity from the grid (not CO_2-emission free) is avoided at the same time, resulting in credits (negative impact) that have been considered in this study. The previous points justify why in some cases the operational emissions are negative (scenario 7 and both replacement cases). However, at the same time, the embodied emissions from the renovation and the replacement stages are higher, compared to when the GCB is used. This higher impact stems from the use of PVs in the case where the HP + GC + PV is used as energy system, as the entire roof is covered by PVs and their production impact is high, showcasing the trade-off occurring between the embodied and operational emissions.

Finally, the embodied impacts due to initial construction vary slightly between scenario 1 and the rest of renovation cases. This is because only 33 % of the embodied impacts from the materials that remain in the base case building are considered in this study. More specifically, in scenario 1 only the energy system is replaced, leaving the existing construction intact, thus carrying more impact during our considered timeframe. For the other renovation cases, both windows and doors are replaced, meaning that the impact of the existing windows and doors is excluded from the analysis, resulting in a minor reduction of the existing building's impact. For these cases, the extra materials added to the envelope and the new windows and doors are part of the renovation impact and not the existing building's impact, which explains why the embodied impacts originating from the initial construction of the building for scenarios 2–7 are the same. Finally, the replacement buildings bring the largest embodied and operational emissions reductions, especially the sustainable case, where the total emissions are the lowest for all cases considered (5.5 kg CO_2-eq/m^2/year). However, the net-zero emissions target is not achieved.

3.2.1. Sensitivity analysis

The resulting emissions provided in Figs. 7 and 8 show that a

significant energy consumption and total emissions reduction can be achieved, yet the net-zero target is not reached. The reason for this is although the sustainable building made of timber has CO_2-absorbing ability, the default EoL handling approach in Ökobaudat datasets is incineration. This causes a high impact due to the release of CO_2 to the atmosphere, thereby minimizing the benefits of using sustainable materials. In this situation, the credits originate from the energy production (heating and electricity), which is produced burden-free from the incineration plant – energy that can be used to provide heat and electricity to buildings.

To overcome this issue, a third option of the replacement building was explored. Since the sustainable building reveals the lowest emissions reductions, this was used as reference, while considering different EoL handling of the materials. Meaning that instead of incinerating the wooden products, it is assumed that the materials are recovered and reused (whenever possible). The credits (avoided impact described in Module D) stem mostly from avoiding the production of new wooden (construction) materials.

In Fig. 9, the total emissions reduction (embodied and operational) from the base case building that can be achieved by replacing it with three different options are presented. The reduction potential is higher for the sustainable building with reuse/recycling considerations for all energy systems considered, compared to the other options. Again, the district heating brings the least emissions' reductions, while the HP + GC + PV brings the largest reductions. Remarkably, the combination of the sustainable building with reuse/ recycling after the EoL of the building in combination with the most sustainable energy system is enough to achieve negative emissions (reduction potential of 101 %), amounting to −2.05 kg CO_2-eq/m2/year. This is due to the significant impact reduction embedded in the EoL (transport impact to storage site is significantly lower than incineration) and simultaneously the credits from avoiding the production of new building materials are higher than energy recovery from incineration. Meaning that the negative emissions are achieved in the third option due to the amount of carbon stored in the materials for a longer time.

3.3. Costs analysis

From the costs analysis, it was found that the investment costs can reach up to 78 % of the total costs for the renovation scenarios (with the HP + GC + PV), while for the replacement cases (both, conventional and sustainable), the investment costs represent more than 85 % in all cases. When considering both investment and operational costs over the analyzed timeframe, the costliest option overall is the district heating coupled with solar PV panels (i.e., approximately 232 k EUR for
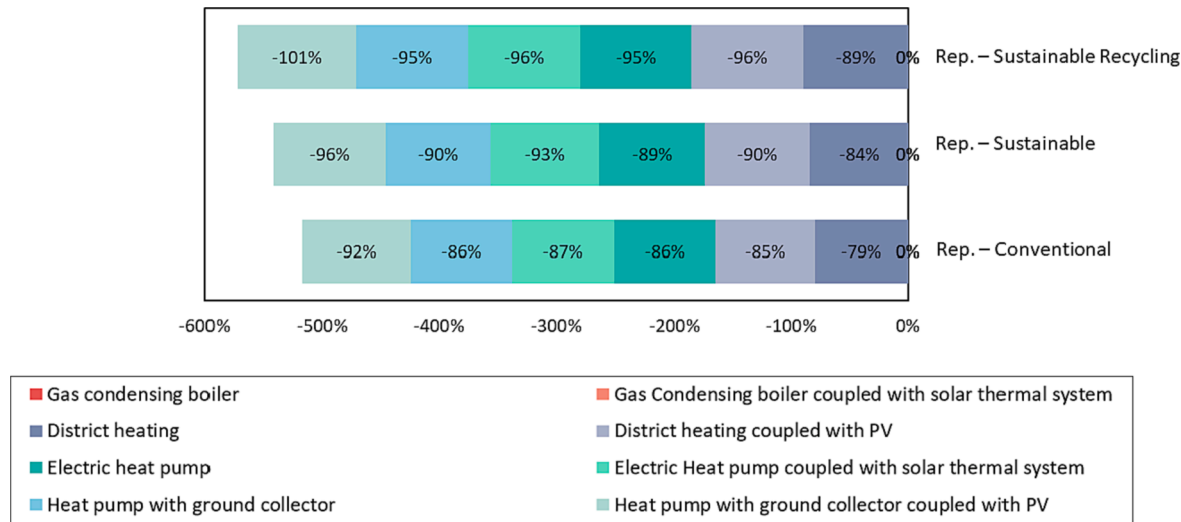
Fig. 9. Total emissions reduction achieved through the replacement buildings (conventional, sustainable with conventional EoL handling of materials and sustainable with reuse/recycling option at EoL).

renovation scenario 1 and 564 k EUR for the conventional replacement case). This is mainly due to the assumption that all the building's roof is going to be covered by solar PV panels, significantly increasing the investment costs. This, combined with the district heating consumption over the years, incurring high operational costs, makes this system less attractive cost-wise. On the other hand, the overall least costly heating system is the heat pump with ground collector (i.e., approximately 239 k

