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BUILDING COMPONENTS AND BUILDINGS

Strategies to improve building environmental and economic performance: an exploratory study on 37 residential building scenarios

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Abstract

Purpose With a contribution of 39% to greenhouse gas (GHG) emissions, reducing the environmental impacts of buildings plays an undisputed role in achieving climate goals. Therefore, the development of projects with a low carbon footprint is of crucial importance. Although several active and passive solutions as well as design strategies have been developed, identifying critical levers to minimise GHG emissions and the cost of future building projects is still a problem faced every day by designers.

Methods Motivated by this knowledge gap in this study, we conducted a life cycle assessment (LCA) and life cycle cost analysis (LCCA) of a residential building situated in Austria. To identify the critical levers for reducing impacts and cost, 37 scenarios with three different advanced energetic standards are created. The scenarios with the various standards are developed through the combination of different construction materials, insulation materials and technical building equipment. In the eco-efficiency assessment (LCA and LCCA), a reference study period of 50 years is assumed. The life cycle of the building scenarios was analysed according to the European standard EN-15978.

Results Results show that improving the energetic standard does not yield an overall cost savings potential. The additional construction cost (23%) for energy efficiency measures, including thermal insulation and change of technical building equipment, is higher than the reduction potential in operating cost over 50 years. On the other hand, the improvement of energetic standards allows a reduction of the environmental impacts by 25%.

Conclusions To ensure a cost-optimal environmental improvement of buildings, it is crucial to conduct an eco-efficiency assessment during the design process of energy-efficient buildings. This study shows how improving the energetic standard of buildings can reduce environmental impacts with slightly increased life cycle cost.

Keywords Life cycle assessment, Life cycle cost analysis · Building optimisation · Sustainable construction

1 Introduction

According to the Intergovernmental Panel on Climate Change's (IPCC) scenarios, the rate of greenhouse gas (GHG) emissions will double by 2030 unless urgent action is taken. This increase in emissions will have catastrophic consequences for many species and the world economy (UNEP 2009). To prevent climate change by limiting global

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Highlights

- Improved energetic standards lead to decreased operational impacts.
- Embodied impacts differ significantly only between the 'low-energy' and 'passive house' standards.
- Maintaining higher energetic standards results in slightly higher construction cost.
- The 'low-energy' standard shows similar life cycle cost analyses results as the 'passive house' standard.

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warming to 1.5 °C, with their ratification of the Paris Agreement, 197 countries indicated their commitment to achieving at least an 80% reduction in global emissions by the year 2050 (UNEP 2015). Worldwide, the building sector is considered to be responsible for 39% of GHG emissions (UNEP 2019), which makes it the biggest field of action. To actively effect changes, scientists have sought solutions either for upstream (material/systems) or for downstream (operational energy) building life cycle stages for more than 30 years.

Two groups of solutions are provided for the reduction of the environmental impacts of the operational stage. The first improves the carbon content of the energy source while the second minimises the required amount of energy. Within the building context, several national and international strategies (Myhrvold and Caldeira 2012) using renewable energy sources that lower the carbon content of the electricity grid have been analysed and proposed. Such solutions promise to reduce both operational and embodied impacts (Alig et al. 2020). The second solution contains active and passive solutions, enabling the improvement of energy efficiency of buildings for heating, cooling, ventilation or technologies producing low-carbon electricity. The application of these active and passive strategies has allowed the development of construction projects with different energy labels regarding consumption (Lasvaux et al. 2017; Drouilles et al. 2019). To reflect the energetic efficiency of building projects, various advanced standards (low-energy house, passive house or plus-energy house) have been introduced. The requirements for energetic standards are defined in the European Energy Performance of Buildings Directive (EPBD) (European Commission 2010). In Austria, these requirements have been transposed into national law through the Austrian Building Code Directive (Österreichisches Institut für Bautechnik 2015).

On the other hand, a recent study carried out to analyse 656 building case studies showed that a significant shift of impacts occurred from the operational stage to the building fabric and its equipment (Röck et al. 2020). Nevertheless, a clear trend is emerging. More investments are being made in the design of more energy-effective buildings, and more attention is being paid to the embodied energy and the related embodied impacts of building concepts, considering the whole life cycle (e.g. the activities of IEA EBC Annex 57 and IEA EBC Annex 72). John and Habert (2013) presented the environmental impacts of 12 buildings situated in Switzerland. They identified the components with larger contribution to buildings' environmental impacts. In the case of new and retrofitting scenarios, Hollberg and Ruth (2016) proposed a parametric approach enabling the minimisation of the embodied impacts of building projects. The novel approach reduced the effort of performing life cycle assessment (LCA) and guided architects towards low carbon projects. Considering both operational and embodied impacts, by varying design parameters and implementation of different passive and active strategies, Jusselme et al. (2016) and Drouilles et al. (2019) identified the most environmentally friendly solutions for the Swiss context. In the study presented by Allacker and De Troyer (2013), optimisation solutions from a life cycle environmental impact and cost perspective were analysed and identified. In the context of eco-efficiency assessment, Galimshina et al. (2021) investigated climate-friendly and cost-effective renovation scenarios for building renovation scenarios by using LCA and LCCA. After using the multi-objective optimisation approach, the study showed that the replacement of the heating system plays a crucial role in the reduction of environmental impacts. A further study applied many-objective optimisation to identify good energy-environment cost renovation solutions. By analysing the Pareto-optimal solutions, refurbishment actions have been identified (Pannier et al. 2019).

However, the literature lacks studies analysing the correlation between embodied and operational impacts through the improvement of the energetic standard in a single case study for the Austrian context.

Furthermore, in the existing LCA literature about buildings, few evaluations are found of different energetic standards and the influence of technical building equipment and/or different building materials (Hoxha et al. 2017). Besides, previous studies have not analysed the correlation between environmental and economic performance in a large number of new constructed building case studies in order to identify actions that can be taken to optimise buildings or their materials to reduce energy consumption and emission.

In our study, we assessed the environmental impacts of 37 building scenarios with different energetic standards. The study also addresses the influence of the energetic standard, the construction material, the insulation material and the technical building equipment on the impact on the environmental and economic performance of the case study building. In this context, the following study aims:

- to highlight the ratio of embodied and operational environmental impacts;
- to highlight the ratio of construction cost and operational cost;
- to identify the scenario with the lowest environmental impacts and lowest life cycle cost;
- and to highlight the correlation between environmental impacts and life cycle cost.

2 Methods

The method applied in this study follows the three steps: (i) definition of case study, (ii) LCA and LCCA, and (iii) critical interpretation of results. In the first step, 37 building scenarios with different energetic standards are developed. Then the environmental impacts and life cycle cost of all scenarios are calculated, and finally the results are analysed with the help of the statistical two-sample *t* test.

2.1 Case study

The case study described in this paper represents a two-storey residential building situated in Austria. Based on the architectural design of the building (Fig. 1), three distinct advanced energetic standard scenarios, (i) 'low-energy', (ii) 'passive house' and (iii) 'plus-energy', are defined, based on a heat-demand perspective that is in accordance with Austrian Standards (Austrian Standard Institute 2011b), The 'low-energy' standard represents the lowest energetic standard addressed, with a heating energy demand of about 40 kWh/m^2_{NFA}/year. The considered 'passive house' standard has a heating energy demand of 10 kWh/m^2_{NFA}/year. The 'plus-energy' standard also requires about 10 kWh/m^2_{NFA}/year, but this energetic standard is assumed to be equipped with 61-m^2 photovoltaic (PV) panels, which produce additional electricity. This generated electricity is only used for self-consumption and was subtracted from the total electricity consumption of the case study. The additionally generated benefit of PV electricity production, e.g. as grid feed-in, is not considered and therefore does not yield any benefit in further calculations.

