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BUILDING COMPONENTS AND BUILDINGS

Transition of the procurement process to Paris-compatible buildings: consideration of environmental life cycle costing in tendering and awarding

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Abstract

Purpose The greenhouse gas (GHG) emissions caused by the construction industry account for an enormous share of total global CO_2 emissions. The numerous construction activities therefore continue to reduce the remaining carbon budget. One lever for the reduction of these GHG emissions lies in the procurement process of buildings. For this reason, a process model was developed that takes embodied and operational emissions into account in the tendering and awarding phase of buildings.

Methods To validate the developed theoretical framework, environmental life cycle costing (eLCC) was conducted on a single-family house case study, taking into account external cost caused by GHG emissions. Various shadow prices were defined for the calculation of external cost to identify changes in award decisions. We further investigated a results-based climate finance (RBCF) instrument, i.e., the GHG emission bonus/malus, to demonstrate an approach for calculating Paris-compatible cost (PCC) scenarios.

Results We show that an award decision based on life cycle costing (LCC) leads to a 12% reduction in GHG emissions. A further reduction in GHG emissions can be achieved by awarding contracts based on eLCC. However, the required shadow prices within the eLCC awards to influence the award decision are quite high. With the development of the LCA-based bonus/malus system, PCC scenarios can be determined at sufficient shadow prices, and further GHG emission reductions can be achieved.

Conclusions Since the implementation of LCA and LCC in the tendering and awarding process is currently not mandatory, in this context, the next step towards Paris-compatible buildings must first be taken by the awarding authorities as well as the policy-makers. However, the application of the LCA-based bonus/malus system and thus the awarding of contracts according to PCC scenarios show the enormous GHG emissions reduction potential and thus represent an innovative and sustainable framework for an adapted procurement process.

Keywords Environmental life cycle costing · External cost · Life cycle assessment · Carbon price · Shadow price · Results-based climate finance · Building procurement · Emission reduction · Sustainable construction

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Highlights

- Award decision based on conventional life cycle costing results in reduction of GHG emissions.
- Further reduction in GHG emissions can be achieved by awarding according to environmental life cycle costing.
- Paris-compatible cost scenarios can be determined with the LCA-based bonus/malus system.
- By Paris-compatible cost scenario awarding, GHG emission reductions can be achieved at a shadow price of 26€/tCO_2eq.
- Further reduction in GHG emissions can be achieved by awarding according to Paris-compatible cost scenario considering higher shadow prices.

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1 Introduction

As part of the Paris Agreement, also known as COP21, 197 nations committed to keep global warming to 1.5–2 °C over pre-industrial levels (United Nations Framework Convention on Climate Change (UNFCCC) 2016). To do this, major efforts must be undertaken to pinpoint emission reduction plans in each industry with a high carbon footprint. Building-related activities account for 37% of the world's greenhouse gas (GHG) emissions (United Nations Environment Programme (UNEP) 2021) and should therefore be a central focus point. In Austria, a recent estimate shows that the "field of action" buildings is responsible for yearly GHG emissions of 22 to 31 Mt CO_2eq, depending on the assessment method, i.e., bottom-up process-based Life Cycle Assessment (LCA) or top-down input–output LCA. In particular, residential buildings are responsible for at least 65% of these emissions (Truger et al. 2022). According to the Paris Agreement, Austria's maximum emission budget by 2050 ranges between 1000 and 1500 million tonnes of CO_2eq. (Meyer and Steininger 2017). If emissions are not decreased below their current level, the emission budget will run out between 2028 and 2035 (Schleicher and Steininger 2017). However, due to the intersectoral nature of building-related activities, as represented by their "field of action," translating a national carbon budget into specific targets for buildings is no trivial task. Numerous European nations have already determined carbon budgets for their own building stocks, and a preliminary estimate was also calculated in Austria by combining top-down and bottom-up methods (Hoxha et al. 2020). Nevertheless, the notion of a carbon budget for buildings is not always unanimously agreed upon, and several methods of calculation can be deemed reasonable (Habert et al. 2020). There is, consequently, not yet a consistently defined Paris-compatible carbon budget for buildings in Austria.