EUR for renovation scenario 7 and 491 k EUR for the conventional replacement case), mainly due to the low operational costs and investment costs when compared to the option where this heating system is coupled with solar PV panels. For scenario 1, however, the least costly option is the gas condensing boiler coupled with solar thermal systems (STS) (approximately 149 k EUR). This is due to the low investment costs required by replacing a gas non-condensing boiler (current system)
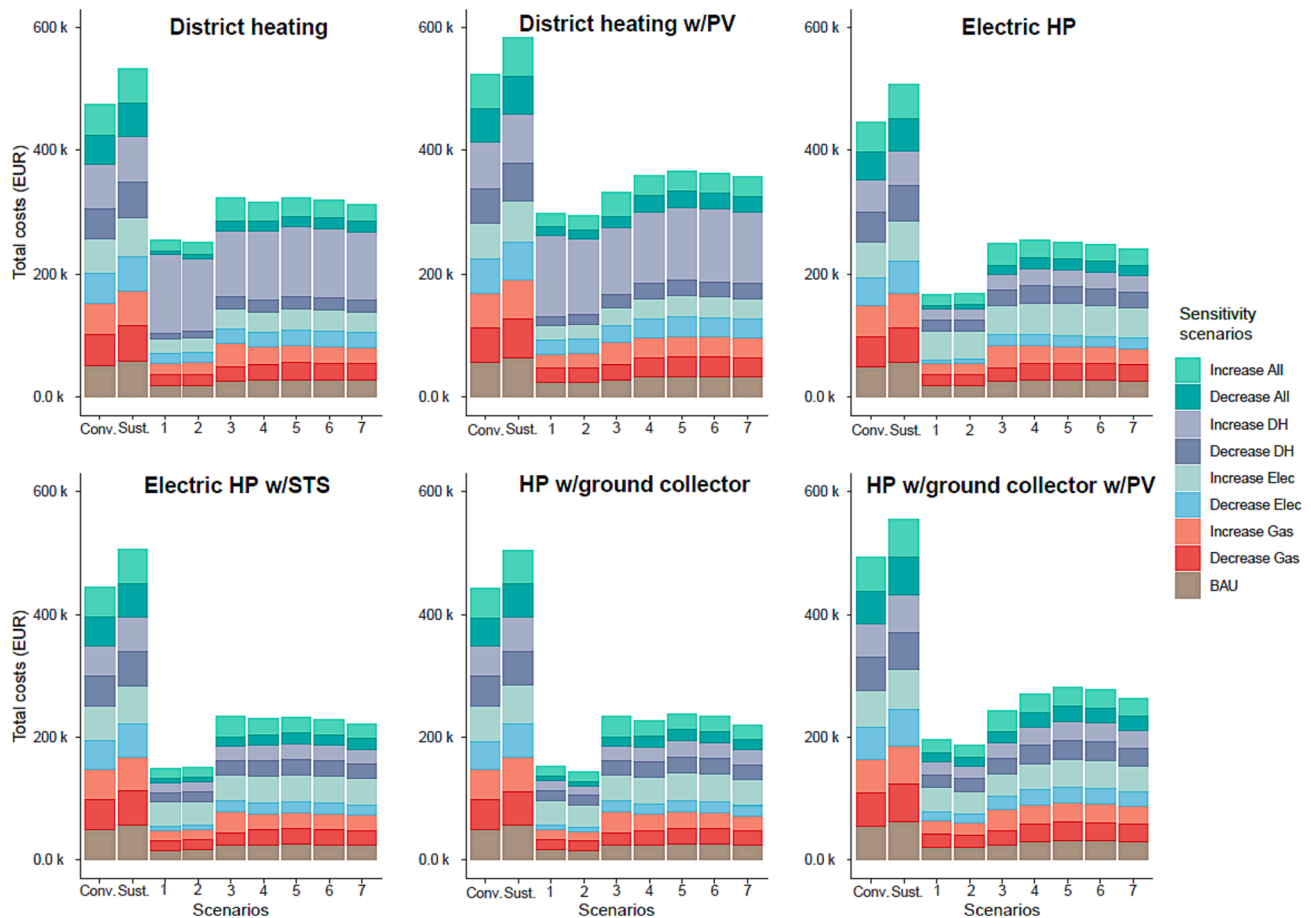

Fig. 10. Results of costs-sensitivity analysis per technology (non-gas dependent) and per replacement and renovation scenarios.

with a gas condensing boiler, plus the energy savings obtained from the STS over the years.

From the cost sensitivity perspective, the largest sensitivity is noted from the changes of natural gas prices, as well as when the prices of all fuels' sources considered in this study increase. When comparing the current status to the gas condensing boiler from the scenario with the lowest cost-sensitivity (scenario 7), a cost reduction of 37 % can be perceived. When comparing the same system but coupled with STS, this reduction increases to 46 %, quantifying that the costs-impact of coupling the gas condensing boiler system with STS is a reduction of 9 %.

The cost-sensitivity results obtained from all other technologies that do not depend on natural gas are presented in Fig. 10, for all replacement and renovation cases. Overall, non-gas dependent technologies are less volatile to fuels' price changes. In most cases, scenario 5 (replacing heating system first and a slow uptake of envelope renovation measures) brings the largest costs, for the district heating options it is mainly due to the relatively high operational costs (aggregated with the investment costs when coupled with solar PV panels). When the electric heat pump options are applied, renovation scenarios 3 and 4 (envelope renovation measures and slow and fast uptake of heating systems) are the costliest of all sensitivity scenarios. As this technology implies a low investment and high-energy savings, it would be more convenient cost-wise to replace the heating system first.

3.4. Overall results

Fig. 11 includes a visual representation of the different scenarios considered in this study, mapped based on their total costs (investment and operational) and total GHG emissions (embodied and operational) over the analyzed timeframe. This considers the type of heating system technology as well as the total energy consumption over the timeframe. All the different scenarios – including the walls and roof renovation combinations from Table 5 for each – are drawn; however, for visualization purposes, only the main scenarios are emphasized.