Based on these three energetic standards, we generated different scenarios by varying the construction material, thermal insulations and technical building equipment (Mötzl 2014; Sölkner et al. 2014; Passer et al. 2016). By applying this approach, a total of 37 scenarios are defined, each fulfilling its respective requirement to meet the respective energetic standard. With a gross floor area (GFA) of 220 m^2 (ground floor and first floor), this building is analysed for a reference study period of 50 years. The selected building scenarios were calculated using the calculation method defined in the energy performance regulation in Austria, and their structures were dimensioned to achieve a consistent heating demand. In all generated scenarios, the outer dimension is not modified and, therefore, only the net floor area (NFA) varies due to modified thicknesses of the construction material and the insulations. This requirement was given due to the Austrian

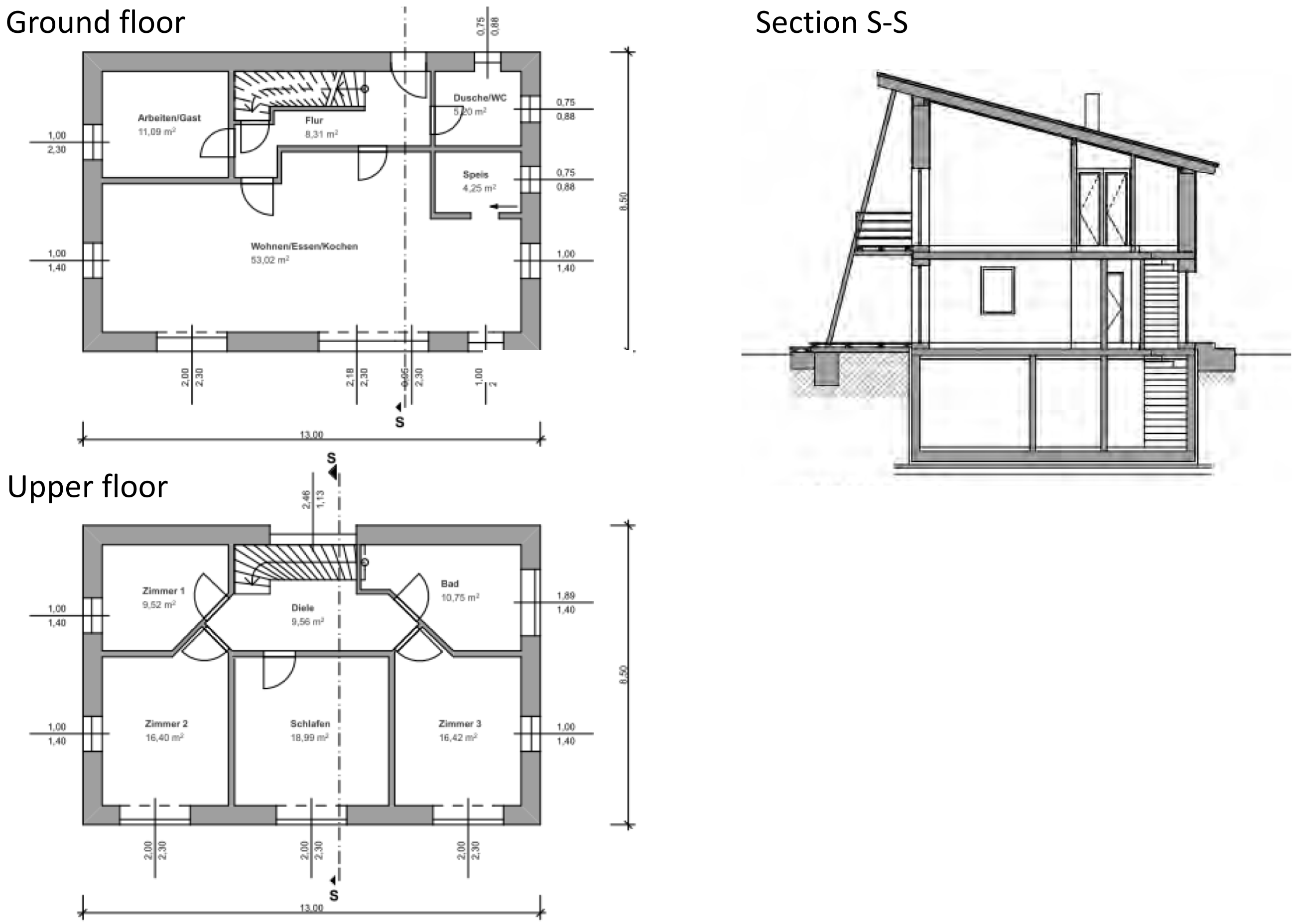

Fig. 1 Floor plans and cross section of the two-storey residential building

building specifications, as it is not always possible to change the outer dimensions of buildings. Furthermore, the parameters of the cellar (built with reinforced concrete) are also kept the same for each scenario.

To ensure that the 37 scenarios developed can be clearly identified, different codes are assigned. These codes consist of a sequence of four letters as shown in Fig. 2. The first letter differentiates the scenarios according to their energetic standard. The three energetic standards are the ‘low-energy’ standard, the ‘passive house’ standard and the ‘plus-energy’ standard with the abbreviations L, P and PE. The second letter indicates the construction material used (codes B, C, Wc, W_f and Ws). The subscript for this letter gives additional information about the thickness (in centimetres) of the construction material. The third defines the insulation materials used (codes E, R, W_f and 0). The subscript for this letter gives additional information about the thickness (in centimetres) of the insulation material. The fourth letter indicates the technical building equipment implemented in the 37 different scenarios. The technical building equipment includes heat pumps based on groundwater and on air-air compact unit and pellet boilers (codes H_{GW}, H_{CU} and P). In the supplementary material, we summarise detailed information about the 37 generated scenarios. In order to achieve the ‘low-energy’ standard in the scenarios without thermal insulation, either bricks with integrated thermal insulation or bricks with a thickness of 50 cm were used.

2.2 Environmental and economic performance of buildings

Based on the prepared plan documents for each construction method and their energetic standards, a construction company drew up service specifications for the buildings, including quantities and unit prices. The construction cost of the individual buildings were calculated by a general contractor, and the bills of quantities were made available for further calculations of the environmental and economic performance of the buildings. All costs for the construction of the building scenarios were calculated by the construction company, and no other literature benchmarks were used. Service life catalogues were used to determine the replacement cycles of materials and components. The electricity price and the pellet price at the time of the study were used to calculate the operational cost.

In the eco-efficiency assessment (LCA and LCCA), a reference study period of 50 years is assumed.