No matter the target or the budget, in light of the high contribution of buildings' activities to climate change (Truger et al. 2022), it is clear that decreasing the environmental impacts associated with buildings is required, to ensure Austria's path to a Paris-compatible vision. In addition, due to their particularly long lifespan, the choices made for buildings constructed today largely determine the level of their long-term environmental impacts (Frischknecht et al. 2019). This is why the scientific literature has put remarkable efforts in identifying emission reduction strategies for buildings, whether targeting the operational emissions, i.e., emissions coming from the functioning of the building (Hoxha and Jusselme 2017; Lasvaux et al. 2017; Drouilles et al. 2019), or the embodied emissions, i.e., emissions related to the materials, transport, construction, and end-of-life (Alig et al. 2020; Zhong et al. 2021; Alaux et al. 2023). Trade-offs between embodied and operational emissions in order to improve the life cycle performance of buildings have also been highlighted in multiple studies (Mirabella et al. 2018; Lützkendorf and Balouktsi 2016). To be able to properly assess the estimated reductions in GHG emissions, these studies usually rely on scientific environmental assessments, such as LCA, a reliable methodology based on ISO 14040/14044 (International Organization for Standardization (ISO) 2006a, b), which was adapted into the specific European standards EN 15978 for buildings (CEN/TC 350 2011) and EN 15804 for building products (CEN/TC 350 2022). However, further emission reduction strategies are still being investigated, especially for the embodied emissions, as the current technological knowledge might not be enough to ensure the whole decarbonization of buildings (Alaux et al. 2022). Having a deep knowledge about GHG emissions reduction strategies is a prerequisite, but is not sufficient to guarantee their implementation in practice. The assessment of building performance taking into account the entire life cycle has been recommended by leading scientists of the Life Cycle Sustainability Assessment Community for decades and declared as a prerequisite for the implementation of sustainable construction (Birgisdottir et al. 2017; Hollberg et al. 2019; Lützkendorf 2021). In this context, further studies emphasize the importance of the systemic interrelationships of early design decisions and their impact on environmental, economic, and sociocultural and functional as well as technical quality of buildings (Kreiner et al. 2015; Scherz et al. 2018).

Currently, the vast majority of decisions still relies on construction cost-based evaluation, despite the availability of developed life cycle costing (LCC) methods, which can be divided into conventional LCC, environmental LCC (eLCC), and societal LCC, being applied for several years in research and (voluntary) certification schemes (e.g., ÖGNI/DGNB and ÖGNB) (Flöegl 2012; Kohler 2010; Langdon 2007; Wübbenhorst 1984). While conventional LCC only includes cost that occur directly within the life cycle of a product, eLCC includes at least the external cost caused by environmental impacts (Ciroth et al. 2008). A guide on application of different LCC methods related to LCA and SimaPro software have been published recently (Ingemarsdotter 2022).

Another recent study on the implementation of LCA and environmental footprint methods in the public procurement stated that the inclusion of LCA-based approaches in the public procurement practice is quite new. In this context, the study also investigated the inclusion of LCC and external cost based on 207 tenders and 17 court cases (Schreiber et al. 2021). eLCC which goes even further by internalizing environmental externalities (Ciroth et al. 2008) and whole life costing (WLC), which additionally includes next to conventional LCC also externalities, non-construction cost, and income (ISO 2008), is mostly not considered (Parikka-Alhola et al. 2012; Cheng et al. 2018; Schreiber et al. 2021). This is especially true concerning the procurement process of buildings. Moreover, the literature identified obstacles to its implementation. These obstacles were classified into five categories, (i) methodological obstacles, (ii) organizational obstacles, (iii) economic obstacles, (iv) legal obstacles, and (v) political obstacles, in a review article on LCA implementation in procurement of buildings (Scherz et al. 2022a). In the current schemes, initiatives to reduce GHG emissions (which might include additional construction cost) are not supported nor encouraged, and there is scarce literature on a possible inclusion of LCA and eLCC in the procurement process of buildings. In particular, the tendering and awarding phases of the process are critical; in the early design steps of a building, the available information concerning the building is incomplete, but the possibility to influence the environmental impacts is the highest (Kohler and Moffatt 2003). The sooner measures to decrease the environmental impacts of a building can be estimated (in the building design process), the more effective it will be, in terms of GHG emissions reduction as much as in terms of cost. The common EU framework level(s), which integrate LCC and LCA in its core-objectives form the early design steps of a building (Dodd et al. 2021), shows first steps of interest in that direction, and that there is much to gain in incorporating eLCC in the procurement process of buildings. Therefore, this article addresses three main research questions:

1. How can GHG emission reduction be influenced by using eLCC within the tendering and awarding of buildings?
2. How high must the shadow price be set to ensure that contracts are awarded to more environmentally friendly bids?
3. What are possible enhancement strategies for residential buildings to move towards a Paris-compatible vision?