From this figure, it is noted that all replacement scenarios are in the upper left, indicating that while these are the options bringing the lowest emissions and energy consumption, these are also the costliest.

In the lower left, scenarios 5, 6 and 7 represent low emissions and consumption, however out of these options, scenario 7 results are more attractive cost-wise. This scenario can be compared with results obtained for scenario 2, which is even less costly, having similar energy consumption and emissions; however, this only applies when having the heat pump with ground collector coupled with solar PV panels as heating system technology. In the lower middle figure, a cluster with scenarios 3 and 4 using all electricity-powered heating technologies is observed. This cluster has relatively high energy consumption and emissions even with the most efficient technologies. These scenarios are the ones assuming an envelope renovation and later adoption of a more efficient heating system, and as previously discussed in Fig. 10, these scenarios result costly when implementing an electric heat pump solution. The last two clusters found in the lower right are all considering natural gas technologies and district heating options, being the gas technologies the least expensive ones, but the most pollutant and energy intensive. Interestingly for these clusters, no significant difference is found in terms of energy consumption from scenario 7 and scenarios 5 and 6, however scenario 7 continues to be preferred emission-wise. Scenarios 1 and 2 have the lowest costs (mainly due to the investment required when compared to other efficient technologies); however, they do bring the highest emissions and energy consumption.
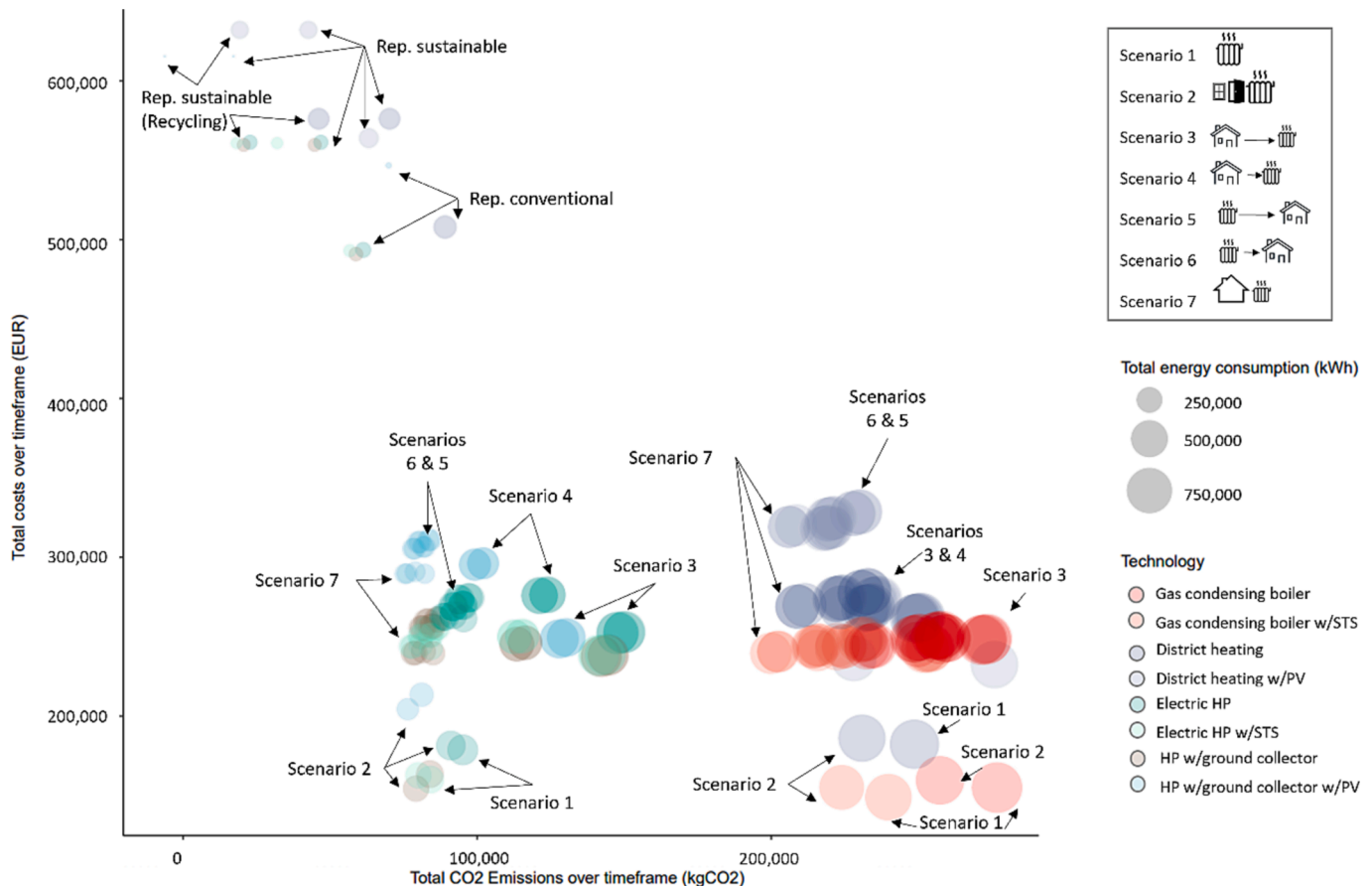

Fig. 11. Overall results based on total costs, total GHG emissions and total energy consumption over the analyzed timeframe, per scenario and per heating system technology.

The most energy efficient solutions from the replacement building scenarios reach an annual energy (heating and electricity) consumption of 13 kWh/m^2 and 15 kWh/m^2 for the sustainable and conventional cases respectively, falling below the "Passivhaus Neubau" regulation of ≤ 15 kWh/m^2 for heating. On the other hand, for renovated buildings, the maximum limit for 2050 in terms of energy consumption is 190 kWh/m^2. This limit is achieved by all renovation scenarios analyzed in this study that use electricity-based heating systems (electric heat pumps and heat pumps with ground source collectors, with both, individually and coupled with solar-based systems), being the highest consumption value 117 kWh/m^2 (for scenario 3) and the lowest 50 kWh/m^2 (for scenario 7).