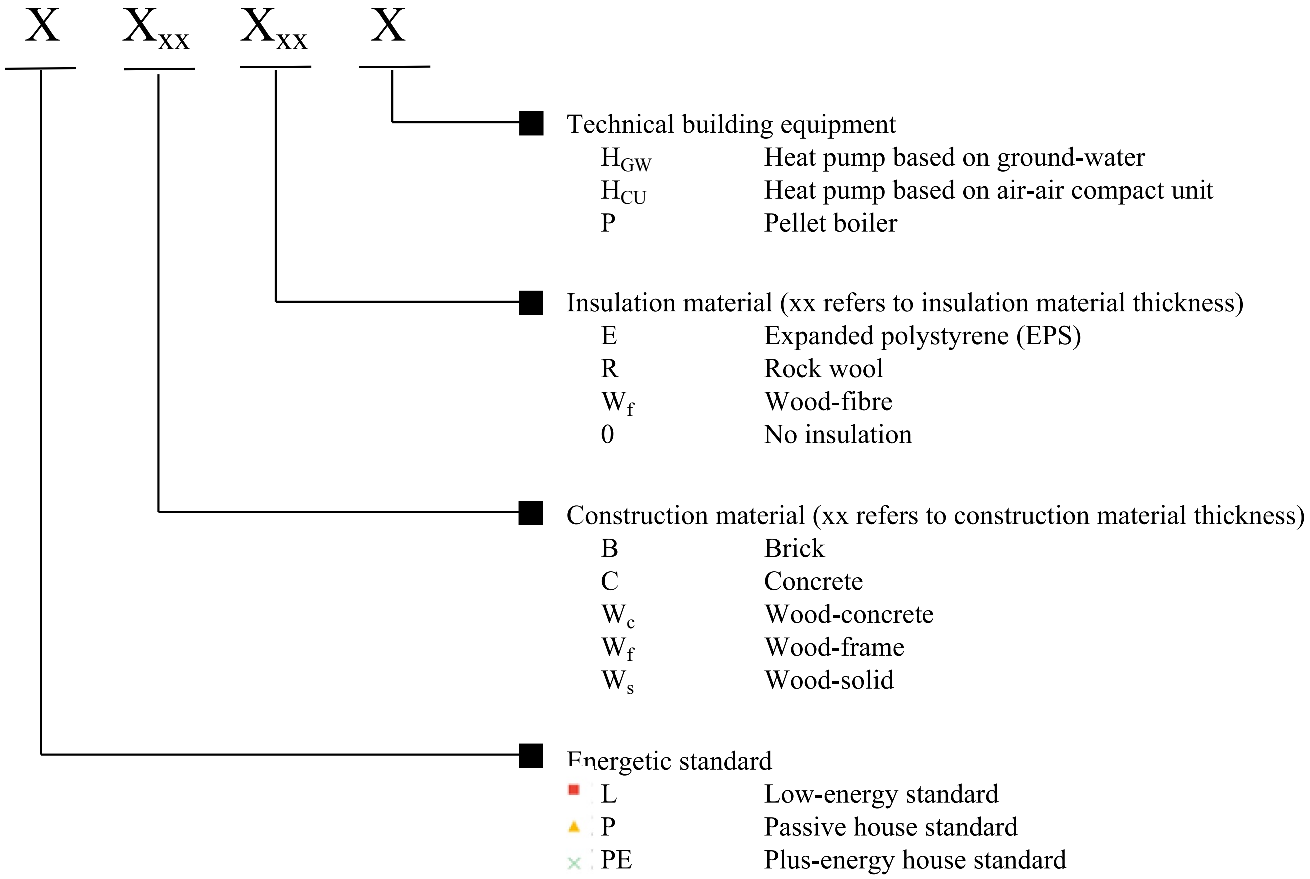

Fig. 2 Codes for the generated scenarios (energetic standard, construction material, insulation material and technical building equipment)

The life cycle of the building scenarios was analysed according to the European standard EN-15978 (CEN/TC 350 2011). This standard breaks down the impacts according to building life cycle stages: product stage (A1–A3), construction process stage (A4–A5), use stage (B1–B6), end-of-life stage (C1–C4) and benefits and loads beyond the life cycle (D).

The LCA includes the operational as well as embodied impacts. Embodied impacts are calculated by examining the construction materials as well as the technical building equipment. The system boundaries are limited to the life cycle stages of the production stage (A1–A3), construction process stage (A4–A5) replacement (B4), operational energy use (B6), demolition (C1), transport (C2), waste processing (C3) and disposal (C4). The impacts of the production stage (A1–A3) and the observed end-of-life modules (C3, C4) are based on the quantities of materials described in the bills of quantities. The environmental impacts of modules A5 and C1 were considered as ratio respectively equal to 5% and 2% of the impact of the product stage (A1–A3) (Hoxha et al. 2016; Lützkendorf et al. 2014). Simplification in assessing the environmental impacts of these stages is due to the lack of data on construction and demolition processes defined per construction type. Furthermore, the impacts of these stages are considered as ratio to also consider the influence of technical building equipment for which there is a lack of information in the literature (Hoxha et al. 2017). The replacement of the building components and materials during its reference study period (B4) are defined based on service life data for building components (Landesverband Steiermark und Kärnten 2020). The impact of the operational stage (B6) for heating, cooling, ventilation, hot water, lighting and appliances is calculated according to Austrian requirements for energy certificates of buildings (Österreichisches Institut für Bautechik 2015) and the Austrian electricity mix. The Swiss Ecoinvent database v.3.6 (Wernet et al. 2016) is used to calculate the environmental indicator of the global warming potential (GWP). The life cycle inventory of 37 building scenarios, hypothesis and the unit process considered in the calculation are provided in the supplementary material. Considering the system model ‘Allocation, recycled content’, which is also referred to as the ‘cut-off approach,’ the GWP indicator is calculated using the IPCC impact assessment method (Stocker et al. 2014). The calculation of the environmental impacts of all building scenarios is conducted in the LCA software SimaPro (Pré Consultants 2018). The environmental impacts are assessed on the basis of the defined functional unit as square metre net floor area (NFA) over the defined reference study period ($m^2{}_{NFA}$).

The life cycle cost analysis (LCCA) can be carried out for the entire building or for individual building components (structural elements, individual building component layers or technical building equipment). The framework for the evaluation of the economic performance of buildings is specified at the European level in EN 16,627:2015 (CEN/TC 350 2015). LCCA takes into account cost components such as construction cost (e.g. professional fees, temporary work, construction of asset), operational cost (e.g. rent, cyclical regulatory cost, utilities), maintenance cost (e.g. maintenance management, repairs and replacement of minor components, replacement of major systems and components, cleaning) and end-of-life cost (e.g. disposal inspections, disposal and demolition).

In this study, the net present cost method is applied in order to compare the economic performance for the scenarios of the two-storey building (Schulte 2015, Nwogug 2016). Based on the service specifications, the construction cost (A1–A3) is calculated in accordance with ÖNORM B 1801–1 and ÖNORM B 1801–2 (Austrian Standard Institute 2009, Austrian Standard Institute 2011a). To ensure comparability between construction cost and embodied impacts, the costs of the replacement of building components as part of the maintenance cost are added to construction cost. The costs of the replacement of building components are based on service life data for building components (Landesverband Steiermark und Kärnten 2020). The operational costs (B6) are based on the defined electricity price (0.17 €/kWh), the defined pellet price (0.25 €/kg) and the different heating demand of the different energetic standards (Eurostat 2020; proPellets Austria 2022). Additional calculation parameters for the dynamic LCCA (discount rate = 5.5%, inflation rate = 2.0%, escalation rate (energy) = 4.0%, and escalation rate (construction services) = 2.0%) are based on the building certification standard of Austrian sustainable building council. For a more detailed analysis we are not applying the average inflation rate for all goods and services. However, we considered the specific escalation rate for construction services and energy. The average inflation rate is used to calculate the real discount rate. In the LCCA, the end-of-life stage (C1–C4) is not considered. The calculated costs of the scenarios are expressed in life cycle cost (€/m^2_{NFA} net).

2.3 Critical interpretation

To strengthen the comparison between two series of data, the statistical two-sample *t* test is found useful. Within the study, there are the following three series of data: (i) low-energy standard buildings with 16 scenarios, (ii) passive house standard buildings with 14 scenarios and (iii) plus-energy house standard buildings with 7 scenarios.