To answer these questions, firstly, we used eLCC on a single-family house case study with 37 building scenarios based on LCA and LCC results published in Scherz et al. (2022b). For this first exploratory study, it was decided to focus solely on residential buildings, as they represent a large majority of the yearly GHG emissions from the Austrian building sector (Statistik Austria 2022; Truger et al. 2022). Secondly, we applied the theoretically developed process model, the so-called LCA-based bonus/malus system, for demonstrating an approach to calculate Paris-compatible cost (PCC) scenarios for 37 building scenarios. Thirdly, we analyzed the effects of the level of shadow prices and their influence on the award decision by calculating environmental break-even points.

The novelty of this study stems from the demonstration of an approach to calculate PCC scenarios as criterion for buildings award decisions based on the LCA-based bonus/malus system, which enables the award of contracts according to more environmentally friendly bids. Furthermore, the analyzed shadow prices in the case study under investigation confirm that the current carbon pricing instruments are set too low. This article aims to take a significant step forward in environmental procurement of buildings, in that awarding authorities no longer award contracts on the basis of construction cost, but instead take into account, in particular, the whole life cycle of buildings. This adapted approach to tendering and awarding also encourages bidders to increasingly implement innovative sustainable building projects in order to demonstrate their environmental advantage over traditional tendering and awarding procedures, as well as over other bidders.

2 Materials and methods

The results and findings of this study are based on a developed theoretical framework for considering GHG emissions in building procurement. The aim of this study is to apply the eLCC within the developed framework and to validate them by using a single-family house case study.

2.1 Tendering and awarding process of buildings

In Austria, the Federal Procurement Act can be used as the basis for contracts for the tendering and awarding of buildings. While private clients are not required to apply the Federal Procurement Act, public awarding authorities are required to comply with it. Section 5 of the Federal Procurement Act explains the principles of tendering. With regard to the performance specifications, § 103 stipulates the constructive or functional performance specification (§ 103 Federal Procurement Act 2018).

On the basis of the tender documents within the constructive performance specification, the bidders prepare their main bids by quoting unit prices for each service item. In this type of tender, changes or modifications by the bidders in the tender documents and in the bill of quantities are not permitted. However, the Federal Procurement Act also permits in § 96 the submission of other, better, more innovative or more favorable solutions by bidders in the form of alternative offers that make the existing know-how of the bidders available to the awarding authority (§ 96 Federal Procurement Act 2018). In the case of a tender with a functional performance specification, the awarding authority must define the performance target in accordance with the Federal Procurement Act (§ 103 (3) and § 104 (2)) as well as the suitability criteria, selection criteria (in the case of a two-stage award procedure), and award criteria (§ 103 and § 104 Federal Procurement Act 2018). Based on the defined performance target, the bidders are responsible for the design of the building and the preparation of the main offer, i.e., bill of quantities and unit prices. In this way, innovative ideas and the know-how of the bidders can be taken into account.

In the case study, the tender was based on the functional performance specifications. The prerequisite for such a tender is that the awarding authority formulates a detailed description of the building's performance target.

Furthermore, the award criteria must be defined by the awarding authority. In the course of the case study, it was assumed that only the lowest PCC scenario, i.e., lowest price after applying the LCA-based bonus/malus system, would be used for the award decision. To enable bidders to calculate the GHG emissions and the necessary eLCC, all calculation bases of the LCA, the LCC calculation as well as the shadow price and the carbon price for the results-based climate fund (RBCF) approach must be specified in the tender documents.

2.2 Case study

The case study is a two-storey single-family house, which was already observed in a previous research project Sölkner et al. (2014a, b) and further analyzed in Passer et al. (2016) and Scherz et al. (2022b). For this building, construction companies created 37 different scenarios and determined the bid prices. These 37 scenarios differ in their energetic standard (low-energy house, passive house, plus-energy house), their construction material (brick, concrete, wood-concrete, wood-frame, solid wood), their insulation material (expanded polystyrene (EPS), rock wool, no insulation), and their technical building equipment (pellet heating or heat pump). Figure 1 shows the floor plans and a section of the building as well as the explanation of the defined buildings codes. A detailed description of the case study as well as of the 37 scenarios can be found in the Supplementary Materials and in Scherz et al. (2022b).