In terms of achieving the 2 °C GHG emissions target of 12–24 kg CO_{2-eq}/m^2 for all buildings, the sustainable replacement building (recycling the materials as much as possible) is placed even below this range with -2.05 kg CO_{2-eq}/m^2, while the best conventional replacement option achieves 18 kgCO_{2-eq}/m^2, falling within the range. For the renovation scenarios, only the best option of scenarios 7 (using electricity-based heating systems) falls in the limit of the range with 24 kg CO_{2-eq}/m^2. Interestingly, scenario 2 is the second closest to the limit with 25 kg CO_{2-eq}/m^2. The low emissions caused by scenario 7 are attributed mainly to the large reduction of energy consumption over the timeframe analyzed (operational emissions), as this scenario includes more layers of insulation materials and replacement of windows, doors and heating system, increasing the embodied emissions. For scenario 2, it is a combination of low operational and embodied emissions, as this scenario only includes the replacement of windows, doors, and heating system, while reducing the energy consumption considerably.

For further analysis, the normalized energy savings over the building's operational years per EUR invested are calculated (Fig. 12). From this, it is observed that the large investment required for PV technologies do not compensate energy savings per m^2 over the studied timeframe. In terms of heating system technologies, the electric heat pump alone, the electric heat pump coupled with STS, and the heat pump with ground collector bring the most relevant cost-energy savings tradeoffs.

4. Conclusion

When taking the decision of whether it is better to renovate or to replace an existing building, multiple aspects need to be considered from the household-owners' point of view. Moreover, this decision should be aligned with the national GHG emissions targets, considering not only the operational but also the embodied emissions. For finding the most optimal solutions, a detailed bottom-up modelling process was proposed. A typical single-family house from a predetermined set of archetypes representing the German building sector has been selected. Then, building simulation approaches were applied to compute its energy consumption over time, considering a wide set of renovation and replacement scenarios. Simultaneously, a Life Cycle Assessment was performed to compute both the embodied and operational emissions over time, considering the building's geometry and materials in detail. As the economic point of view needs to be considered as well, a cost analysis was included, accounting for multiple sensitivity scenarios of fuels' prices variation over time.

Results show that the lowest GHG emissions during the lifetime of the analyzed building can be achieved with a sustainable replacement building (-2.05 kg CO_{2-eq}/m^2/year) by using a heat pump with ground collector coupled with PV under the condition of re-using the materials as much as possible, so that carbon remains stored in the wooden materials. However, that comes at a relatively high cost, which goes up to 2.12 times the cost of the best renovation solution (full envelope renovation and replacement of heating system). Interestingly, the application of small renovation measures, such as replacing the windows, doors and replacing the natural gas-based heating system with an electricity-based one is on the edge for achieving the 2 °C GHG emissions target at much lower costs. These results show that in terms of environmental impact the replacement building would be the favorable option, however the preferred option might change if also other indicators such as costs are considered.

When applying different renovation measures over time, it is observed that replacing the heating system first would bring the greatest benefits over time. The best performing heating system is the heat pump with ground collector coupled with solar PV panels,; while gas-based technologies are the least efficient and the most volatile to fuels'
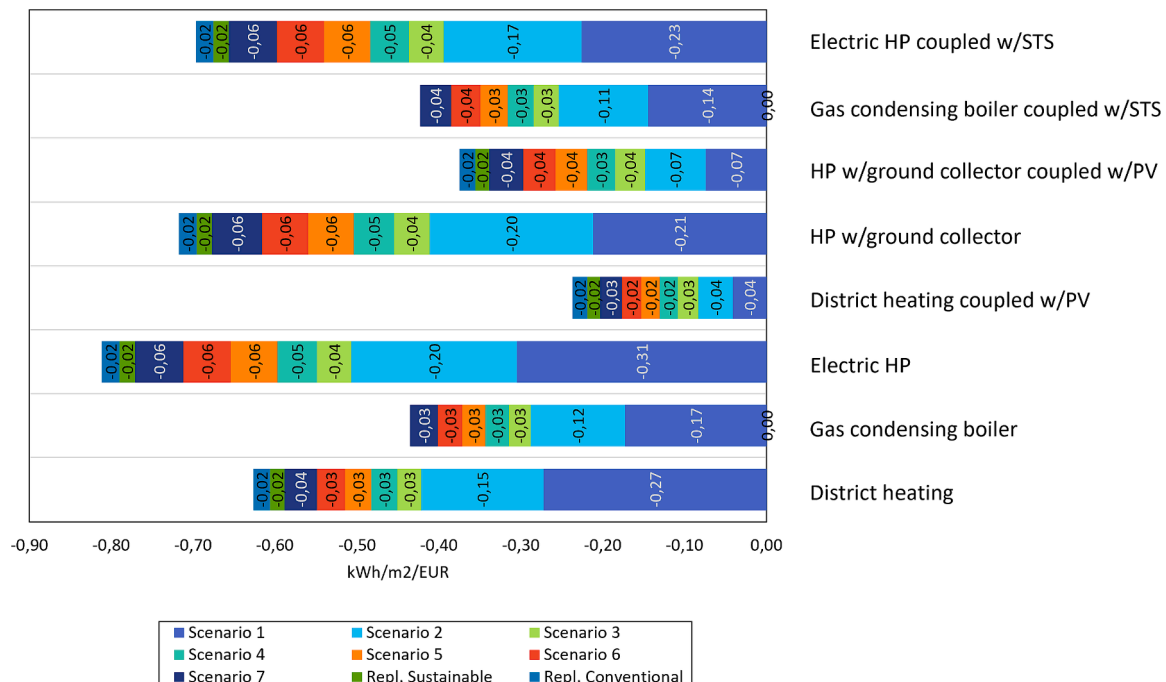

Fig. 12. Normalized energy savings over timeframe per EUR invested.

prices changes over the years. Results also show that the vast of CO_2 emissions come from fossil fuel based heating systems. When a a fossil fuel based energy system is chosen, the operational emissions dominate the total impact of each case, being responsible for over 90 % of the total impact for all renovation options, 72 % for the replacement conventional case and 84 % for the sustainable one.