Within the objective of this study, the test is used to compare the environmental impacts of the building scenarios with different energetic standards. The defined null hypothesis (H_0) is tendentially that no difference exists between the means of the two populations:

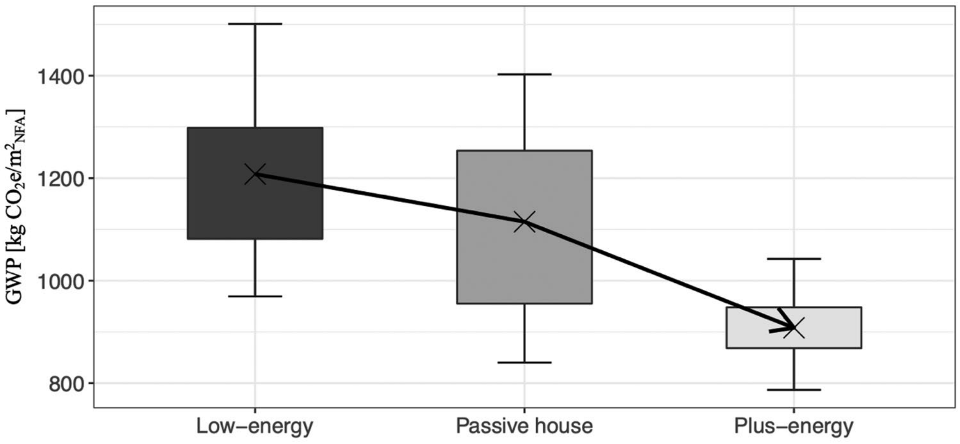

Fig. 3 Life cycle global warming potential (GWP) of building scenarios, clustered by their energetic standards

$$H_0 : \mu_1 - \mu_2 = 0 \tag{1}$$

where μ_1 and μ_2 present the mean values of the first and second series of data.

The *t* value is calculated with the equation:

$$t = \frac{\mu_1 - \mu_2}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}} \tag{2}$$

where σ_1^2 and σ_2^2 present the variances, and n_1 and n_2 the number of samples.

The threshold t_{crit} for rejecting or accepting the null hypothesis is calculated using the equation:

$$t_{\text{crit}} = (1 - \frac{1}{2} * \alpha, n_1 + n_2 - 2) \tag{3}$$

where α represents the level of significance.

For $\alpha = 0.05$, the *t* value calculated with Eq. (2) is compared with the t_{crit} from *t* distribution tables. If $t < t_{\text{crit}}$, then no significant difference between the two groups of building scenarios is observable, otherwise a significant difference is observable.

3 Results

3.1 Environmental impacts

Figure 3 shows the results of the LCA of the global warming potential (GWP) indicator for 37 scenarios, clustered by their energetic standards. For the ‘low-energy’ standard, the scenarios have an average impact of 1208.1 kgCO$_2$e/m$^2_{\text{NFA}}$. An increase in the energetic standard to that of the ‘passive house’ standard brings an average reduction in impact of 93.1 kgCO$_2$e/m$^2_{\text{NFA}}$. By improving the standard further to the ‘plus-energy’ standard, we observe an average reduction of 300.0 kgCO$_2$e/m$^2_{\text{NFA}}$ compared with the ‘low-energy’ standard. The impact reduction between the ‘passive house’ standard and ‘plus-energy’ standard is 206.9 kgCO$_2$e/m$^2_{\text{NFA}}$. To increase the robustness of the comparison of results, the analyses should be carried out taking into account the intervals between the values, so that a statistical test is required. For this purpose, a two-sample *t* test is performed to assess the statistical differences between the results.

A significance level of 5% ($\alpha = 0.05$) is chosen, which means that the difference of the compared mean values is significant if the *p* value in the test falls below 0.05. In Table 1, the calculated *p* values are shown. The results of the *t* tests show that the differences among the analysed mean values between the ‘low-energy’ and ‘plus-energy’ standards, as well as the differences between the ‘passive house’ and the ‘plus-energy’ standards, are significant. In contrast, the *p* value for the difference in the mean values between the ‘low-energy’ and ‘passive house’ standards falls below the chosen significance level of 5% ($\alpha = 0.05$). Consequently, the environmental impact differences between the scenarios of the ‘low-energy’ and ‘passive house’ standards are not significant.

3.2 Differentiation between embodied and operational impacts

To identify the contributors to the GWP indicator, a distinction must be made between embodied and operational impacts. Figures 4 and 5 show the distribution of

Table 1 Independent *t* test for the comparison of GWP (total impacts) reduction potential

Comparison between			*P* value	Significance
Low-energy standard	and	Passive house standard	0.060	No
Passive house standard	and	Plus-energy standard	0.004	Yes
Low-energy standard	and	Plus-energy standard	0.000	Yes

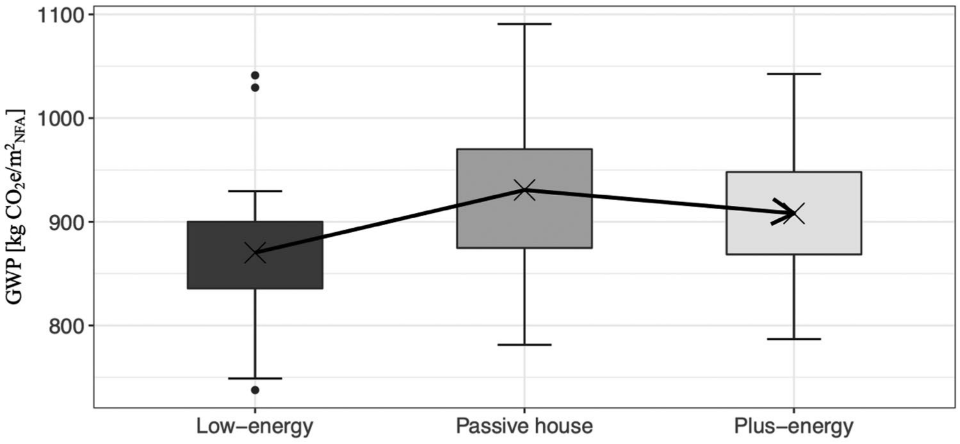

Fig. 4 Variations among embodied impacts

the environmental impacts of GWP in terms of embodied impacts and operational impacts for the 37 scenarios, clustered according to their energetic standards.

The results for the embodied impacts show that there is an increase in impacts between ‘low-energy’ and ‘passive house’ standards in an amount of 60.5 kgCO_2e/m^2_{NFA} and a decrease in embodied impacts between ‘passive house’ and ‘plus-energy’ standards in an amount of 22.6 kgCO_2e/m^2_{NFA}.

The statement that a reduction of embodied impacts occurs between ‘passive house’ standard and ‘plus-energy’ standard cannot be generalised, but results from the composition of the scenarios. In addition, among the seven ‘plus-energy’ standard scenarios, there are four scenarios with wooden construction materials, namely Ws_{40}-R_{40}-Hcu, Wf_{40}-R_{40}-Hcu, Wc_{18}-E_{26}-Hcu and $Wc_{36,5}$-E_{11}-Hcu, which also leads to this reduction. Furthermore, it should be mentioned that the *t* test classifies the comparison of these two energy standards as not significant based on the selected scenarios.

The increase between ‘low-energy’ and ‘plus-energy’ standards is 37.9 kgCO_2e/m^2_{NFA}.

For the ‘low-energy’ standard, four outliers can be identified. Of these, two are below the boxplot antennas (the second one is not visible in Fig. 4, because the values are almost identical) and two are above the boxplot antennas. The scenarios with the lowest embodied impacts are scenarios Wf_{26}-R_{26}-P and Wf_{26}-R_{26}-Hgw. These two scenarios have the lowest embodied impacts because the construction material is wood with a thickness of 26 cm. Regarding the embodied impacts, the installed rock wool insulation does not worsen the ranking of these two scenarios compared to the other 35 scenarios. The scenarios with the highest embodied impacts are scenarios B_{50}-0-P and B_{50}-0-Hgw. Despite the absence of thermal insulation in these two scenarios, they have the highest embodied impacts. This is due to the fact that a 50-cm-thick brick (including the required cement mortar) was used to achieve the ‘low-energy’ standard requirements.