2.3 Life cycle assessment–based bonus/malus system for calculating Paris-compatible cost scenarios

The LCA-based bonus/malus system is a theoretical framework for considering GHG emissions in building procurement decisions. The prerequisites for the application of the LCA-based bonus/malus system are (i) an adapted call for tender, (ii) the implementation of the LCA by the bidders as well as the verification of the LCA results by the awarding authority, (iii) the determination of a shadow price and a carbon price for the RBCF approach, and (iv) the establishment of a climate fund. Figure 2 shows the adapted tendering and awarding phase for the application of the LCA-based bonus/malus system.

For the calculation of the PCC scenarios, Eqs. (1) and (2) are used. The index n represents the number of bids.

$$\mathrm{PCC}_n\,[€] = \mathrm{eLCC}_n\,[€] + \mathrm{GHG\ emissions}_{\mathrm{BONUS/MALUS}\ n}\,[€] \tag{1}$$

where

$$\mathrm{GHG\ emissions}_{\mathrm{BONUS/MALUS}\,n}\,[€] = \left(\mathrm{GWP}_n\left[\mathrm{tCO_2\,eq}\right] - \frac{\sum_1^n \mathrm{GWP}}{n}\right) \times \mathrm{RBCF}_{carbon\ price}\,[€/\mathrm{tCO_2\,eq}] \tag{2}$$

In the first step, the awarding authority must define all the information required for a tender in accordance with PCC scenarios in the tender documents. At the beginning, this includes the decision as to whether the tender is to be based on constructive or functional performance specifications. In