The methods proposed in this study were applied to one specific building typology from the German building stock; hence, the results and assumptions cannot easily be transferred to other buildings. Furthermore, the insightful results obtained offer the opportunity of expanding the study to other building typologies, construction types of buildings, further retrofitting measures such as mechanical ventilation systems and different climatic conditions to have a better overview of potential solutions to decarbonize the building sector around the world. In this study, the prices and efficiencies that the heating systems and solar-based technologies will have in the future were considered as constant values. For further analysis, a dynamic sensitivity range for these values could increase the robustness of the results. The future emissions intensity of the German electricity grid were taken from the Ökobaudat database, and were introduced in 2018; therefore, when more recent values are available, the calculations need to be revised accordingly. Finally, there are subsidies schemes in Germany allowing the affordability of adoption of renovation measures and replacement of heating systems to homeowners. For further analysis, these schemes can be considered to evaluate the financial performance of each scenario.

Declaration of Competing Interest

Data availability

Data will be made available on request.

Acknowledgments

Appendix

Table A1
Summary list of materials used for the building components.

Building Element	Materials
External wall	Hollow bricks
Window	Wood frame
	Double glazing
Roof	Mineral bonded wood-wool board
	Roof ceramic tiles
	Wooden construction
	Mineral wool insulation
Floor	Wood boards
	Foot steep insulation
	Concrete
	Reinforcing steel
Doors	Exterior wooden door
	Interior wooden door

Table A2
Thermal properties of materials used for the building components.

Building element	Value	Source
Exterior wall material		
Hollow brick		
Thickness (m)	0.32	
Density (kg /m3)	1600	[2]
Thermal conductivity (W/mK)	0.46	[2]
Specific heat (J/kgK)	840	(National Concrete Masonry [26]
Thermal absorptance	0.9	[27] (8in concrete HW)
Solar absorptance	0.65	[27] (8in concrete HW)
Visible absorptance	0.65	[27] (8in concrete HW)
Exterior door		
Wooden door		
Thickness (m)	0.35	
Density (kg /m3)	700	DesignBuilder, Nussbaumer et al. [28] (assuming oak wood)
Thermal conductivity (W/mK)	0.18	DesignBuilder, Nussbaumer et al. [28] (assuming oak wood)
Specific heat (J/kgK)	2000	DesignBuilder, Material properties (2022)(assuming oak wood)
Thermal absorptance	0.9	[27] (G05 25 mm wood)
Solar absorptance	0.5	[27] (G05 25 mm wood)
Visible absorptance	0.5	[27] (G05 25 mm wood)
Windows		
Wooden frame, double glazing		
U-value (W/m2K)	2.8	[36]

Table A2 (*continued*)

Building element	Value	Source
Solar heat gain coefficient	1.41	[27] (Fixed Window 3.53/0.41/0.32)
Visible transmittance	0.32	[27] (Fixed Window 3.53/0.41/0.32)
Roof:		
Mineral bonded wood-wool board		
Thickness (m)	0.0095	[27] (Roof Membrane)
Density (kg /m3)	1121.29	[27] (Roof Membrane)
Thermal conductivity (W/mK)	0.16	[27] (Roof Membrane)
Specific heat (J/kgK)	1460	[27] (Roof Membrane)
Thermal absorptance	0.9	[27] (Roof Membrane)
Solar absorptance	0.7	[27] (Roof Membrane)
Visible absorptance	0.7	[27] (Roof Membrane)
Wooden construction		
Thickness (m)	0.04	[39]
Density (kg /m3)	480	[37]
Thermal conductivity (W/mK)	0.11	[37]
Specific heat (J/kgK)	1630	[27] (G05 25 mm wood)
Thermal absorptance	0.9	[27] (G05 25 mm wood)
Solar absorptance	0.5	[27] (G05 25 mm wood)
Visible absorptance	0.5	[27] (G05 25 mm wood)
Mineral wool insulation		
Thickness (m)	0.211	[27] (Roof Insulation [21])
Density (kg /m3)	265	[27] (Roof Insulation [21])
Thermal conductivity (W/mK)	0.049	[27] (Roof Insulation [21])
Specific heat (J/kgK)	836.8	[27] (Roof Insulation [21])
Thermal absorptance	0.9	[27] (Roof Insulation [21])
Solar absorptance	0.7	[27] (Roof Insulation [21])
Visible absorptance	0.7	[27] (Roof Insulation [21])
Floor		
Wood board		
Thickness (m)	0.04	[39]
Density (kg /m3)	480	[37]
Thermal conductivity (W/mK)	0.11	[37]
Specific heat (J/kgK)	1630	[27] (G05 25 mm wood)
Thermal absorptance	0.9	[27] (G05 25 mm wood)
Solar absoptance	0.5	[27] (G05 25 mm wood)
Visible absorptance	0.5	[27] (G05 25 mm wood)
Foot steep insulation		
Thermal resistance (m2K/W)	0.1	[27] (CP02 CARPET PAD)
Thermal absorptance	0.9	[27] (CP02 CARPET PAD)
Solar absoptance	0.8	[27] (CP02 CARPET PAD)
Visible absorptance	0.8	[27] (CP02 CARPET PAD)
Concrete		
Thickness (m)	0.15	[39]
Density (kg /m3)	2400	[39]
Thermal conductivity (W/mK)	1.311	[27] (MAT-CC05 4 HW CONCRETE)
Specific heat (J/kgK)	836.8	[27] (MAT-CC05 4 HW CONCRETE)
Thermal absorptance	0.9	[27] (MAT-CC05 4 HW CONCRETE)
Solar absoptance	0.85	[27] (MAT-CC05 4 HW CONCRETE)
Visible absorptance	0.85	[27] (MAT-CC05 4 HW CONCRETE)

Table A3
Building components used in conventional replacement building scenario.