The reduction of embodied impacts between ‘passive house’ and ‘plus-energy’ standard requires more detailed consideration. In terms of embodied impacts, the ‘passive house’ standard scenarios with the heat pump are on average slightly below the average embodied impacts of the ‘plus-energy’ standard scenarios, while the ‘passive house’ standard scenarios with the pellet heating system are on average slightly above the ‘plus-energy’ standard scenarios.

The *t* test results in Table 2 show insignificant differences regarding the embodied impacts between the ‘passive

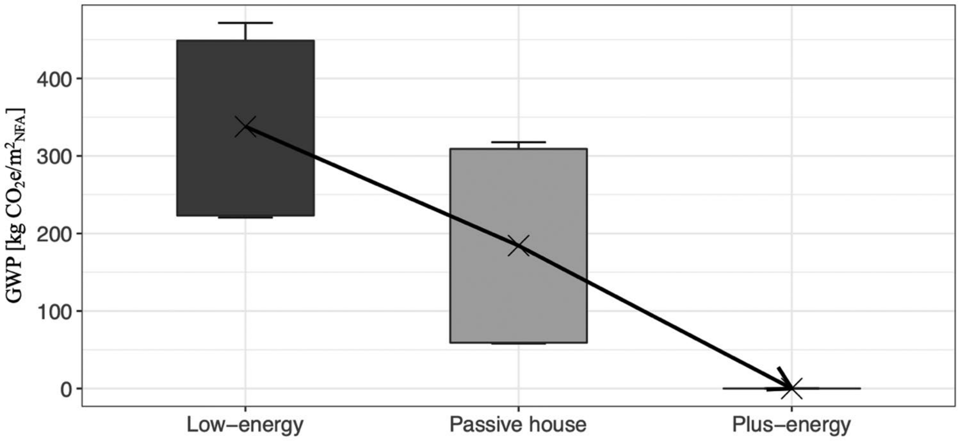

Fig. 5 Variations among operational impacts

Table 2 Independent *t* test for the comparison of GWP (embodied impacts) reduction potential

Comparison between			*p* value	Significance
Low-energy standard	and	Passive house standard	0.028	Yes
Passive house standard	and	Plus-energy standard	0.282	No
Low-energy standard	and	Plus-energy standard	0.160	No

Table 3 Independent *t* test for the comparison of GWP (operational impacts) reduction potential

Comparison between			*p* value	Significance
Low-energy standard	and	Passive house standard	0.001	Yes
Passive house standard	and	Plus-energy standard	0.000	Yes
Low-energy standard	and	Plus-energy standard	0.000	Yes

house' standard and the 'plus-energy' standard and between the 'low-energy' standard and 'plus-energy' standard. From the results of the *t* test, it can be concluded that the chosen building materials for the investigated two-storey residential building only have a significant influence on the difference of the embodied impacts between the 'low-energy' standard and the 'passive house' standard. Due to the insignificant differences between the 'passive house' standard and the 'plus-energy' standard, the change in total impacts over the whole life cycle, therefore, can be explained by examining the reduction in operational impacts for each of the individual energetic standards.

The results for the operational impacts show that there is a decrease in impacts between 'low-energy' and 'passive house' standards in an amount of 153.6 $kgCO_2e/m^2_{NFA}$ and a decrease in operational impacts between 'passive house' and 'plus-energy' standards in an amount of 184.3 $kgCO_2e/m^2_{NFA}$. The decrease between 'low-energy' and 'plus-energy' standards is 337.9 $kgCO_2e/m^2_{NFA}$.

The 'plus-energy' standard is equipped with an energy supply concept that pursues a similar goal as a zero-energy house, but in this case the annual energy balance is positive. Within the scope of the study, the energy demand for heating and cooling and the energy demand for ventilation were taken into account. Within the 'plus-energy' standard scenarios, this total electricity consumption is completely covered by the PV electricity production. The energy demand for lighting, household electricity or electric charging infrastructure for mobility needs was not taken into account.

The *t* test results highlighted in Table 3 show significant differences regarding the operational impacts between all considered energetic standards.

3.3 Life cycle cost

In Fig. 6, we show the life cycle cost of the 37 scenarios, clustered by their energetic standards. The scenarios with a 'low-energy' standard have an average life cycle cost of 2562 $€/m^2_{NFA}$. The adjustment of the energetic standard to that of 'passive house' standard leads to an average increase in the life cycle cost of approximately 251 $€/m^2_{NFA}$. An increase from the 'low-energy' standard to the 'plus-energy' standard leads to an additional life cycle cost of approximately 396 $€/m^2_{NFA}$. The increment in life cycle cost observed when the energetic performance of buildings is improved from 'passive house' to 'plus-energy' standard is 145 $€/m^2_{NFA}$. In terms of life cycle cost, the results also show an outlier for the 'plus-energy' standard. The solid wood construction (Ws) with 40 cm

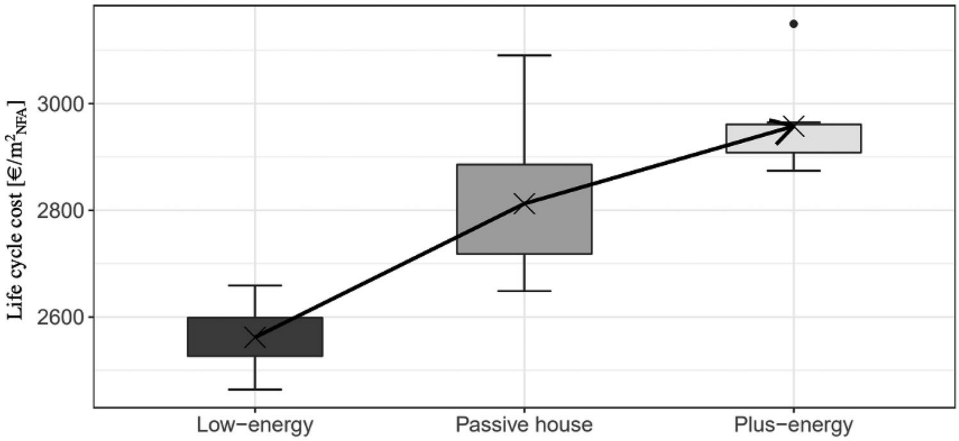

Fig. 6 Average life cycle cost of building scenarios, clustered to their energetic standards

Table 4 Independent *t* test for the comparison of life cycle cost

Comparison between			*p* value	Significance
Low-energy standard	and	Passive house standard	0.000	Yes
Passive house standard	and	Plus-energy standard	0.006	Yes
Low-energy standard	and	Plus-energy standard	0.000	Yes

mineral wool thermal insulation is 3150 €/m$^2_{\mathrm{NFA}}$. This outlier is due to the high construction cost of the 40-cm-thick solid wood construction and the additional mineral wool insulation.

The *t* test results for the comparison of life cycle cost between scenarios with different energetic standards are presented in Table 4. The comparisons between the considered energetic standards show significant differences in terms of the calculated average of the building scenarios within a chosen significance level 5% ($\alpha = 0.05$).

3.4 Differentiation between construction cost and operational cost

Figures 7 and 8 show the distribution of the construction and operational cost for the 37 scenarios, clustered according to their energetic standards. Unlike the distribution of environmental impacts, the construction cost differs in a broader range within the individual energetic standards. It has to be mentioned that the cost of the replacement of building components as part of the maintenance cost has been added to the construction cost in order to compare them with the results of the embodied impacts.