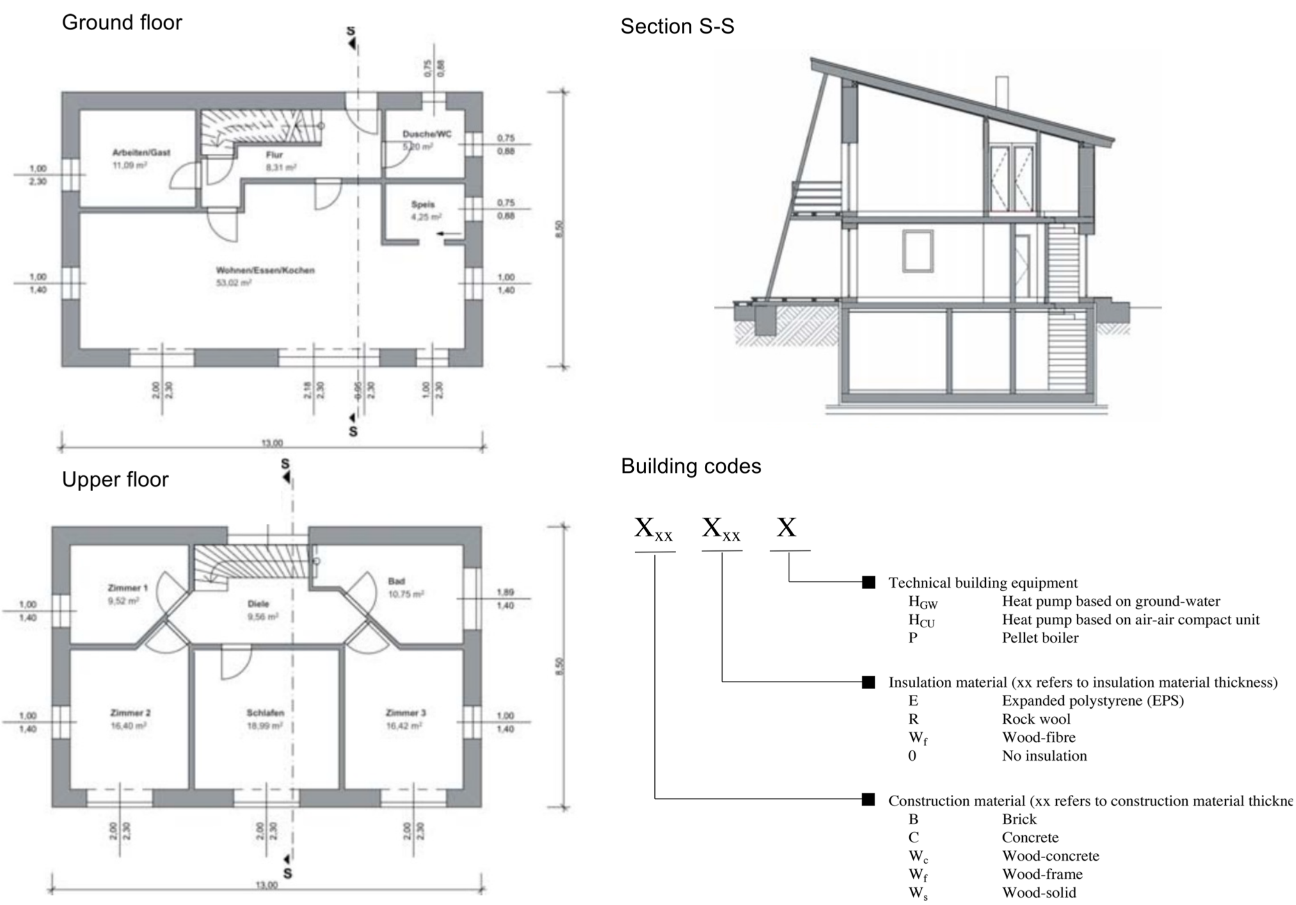

Fig. 1 Floor plans and cross section of the two-storey residential building and explanation of the defined building codes (Sölkner et al. 2014b; Passer et al. 2016; Scherz et al. 2022b)

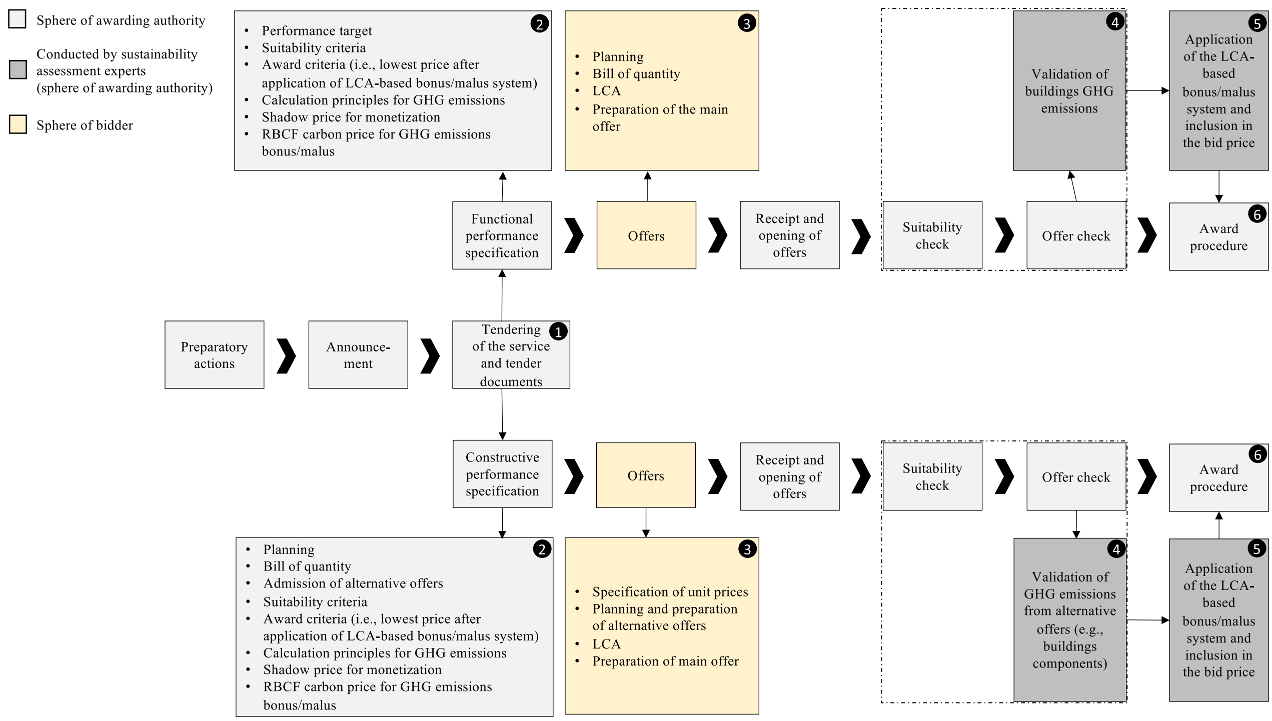

Fig. 2 Theoretical framework of the LCA-based bonus/malus system. Spheres of awarding authorities and bidders for the two tender types (i) tender with functional performance specifications and (ii) tender with constructive performance specifications

case of an award on the basis of a constructive performance specification, the awarding authority must define a precise performance target according to ÖNORM B 2110 (Austrian Standards Institute (ASI) 2013). In addition, suitability criteria, selection criteria (in the case of a two-stage award procedure) and award criteria must be defined. If this procedure is chosen, the awarding authority is responsible for the design of the building and the preparation of detailed bill of quantities, i.e., service items and quantity determination. Since the bidders are not allowed to change the constructive specifications, alternative offers must be permitted in this variant. If the functional performance specification is selected, alternative offers are not required, since in this variant, the bidders are responsible for the performance specifications and determination of quantities.