Building element	Components	Thickness (mm)	U-Value (W/m²K) Entire element U-value	Max U-value (KFW 55)
External walls	Gypsum plaster	15	0.173	0.20
	areated concrete	120		
	EPS insulation	100		
	Gypsum plasterboard	15		
	Breather membrane	0.5		
Roof	Roof tiles	-	–	–
	Spruce wood battens	30		
	Spruce wood counterbattens	30		
	wooden softboard	22		
	EPS (0 3 5)	60		
	Sealing sheet (air tight)	0.2		
	Cross laminated timber	120		
	Spruce wood battens	60		
	Stonewool	60		
	Gypsum plasterboard	12.5		

Table A3 (*continued*)

Building element	Components	Thickness (mm)	U-Value (W/m^{2}K) Entire element U-value	Max U-value (KFW 55)
Floor	Parket	10	0.235	0.25
	Cement screed	60		
	PE foil	0.2		
	EPS	155		
	BITUMAT PVC membrane	5		
	Reinforced concrete	200		
	PE foil	0.1		
	Gravel	100		
Ceiling	Parket	10	0.186	0.25
	Cement screed	50		
	PE foil	0.4		
	EPS	170		
	Reinforced concrete	200		
Windows	Triple glazing, argon filled, low-E, insulated frame	–	0.8	0.9

Table A4
Building components used in sustainable replacement building scenario.

Building elements	Components	Thickness (mm)	U-Value (W/m^{2}K) Entire element U-value	Max U-value (KFW 40)
External walls	Plaster	7	0.15	0.15
	wood-fibre insulation board	60		
	construction timber	160		
	mineral wool	160		
	cross laminated timber	100		
	spruce wood battens	50		
	mineral wool	50		
	gypsum fibre board	15		
	gypsum plaster board type DF	15		
Roof	Roof tiles	–	–	–
	spruce wood battens (30/50)	30		
	spruce wood counter battens	30		
	softboard [045; 250] - rigid underlay	22		
	Stone wool	60		
	sealing sheet (air tight)	0.2		
	cross laminated timber	120		
	spruce wood battens (60/60; e = 400)	60		
	stonewool	60		
	gypsum plaster board type DF	12.5		
Floor	parquett	10	0.216	0.22
	cement screed	50		
	Polyethylene membrane	0.4		
	spruce wood battens (40/60, e = 400)	40		
	Wood-fiber insulation boards	130		
	Polyethylene membrane	0.4		
	Concrete reinforced slab	200		
Ceiling	Parquett	10	0.162	0.20
	cement screed	60		
	plastic separation layer (PE foil)	0.2		
	Impact sound absorbing insulation (mineral wool)	180		
	Trickling protection (PE foil)	0.2		
	cross laminated timber	150		
	gypsum fibre board (2x)	12.5		
Windows	Triple glazing, plastic, insulated frame	–	0.7	0.7

Table A5
Changes made to sustainable building elements taken from Dataholz.eu website.

Building element	Code in Dataholz website	Changes / Comments
Outside wall	awmopi05a	None.
Roof	sdmhzi03a	Thickness of cross laminated timber and EPS raised to 260 to reach the required U-value (0.11 W/m^{2}K).
Floor	–	Website does not contain floor elements.
Ceiling 1st floor	gdmnxn01a	60 mm of sound absorbing insulation considered. Elastic bond fill not considered.

Table A6
Energy technology costs for renovation scenarios 1, 5 and 6.

Energy system	Capacity (kW)	Cost (€)	Labor cost (€)	Total cost (€)
Gas Condensing Boiler	24	4717.51	3267.43	7984.94
Gas Condensing Boiler + Solar thermal system	24 and 2	7278.15	6267.43	13545.58
District Heating	24	0	5850.86	5850.86
District Heating + Solar PV	24	35975.7	8850.86	44826.56
Electric Heat Pump	8	11,128	1302.6	12430.6
Electric Heat Pump + Solar thermal system	8 and 2	13688.64	4302.6	17991.24
Heat Pump with ground collector	8	13,980	5200	19,180
Heat Pump with ground collector + Solar PV	8	49955.7	8200	58155.7

Table A7
Energy technology costs for renovation scenarios 2, 3, 4 and 7.

Energy system	Capacity (kW)	Cost (€)	Labor cost (€)	Total cost (€)
Gas Condensing Boiler	24	4717.51	3267.43	7984.94
Gas Condensing Boiler + Solar thermal system	24 and 2	7278.15	6267.43	13545.58
District Heating	24	0	5850.86	5850.86
District Heating + Solar PV	24	35975.7	8850.86	44826.56
Electric Heat Pump	8	11,128	1302.6	12430.6
Electric Heat Pump + Solar thermal system	8 and 2	13688.64	4302.6	17991.24
Heat Pump with ground collector	4	11,520	2600	14,120
Heat Pump with ground collector + Solar PV	4	47495.7	5600	53095.7

Table A8
Building element costs for different renovation options and combinations (different roof (R) and walls (W) renovation options proposed in Table 3 (R1 and W1 indicating the highest U-values and R2 and W2 the lowest ones).

Renovation option	Combination of roof and walls renovation types	Total cost (€)
OP2: Partial renovation	-	13654.14
OP3: Building envelope	R1W1	109853.73
	R1W2	111912.43
	R2W1	110559.73
	R2W2	112618.43
OP4: Full renovation	R1W1	121082.53
	R1W2	123141.23
	R2W1	121788.53
	R2W2	123847.23

Table A9
Energy technology costs for both replacement building scenarios.

Energy system	Total costs (€)
District Heating	5850.86
District Heating + Solar PV	44826.56
Electric Heat Pump	12430.6
Electric Heat Pump + Solar thermal system	17991.24
Heat Pump with ground collector	14,120
Heat Pump with ground collector + Solar PV	53095.7

Table A10
Total building costs in EUR (construction & labor costs) for the conventional building. Costs are displayed per cost group according to DIN 276. The average costs were calculated based on the average per unit costs for each cost group (FPC = Foundation pit content, FA = Foundation Area, EWA = Exterior Wall Area, IWA = Interior Wall Area, CA = Ceiling Area, RA = Roof Area, GFA = Gross Floor Area).