The results for the construction cost show that there is an increase in cost between 'low-energy' and 'passive house' standards in an amount of 291 €/m$^2_{\mathrm{NFA}}$ and a further increase in construction cost between 'passive house' and 'plus-energy' standards in an amount of 256 €/m$^2_{\mathrm{NFA}}$. The increase between 'low-energy' and 'plus-energy' standards is 547 €/m$^2_{\mathrm{NFA}}$. The solid wood construction is again an outlier, mainly due to the construction cost. These, like the total life cycle cost, amount to 3150 €/m$^2_{\mathrm{NFA}}$, since the operational cost in the 'plus-energy' standard scenarios is equal to zero. This high construction cost in scenario Ws$_{40}$-R$_{40}$-Hcu in the 'plus-energy' standards arises from the solid wood construction with a thickness of 40 cm. This result is also evident in scenario Ws$_{40}$-R$_{40}$-Hcu in the 'passive house' standards. The higher construction cost of the 'plus-energy' standard scenario Ws$_{40}$-R$_{40}$-Hcu compared to the same constructive scenario Ws$_{40}$-R$_{40}$-Hcu in the 'passive house' standard can be explained by the increased technical building equipment requirements.

The *t* test results for the comparison of construction cost between scenarios with different energetic performance are presented in Table 5. The comparisons between the considered energetic standards show significant differences in terms of the calculated average of the building scenarios within a chosen significance level 5% ($\alpha = 0.05$).

The results for the operational cost show that there is a decrease between 'low-energy' and 'passive house' standards in an amount of 41 €/m$^2_{\mathrm{NFA}}$ and a decrease between 'passive house' and 'plus-energy' standards in an amount of 110 €/m$^2_{\mathrm{NFA}}$. The decrease between 'low-energy' and 'plus-energy' standards is 151 €/m$^2_{\mathrm{NFA}}$. The operational cost for the scenarios of the 'plus-energy' buildings is equal to zero because the net electricity consumption after subtracting the PV electricity production is zero. Furthermore, no benefit is attributed due to the potential overproduction.

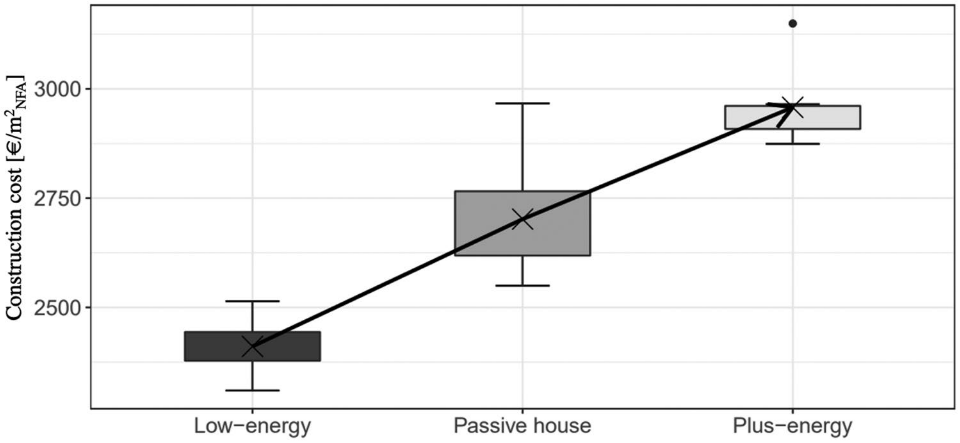

Fig. 7 Variations among construction cost (incl. replacement cost) for scenarios with different energetic standards

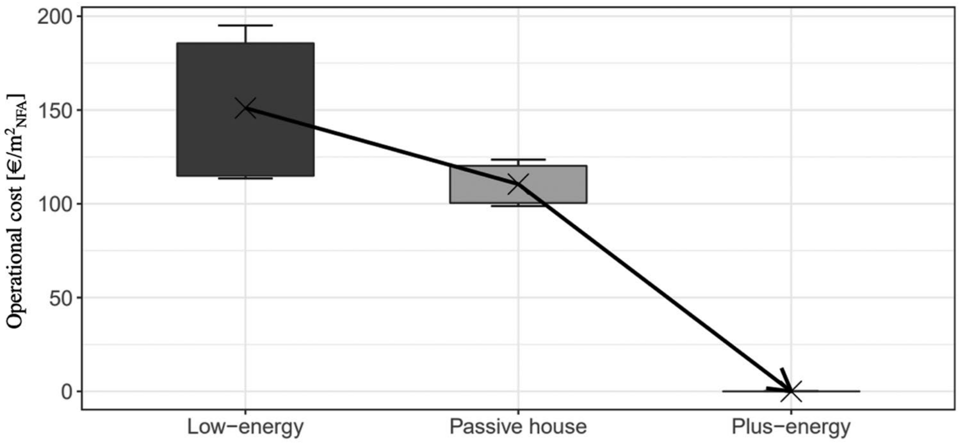

Fig. 8 Variations among operational cost for scenarios with different energetic standards

Table 5 Independent *t* test for the comparison of construction cost (incl. replacement cost) reduction potential

Comparison between			*p* value	Significance
Low-energy standard	and	Passive house standard	0.000	Yes
Passive house standard	and	Plus-energy standard	0.000	Yes
Low-energy standard	and	Plus-energy standard	0.000	Yes

The *t* test results for the comparison of operational cost between scenarios with different energetic performance are presented in Table 6. The comparisons between the considered energetic standards show significant differences in terms of the calculated average of the building scenarios within a chosen significance level 5% ($\alpha = 0.05$).

3.5 Change in construction cost to reduce GWP impacts of buildings

The relative influence of energetic standard improvement to overall impacts and cost is summarised in Table 7, where the 'low-energy' standard was assumed as equal to 100%. The most significant reduction potential can be achieved by increasing the energetic performance so that the 'low-energy' building meets the 'plus-energy' standard, but, on the other hand, this results in increased construction cost for the building project. The percentage comparison shows that this improvement in the energetic standard results in a 24.8% reduction in impacts, while an additional investment cost of 22.7% can be expected. The adaptation of the energetic standard to that of the 'passive house' standard leads to a reduction in the impacts by an average of 93 kgCO$_2$e/m$^2_{NFA}$ but causes an additional construction cost of 291 €/m$^2_{NFA}$. Measured in relative values, this translates to a 7.7% reduction in impacts with an additional construction cost of 12.1%. By improving the 'passive house' parameters to meet the 'plus-energy' standard, the additional construction cost amounts to 256 €/m$^2_{NFA}$ and reduces the GWP indicator by 207 kgCO$_2$e/m$^2_{NFA}$. The percentage comparison indicates that this improvement in the energetic standard allows us to reduce the impacts by 17.1%, while an additional construction cost of 10.6% is predicted.

Finally, the results illustrate that an increase from a 'passive house' to a 'plus-energy' standard significantly reduced impact at a relatively low additional construction cost.