The second important step, for both performance specification types, is the definition of the principles for the calculation of the PCC scenarios. On the one hand, this means that all the necessary calculation parameters for performing the LCA, such as life cycle modules to be considered, reference study period, databases for background data, calculation software, data sets for energy mix, and service life data must be defined. On the other hand, all calculation parameters for the calculation of the eLCC must also be specified, such as inflation rate, interest rate, price increase rates, and energy prices. Finally, the shadow price and the carbon price for the RBCF approach must also be determined. If the know-how for conducting an LCA is not available within the organization of the bidders, they must seek the assistance of external sustainability assessment experts to conduct the LCA. This issue is particularly relevant for small and medium-sized enterprises, as they may not have the expertise to conduct a LCA themselves. This organizational obstacle can be overcome by using external experts, thus ensuring that the results of the LCA are reliable and credible. Assuming that all information are available and therefore the LCA and eLCC can be carried out, the bidders will prepare their planning including bill of quantities and submit the bids. In the considered case study, 37 valid offers, i.e., 37 different building scenarios, were submitted. After submitting, the offers must be checked for correctness. The awarding authority must also check the results of the LCA and eLCC. For this step, if there is a lack of expertise within the awarding authority, sustainability assessment experts can be consulted, similar to the bidders' sphere, to ensure a transparent and objective verification of the results. After reviewing the bids, the PCC scenarios of the 37 scenarios are calculated using the LCA-based bonus/malus system. For the calculation of the GHG emissions bonus/malus, the mean value of the GHG emissions of all submitted bids is determined (see Eq. (2)). The deviation of the GHG emissions from this mean value is then determined for each bid. If the bid is below the mean value, it is a more environmentally friendly bid, and a bonus is deducted from the bid price by monetization using the defined RBCF carbon price. If the offer is above the mean value, it is a non-environmental offer, and a malus is added to the bid price by monetization using the RBCF carbon price (see Eq. (1)).

2.4 Environmental life cycle costing

Life cycle costing (LCC) can be divided into the three types: (i) conventional LCC, (ii) environmental LCC (eLCC), and (iii) societal LCC (Ciroth et al. 2008). While conventional LCC only includes cost that occurs directly within the life cycle of a product, eLCC includes at least the external cost caused by environmental impacts. Societal LCC goes much further and includes all current and future external cost that can be monetized, such as impacts on, among others, public health, social well-being, job quality, and family life (Bickel and Friedrich 2005).

The term eLCC was first used in a study on the economic evaluation of municipal waste management systems (Reich 2005) in 2005 and derived from the term life cycle inventory-based LCC used by Rebitzer (2005).

The LCC framework for the application within the construction industry is standardized in the EN 16627, EN 15643–4, and ISO 15686–5 (CEN/TC 350 2012, 2015; ISO 2008).

Compared to the ISO 15686–5, which defines LCC for buildings and constructed assets (ISO 2008), the conventional LCC can be understood with the LCC in the narrower sense, which includes the cost groups construction cost, operation cost, maintenance cost, and end-of-life cost. While eLCC only includes external cost of environmental impacts, ISO 15686–5 also defines LCC in a broader sense under the term whole life costing (WLC), which takes into account not only externalities but also non-construction costs and income. Since in this study, only external cost due to GHG emissions calculated by the method of LCA are considered, the method eLCC as defined in Ciroth et al. (2008) is used and is calculated by using Eqs. (3) and (4). The index n represents the number of bids:

$$\mathrm{eLCC_n}\ [€] = \mathrm{LCC_n}\ [€] + \mathrm{External\ cost_n}\ [€] \tag{3}$$

where

$$\mathrm{External\ cost_n}\ [€] = GWP_n \left[\mathrm{tCO_2\,eq}\right] \times \mathrm{shadow\ price}\ [€/\mathrm{tCO_2eq}] \tag{4}$$

The GWP for the 37 building scenarios were calculated by using the LCA method in Scherz et al. (2022b). The method of LCA has become established for evaluating the environmental impacts of buildings. The calculation principles of LCA are defined in standards ISO 14040 and ISO 14044 (ISO 2006a, b). In addition, standard EN 15978 regulates the application of LCA in the construction industry (CEN/TC 350 2011). Detailed description of the system boundaries, the assumed reference study period (50 years), and further assumptions for the LCC and LCA calculations can be found in Scherz et al. (2022b).