Cost group	2nd-level cost group	Unit	Area (m²)	Thickness (m)	min.	average	max.	min. %	average %	max. %	Average costs	% of total
310	Excavation / Earthworks	m³ FPC	133	0.5303	25	**43**	103	1.5	**3.3**	10.0	3033	1.19
320	Foundation, substructure	m² FA	133	–	302	**382**	514	7.3	**10.8**	15.0	50,806	19.95
330	Exterior walls / vertical exterior	m² EWA	145.5	–	412	**498**	573	40.9	**43.5**	47.0	72,469	28.45
340	Interior walls / vertical interior	m² IWA	89.91	–	189	**211**	248	9.2	**10.8**	12.9	18,971	7.45
350	Ceilings / horizontal	m² CA	133	–	297	**369**	466	11.4	**14.8**	20.2	49,077	19.27
360	Roofs	m² RA	136.7	–	319	**393**	458	11.5	**13.8**	16.4	53,703	21.08
370	Infrastructure installations			–	–	**–**	–	–	**–**	–	0	0.00
380	Structural installations	m² GFA	133	–	6	**10**	14	0.0	**0.1**	0.9	1330	0.52
390	Other. Measures for building const.	m² GFA	133	–	26	**40**	67	1.9	**3.0**	4.7	5320	2.09
Cost group 300 total costs											**254,709**	**100**
410	Sewage, water, gas plants	m² GFA	133	–	71	**101**	139	18.2	**27.6**	36.9	13,433	24.16
420	Heat supply systems	m² GFA	133	–	65	**117**	181	18.1	**30.6**	44.0	15,561	27.99
430	Air-conditioning systems	m² GFA	133	–	46	**81**	139	5.4	**18.9**	35.0	10,773	19.38
440	Electrical installations	m² GFA	133	–	46	**72**	188	12.2	**18.0**	35.0	9576	17.22
450	Communication systems	m² GFA	133	–	6	**12**	20	1.1	**2.9**	5.0	1596	2.87
460	Conveyor systems	m² GFA	133	–	–	**0**	–	–	**0**	–	0	0.00
470	Usage-specific / process technology Equipment	m² GFA	133	–	–	**0**	–	–	**0**	–	0	0.00
480	Building and plant automation	m² GFA	133	–	8	**32**	44	0.0	**1.8**	9.2	4256	7.66
490	Other Measures for technical equipment	m² GFA	133	–	3	**3**	3	0.0	**< 0.1**	0.7	399	0.72
Cost group 400 total costs											**55,594**	**100**
Labor costs (42.3 % of the cost groups 300 + 400)											**131,258**	**–**
Total Costs											**441,561**	**–**

Table A11

Total building costs in EUR (construction & labor costs) for the sustainable building. Costs are displayed per cost group according to DIN 276. The average costs were calculated based on the average per unit costs for each cost group (FPC = Foundation pit content, FA = Foundation Area, EWA = Exterior Wall Area, IWA = Interior Wall Area, CA = Ceiling Area, RA = Roof Area, GFA = Gross Floor Area).