3.6 Clustering analysis

In order to compare the additional life cycle cost for the reduction of GWP indicator more effectively, we conducted a detailed investigation of the single scenarios. Figure 9 shows the 37 scenarios on a cost-environmental impact diagram. The *x* axis shows

Table 6 Independent *t* test for the comparison of operational cost reduction potential

Comparison between			*p* value	Significance
Low-energy standard	and	Passive house standard	0.000	Yes
Passive house standard	and	Plus-energy standard	0.000	Yes
Low-energy standard	and	Plus-energy standard	0.000	Yes

Table 7 GWP reduction potential compared to construction cost for different energetic standards over a reference study period of 50 years

		Low-energy standard		Passive-house standard		Plus-energy standard	
		GW reduction potential*	Construction cost**	GW reduction potential*	Construction cost**	GW reduction potential*	Construction cost**
Relative value output	Low-energy standard			−93 (−7.7%)	+291 (+12.1%)	−300 (−24.8%)	+547 (+22.7%)
	Passive-house standard	+93 (+7.7%)	−291 (−12.1%)			−207 (−17.1%)	+256 (+10.6%)
	Plus-energy standard	+300 (+24.8%)	−547 (−22.7%)	+207 (+17.1%)	−256 (−10.6%)		

*in kg CO_2e/m^2 NFA.

**in €/m^2 NFA.

the environmental impacts for the GWP indicator in $kgCO_2e/m^2_{NFA}$, and the *y* axis shows the LCC results in €/m^2_{NFA}.

It can be observed that scenarios with installed heat pumps (Hcu, Hgw) show lower impacts for all used construction materials. Looking more closely at the scenarios with heat pumps, it can be seen that those scenarios with wood construction (Wf, Wc and Ws) have lower impacts than the scenarios with other construction materials. On the other hand, the scenarios with the construction material brick (B) are the ones with higher environmental impacts.

Regarding insulation materials, the scenarios without insulation materials do not fall into the low environmental impact range due to weak performance during the building's use phase. No clear statement can be derived for the other insulation materials used.

Examining the scenarios from an economic perspective, the construction materials solid wood (Ws) can be classified as LCC driver. However, the other construction materials (Wf, C, B and Wc) and the insulation materials (R, E, Wf, 0) cannot be classified as LCC drivers. Regarding the technical building equipment, the heat pumps with groundwater (Hgw) scenarios incur the lowest life cycle cost. Scenarios with heat pumps with air-air compact units (Hcu), on the other hand, are in the upper cost range. Scenarios with pellet heating systems can be placed between these two ranges. In summary, for the considered reference study period and the

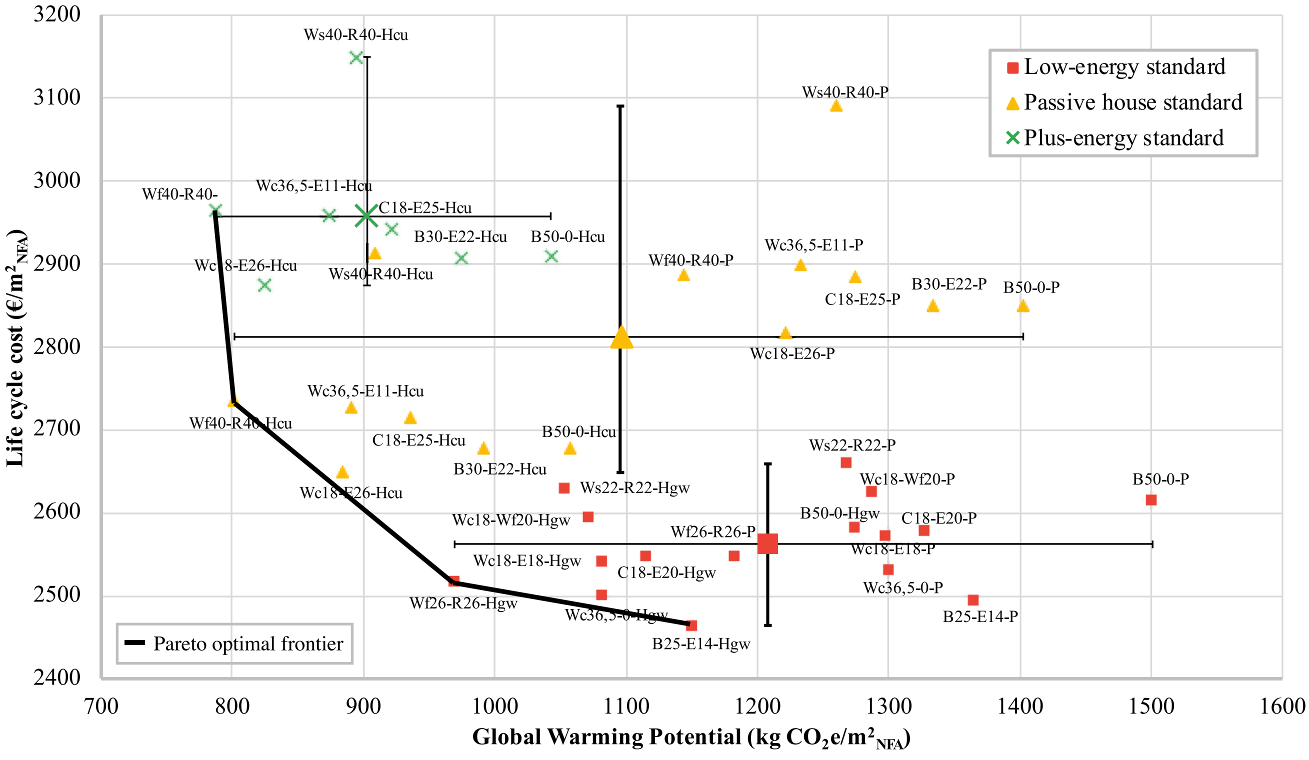

Fig. 9 Cost-environmental impact diagram for the 37 two-storey residential building scenarios over a reference study period of 50 years

assumed input parameters, a higher life cycle cost must be accepted to reduce the GWP impact.

Using the Pareto optimality logic, four pareto optimal solutions (PE-Wf40-R40-Hcu, P-Wf40-R40-Hcu, L-Wf26-R26-Hgw, L-B25-E14-Hgw) can be identified. For visualisation, the Pareto optimal frontier (solid line) based on the 37 defined scenarios was added as shown in Fig. 9.

4 Discussion

This study presents the life cycle environmental impact and cost of 37 scenarios with different energetic standards. These scenarios are based on common building practice and technical feasibility by varying the construction material, the insulation material and the technical building equipment. The analysed scenarios represent more than half of the possible cases that can be created. Moreover, according to the theory of probability and statistics, the minimum number of scenarios is 16 in order to obtain unbiased results. Therefore, these criteria, which were taken into account when creating the scenarios, allow for a robust and unbiased population of the cases studied. For the selected 37 scenarios of the presented case study, the improvement of the energetic standard in terms of embodied impacts has to be discussed from two perspectives. On the one hand, the improvement from ‘low-energy’ standard to ‘passive house’ standard results in a significant increase in the embodied impacts. This is due to the use of thicker construction and insulation materials. On the other hand, there is an insignificant decrease in embodied impacts when improving the energetic standards from ‘passive house’ standard to ‘plus-energy’ standard. However, this statement cannot be generalised and is due to the fact that, firstly, four of the seven ‘plus-energy’ standard scenarios are wooden buildings and, secondly, different technical building equipment were used due to the technical feasibility, i.e. no pellet boilers are used in the ‘plus-energy’ standard buildings.

Regarding the operational phase, an improvement in energetic standards leads to a reduction in operational impact. This is due to the reduction in the energy demand. It is important to mention that the energy demand for heating, cooling and ventilation has been taken into account and that the total energy demand of the ‘plus-energy’ standard is covered by PV electricity production.