2.5 Carbon pricing

Social cost of carbon are used to describe the costs resulting from the impact of emitting an additional ton of CO_2eq on the environment and human health (Nordhaus 2017). These cost are not included in the market prices from products or services and are therefore not borne by the stakeholders directly involved, such as the manufacturers, suppliers, consumers, or users. Social cost of carbon can be determined by various carbon pricing instruments. The two main mandatory carbon pricing instruments are the emission trading system (ETS) and carbon taxes (The World Bank 2021). In Europe, the ETS follows the cap-and-trade principle. Under this system, participating entities are set an upper limit (cap) on their GHG emissions, and allowances are allocated for their emissions. If this limit is exceeded or not reached, certificates can be bought from or sold to other entities (European Commission 2021). Over time, this limit is reduced, resulting in a reduction in emissions. In relation to the construction industry, the major steel, cement, and brick manufacturers, among others, are subject to the European ETS (Environment Agency Austria 2022). Carbon taxes were already proposed in 1973 (Berdik 2014) and have been adopted in some countries since many years (The World Bank 2021). In Austria, a carbon tax of 30€/tCO_2eq was established in 2022 and taxes the import and combustion of fossil fuels. Entities that are already subject to the ETS are exempt from the carbon tax and will not be taxed twice. In Austria, the carbon tax is to be increased to 55€/tCO_2eq by 2025 (International Carbon Action Partnership 2022). In contrast to these mandatory carbon pricing instruments, there are also forms of voluntary carbon pricing instruments. These include RBCF and internal carbon pricing types such as internal carbon fees and shadow prices. In RBCF, target values such as CO_2eq benchmarks for emission reduction are set in advance and usually evaluated by third parties after project completion. Based on the achieved outputs and the defined emission reduction targets, fundings are paid out. The internal carbon fee is an internal monetary value within entities for one ton of CO_2eq. This fee generates revenues, which can then be invested in the entities' emission reduction targets. In contrast, the shadow price is a theoretical price that supports entities in the long-term transition to low-carbon technology. The shadow price is defined as the price that reflects social cost and benefits (Kanbur 1991).

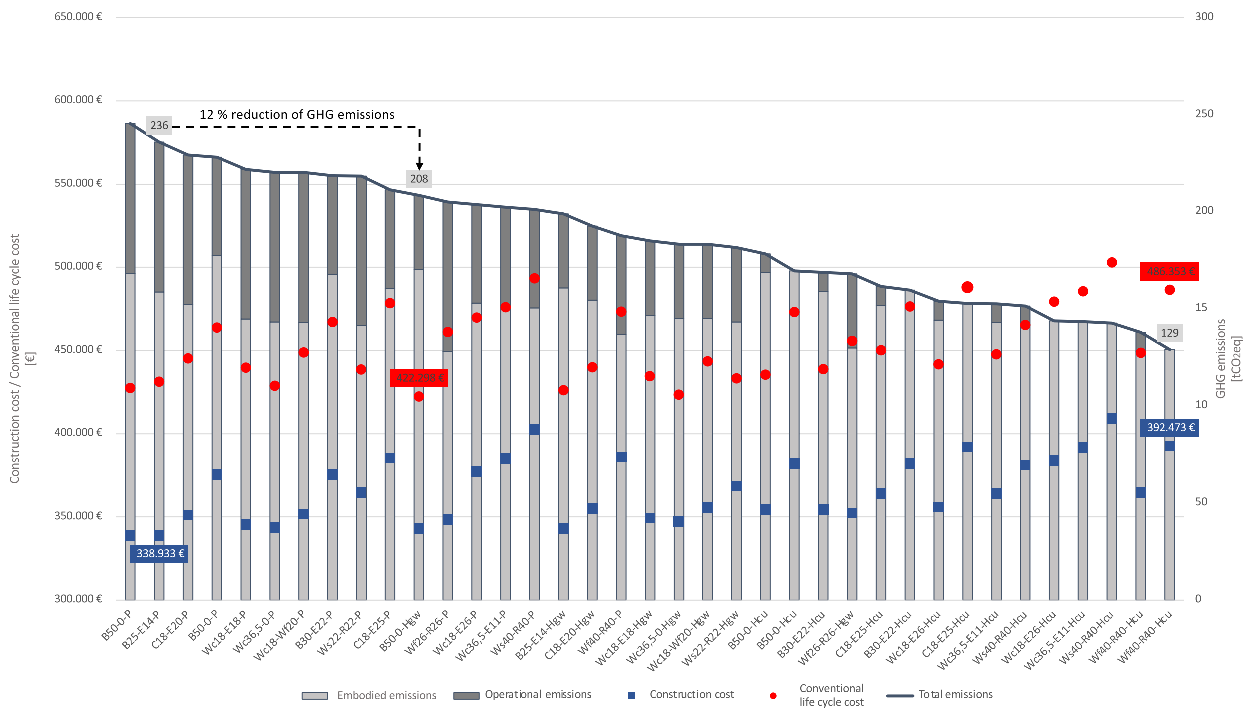

Fig. 3 Comparison of awarding according to construction cost and according to conventional LCC illustrating the GHG emission reduction potential