| Cost group	2nd-level cost group	Unit	Area (m²)	Thickness (m)	min.	average	max.	min. %	average %	max. %	Average costs	% of total
310	Excavation / Earthworks	m³ FPC	133	0.4308	30	**47**	76	1.2	**2.1**	3.9	2693	0.94
320	Foundation, substructure	m² FA	133	–	243	**399**	492	6.3	**11.7**	14.9	53,067	18.47
330	Exterior walls / vertical exterior	m² EWA	145.5	–	472	**567**	705	41.0	**44.0**	47.4	82,510	28.72
340	Interior walls / vertical interior	m² IWA	89.91	–	195	**240**	310	7.8	**10.5**	12.5	21,578	7.51
350	Ceilings / horizontal	m² CA	133	–	340	**428**	488	10.0	**13.5**	17.3	56,924	19.81
360	Roofs	m² RA	136.7	–	356	**422**	518	11.2	**14.2**	15.9	57,666	20.07
370	Infrastructure installations		0	–	–	**–**	–	–	**–**	–	0	0.00
380	Structural installations	m² GFA	133	–	13	**52**	91	< 0.1	**0.9**	4.9	6916	2.41
390	Other. Measures for building const.	m² GFA	133	–	28	**45**	56	2.3	**3.0**	4.4	5985	2.08
Cost group 300 total costs											**287,339**	**100**
410	Sewage, water, gas plants	m² GFA	133	–	78	**113**	161	18.6	**27.0**	37.7	15,029	23.94
420	Heat supply systems	m² GFA	133	–	72	**128**	204	7.8	**23.7**	43.8	17,024	27.12
430	Air-conditioning systems	m² GFA	133	–	72	**108**	169	12.7	**24.3**	39.1	14,364	22.88
440	Electrical installations	m² GFA	133	–	60	**101**	212	16.0	**22.5**	45.6	13,433	21.40
450	Communication systems	m² GFA	133	–	7	**13**	20	0.7	**2.3**	3.7	1729	2.75
460	Conveyor systems	m² GFA	133	–	–	**–**	–	–	**–**	–	0	0.00
470	Usage-specific / process technology Equipment	m² GFA	133	–	9	**9**	9	0.0	**0.2**	2.2	1197	1.91
480	Building and plant automation	m² GFA	133	–	–	–	–	–	–	–	0	0
490	Other Measures for technical equipment	m² GFA	133	–	–	–	–	–	–	–	0	0
Cost group 400 total costs											**62,776**	**100**
Labor costs (47.6 % of the cost groups 300 + 400)											**166,655**	**–**
Total Costs											**516,770**	**–**
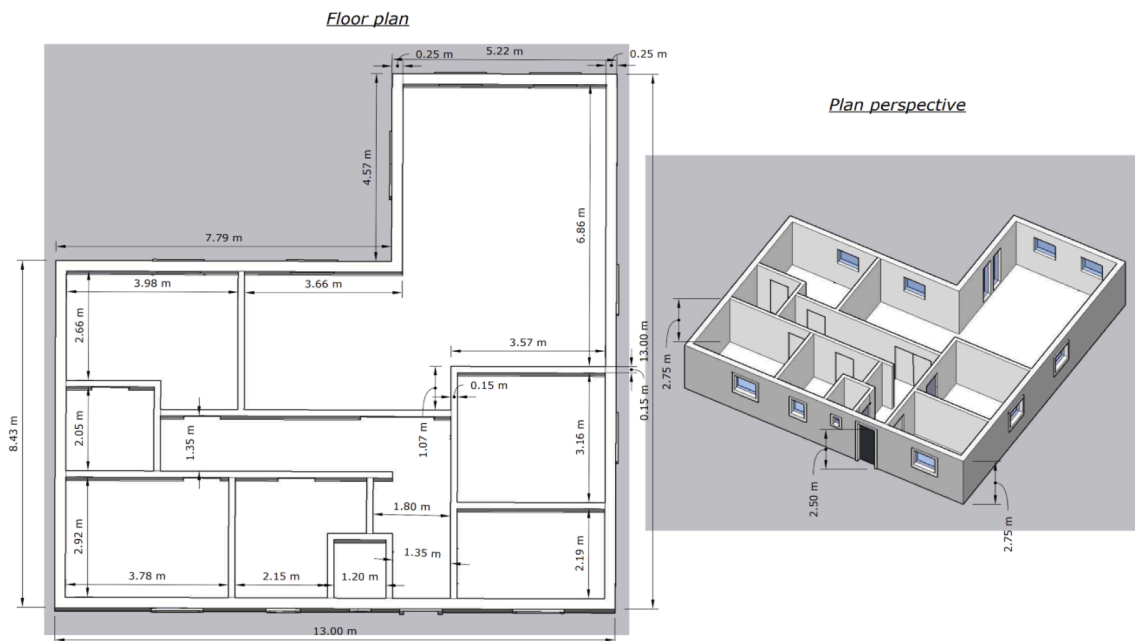
Fig. A1. Replacement building used for both scenarios (adaptation based on reference floor plan taken from [17].
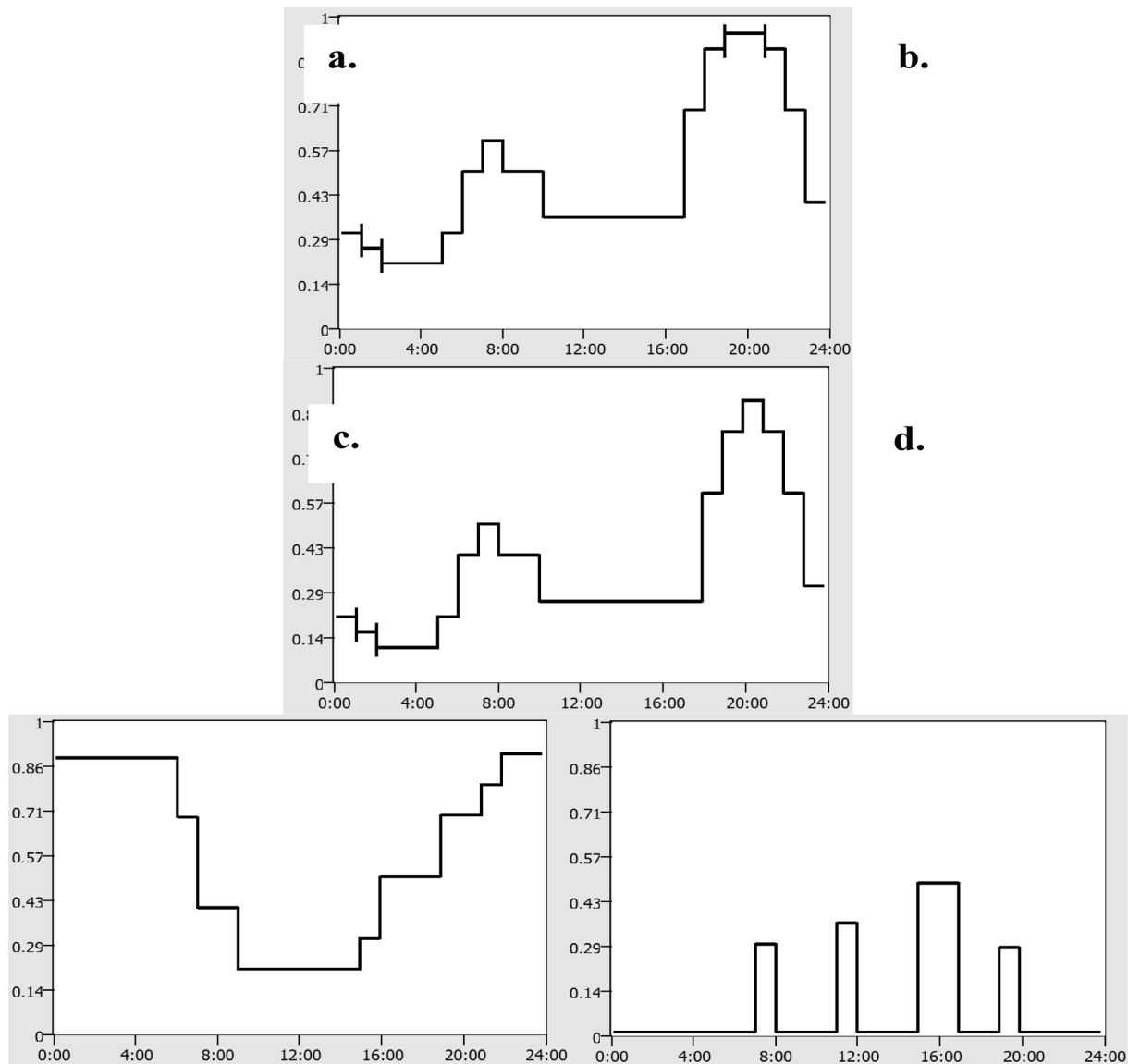
Fig. A2. Schedules used for a. Activity, b. Lighting, c. Occupancy, d. Domestic hot water usage. Extracted from OpenStudio (National Renewable Energy Laboratory (NREL), 2022).

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