In terms of the total environmental impact, the scenarios with the ‘plus-energy’ standard show on average the lowest GWP values, equal to 908.5 kg CO_2e/m^2_{NFA} which are completely allocated to the building materials and components. The GWP impacts obtained for scenarios with the ‘plus-energy’ standard are 70% lower than the impacts of traditional Austrian buildings published in previous studies (e.g. Passer et al. 2012). Furthermore, the environmental impacts of the ‘plus-energy’ standard buildings are almost equal to the environmental impacts of an innovative Austrian timber building created as part of a pilot project entitled ‘+ERS-Plus Energy Network Reininghaus Süd’ (Hoxha et al. 2020a). When compared with buildings located in different countries, the impacts of the two-storey building assessed in this work can be assigned to the group of new advanced buildings (Röck et al. 2020). The comparison supports the development of scenarios that use the ‘plus-energy’ standard and underlines the robustness of the GWP results. However, it is not possible to achieve the 2050 targets by merely improving the energetic standard of buildings with a reduction in the operational environmental impacts of new projects (Hoxha et al. 2020b). Further reductions, and especially in the embodied impacts, will be necessary.

To perform the LCCA, all 37 scenarios were calculated based on a bottom-up approach. The obtained results indicate that, on average, the three considered energetic standards generate a life cycle cost between 2562 $€/m^2_{NFA}$ and 2958 $€/m^2_{NFA}$. This range of calculated life cycle costs for the two-storey building is verified by the fact that they fall within the range provided in the construction cost index for new buildings (Baukosteninformationszentrum 2018). The construction cost index is an important metric in the field of construction cost planning that shows the evolution of construction prices over time. In this context, the underlying construction cost databases comprise several thousand billed projects on new buildings, old buildings and outdoor facilities. Furthermore, the additional construction cost calculated in this study (i.e. 12.1%) when comparing scenarios built to the ‘low-energy’ standard and ‘passive house’ standard are also in line with other studies (Schöberl et al. 2011). Studies on cost benchmarks for ‘plus-energy’-standard buildings are still rare, as the construction of ‘plus-energy’ houses is not yet state-of-the-art.

4.1 Critical remarks

The research design and the methodological approach used in this study can also be applied to other countries. However, the energetic standards have both different names and classifications based on the national or regional energy performance regulations. EU member states are obliged to transpose the Energy Performance of Buildings Directive (EPBD) from the European Parliament into national law. According to the EPBD, all new buildings must be constructed as nearly zero-energy houses from 2021 onwards. This requirement has already been applied to new buildings that have been built for state authorities since 2019 (European Commission 2010).

These results, therefore, apply primarily to the Austrian context and must be adapted to fit specific circumstances in other countries.

In the present study, we calculated the environmental impact of buildings using a 0/0 approach. As the aim of the study was not to address biogenic carbon from bio-based materials, the 0/0 approach can be considered the most understandable and robust method (Hoxha and Passer 2021), although the 0/0 approach allows us to identify discrepancies in the range of 30% compared to the dynamic impact calculation method, which is considered more reliable, especially for bio-based materials (Hoxha et al. 2020a). However, the conclusions we have reached are not influenced by the uncertainties associated with the evaluation method.

Due to the application of fixed calculation parameters for the dynamic LCCA, the additional cost for the construction of buildings with a higher energetic standard (e.g. 'passive house' or 'plus-energy' buildings) cannot be amortised by the savings based on the underlying assumptions in the LCCA, regarding the operational cost over the life cycle of 50 years. This result is also consistent with Galimshina's study on the analysis of climate-friendly and cost-effective renovation scenarios, which found that the investment for renovation measures in buildings with good energy performance is not paid off by the operational savings (Galimshina et al. 2021). One sensitive parameter regarding the calculation of the operational cost is for example the escalation rate (energy), whereby an increase in the annual escalation rate (energy) can result in an amortisation of the additional construction cost within the different energetic standards within 50 years. Therefore, we performed a sensitivity analysis for the escalation rate (energy) by using three additional escalation rates (energy). Considering the average LCC of the energetic standards, an increase in the escalation rate (energy) to 6% does not result in an amortisation of the increased construction cost. At an escalation rate (energy) of 8%, the average LCC of the 'plus-energy' standard scenarios is already lower than that of the 'passive house' standard scenarios. At an escalation rate (energy) of 10%, the 'plus-energy' standard scenarios represent the lowest LCC, whereby the increased construction costs are paid off over the 50-year reference study period due to the low or non-existent operational cost. The results have been added to the supplementary materials.

4.2 Limitations

The results of this study must be interpreted based on the 37 chosen scenarios. Therefore, when comparing two scenarios or two energetic standards, the used construction materials, insulation materials and technical building equipment must be taken into account. In this context, due to the technical feasibility the 'plus-energy' standard does not include pellet boilers, as in practice these are implemented with heat pumps.

In conducting the sustainability assessment, only the installed materials and the technical building equipment were considered. No use of alternative materials such as hemp or straw was investigated. In addition, no possible optimisation of materials was considered, such as CO_2-optimised concrete or CO_2-optimised steel production.

Limitations regarding the applied methods arise in the LCA in the choice of environmental indicators. Due to the large amount of data, in this study we only addressed the environmental indicator GWP. Regarding the comparison of embodied impacts between 'passive house' standard and 'plus-energy' standard, it must be mentioned that the comparison based on average values is not significant (see Table 2). This insignificance results from the small number of scenarios within the plus-energy' standard (i.e. 7 scenarios). However, if we compare the same building types between 'passive house' standard and 'plus-energy' standard (i.e. same construction material, same insulation material, same technical building equipment), the embodied impacts are higher due to the additional PV in the 'plus-energy' standard buildings (pls. see supplementary materials).

Another limitation also occurs within the LCCA. In the present study, the LCCA based on the EN 16627 (CEN/TC 350 2015) was applied. The whole life cycle cost (WLC) approach, which includes additional costs such as externalities, non-construction cost or income, was not taken into account.

In the course of dynamic LCCA, values based on literature were assumed for calculation parameters such as discount rate, inflation rate, escalation rate (energy) and escalation rate (construction services). Since these parameters have an increasing influence on the LCC results with increasing reference study period, varying ranges for the parameters as well as sensitivity and risk analyses have to be performed to validate the LCCA results.

5 Conclusions

To ensure a cost-optimal environmental improvement of buildings, it is crucial to conduct an eco-efficiency assessment during the design process of energy-efficient buildings. We referenced the well-established energetic standards used in Austria and the main construction types (i.e. brick, concrete, wood-concrete and wood-frame or wood-solid construction) and combined these to create new building scenarios. Additional combinations of different technical building equipment (pellet heating and different types of heat pumps) were considered. In this study, we conducted an LCA and an LCCA of 37 scenarios with three defined energetic standards (i.e. the 'low-energy', 'passive house' and 'plus-energy' standards) for a two-storey residential building situated in Austria.

This study shows how improving the energetic standard of buildings can reduce environmental impacts with slightly increased life cycle costs. The results enable us to conclude that improving the energetic standard reduces the environmental impacts. Overall, it was possible to reduce the GWP impacts by 300 kg CO_2e/m^2_{NFA} or 24.8% when the energetic standard was improved from the 'low-energy' to the 'plus-energy' standard. The largest range of reduction of impacts between one energetic standard and the next better one (i.e. 207 kg CO_2e/m^2_{NFA}) was observed when the standard was improved from a 'passive house' to a 'plus-energy' standard. On the other hand, improving the energetic standard increased the cost by 547 €/m^2_{NFA} or 22.7%. The largest increment between one energetic standard and the next better one, equal to 256 €/m^2_{NFA}, was allocated to the improvement of the energetic standard from the 'passive house' to the 'plus-energy' standard. A deeper analysis of the results for these 37 scenarios shows that the value of the GWP indicator was reduced by minimising the impacts of the operational stage, while the LCC of the building increased due to construction costs in materials and technical building equipment.

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Data availability All data generated or analysed during this study are included in this published article and its supplementary information files.

Declarations

Competing interests The authors declare no competing interests.

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