Studies show that companies mostly apply a higher shadow price than proposed by governments through ETS and carbon taxes (The World Bank 2021).

In order to calculate the external cost, values from the scientific literature were used to define the shadow prices. In the literature, there are already numerous studies on the definition of carbon prices (Rennert et al. 2022; Arendt et al. 2020; CCCA-Experten 2020; Schneider-Marin and Lang 2020; De Nocker and Debacker 2017; Allacker and De Nocker 2012). The defined shadow price range and the RBCF carbon price range set for this study, i.e., 50 €/tCO_2eq to 400 €/tCO_2eq is based on the CCCA experts' factsheet (CCCA-Experten 2020). This initial value of 50 €/tCO2eq is also in line with the European Union average value of carbon prices (The World Bank 2021).

3 Results

3.1 Award based on conventional LCC

The eLCC results of the 37 buildings scenarios build upon the LCA and LCC results published in Scherz et al. (2022b) and are analyzed from the perspective of the award decision. The results of the conventional LCC show that already by considering the application of conventional LCC in the tender documents, their calculation and finally the award according to the lowest conventional LCC bring a reduction of GHG emissions. Figure 3 shows, on the one hand, the total emissions (right axis), i.e., embodied emissions and operational emissions, of the 37 scenarios based on the LCA, ranked in descending order from the scenario with the highest emissions (50-cm brick construction, no insulation material and pellet heating system; B_{50}-0-P) to the scenario with the lowest emissions (40-cm wood-frame construction, 40-cm rock wool insulation, and heat pump system; Wf_{40}-R_{40}-Hcu) and, on the other hand, the construction cost based on the bills of quantities and the conventional LCC (left axis). Additionally highlighted in the figure are the construction cost (written in blue) and the conventional LCC (written in red) of each scenario. An award according to construction cost leads to the acceptance of scenario B_{25}-E_{14}-P (25-cm brick construction, 14-cm EPS insulation, and pellet heating system) with total emissions of 236 tCO_2eq[1] (which is almost the most GHG emitting scenario). In the case of an award based on conventional LCC, scenario B_{50}-0-H_{gw} (50-cm brick construction, no insulation material and heat pump system) with total emissions of 208 tCO_2eq[1] is awarded the contract. This means that, by awarding contracts according to conventional LCC, approximately 12% of GHG emissions can be saved.

[1] The detailed LCA and LCC results can be found in the supplementary materials of Scherz et al. (2022b).

A comparison of awarding contracts according to construction cost and conventional LCC on the basis of the cost difference seems to show that awarding contracts according to conventional LCC results in a higher amount in cost of around 20%. In this context, however, this cost difference cannot be described as an additional cost, since the awarding according to construction cost (338.933 €)[1] does not take into account the operational cost over 50 years. Therefore, in this case, the conventional LCC of the scenario with 25-cm brick construction, 14-cm EPS insulation, and pellet heating system (B_{25}-E_{14}-P) over 50 years is higher than the lowest conventional LCC scenario with 50-cm brick construction, no insulation material, and heat pump system (B_{50}-0-H_{gw}), and the GHG emissions are reduced, which results in a win–win solution. For the maximum reduction in GHG emissions, the award has to go to the scenario with 40-cm wood-frame construction, 40-cm rock wool insulation, and heat pump system (Wf_{40}-R_{40}-H_{cu}). This allows a further 38% reduction in GHG emissions compared to the awarded scenario with 50-cm brick construction, no insulation material, and heat pump system (B_{50}-0-H_{gw}) according to conventional LCC. In this case, however, we are talking about additional cost, since the conventional LCC of the scenario with 40-cm wood-frame construction, 40-cm rock wool insulation and heat pump system (Wf_{40}-R_{40}-H_{cu}) is around 13% higher than the award to scenario with 50-cm brick construction, no insulation material, and heat pump system (B_{50}-0-H_{gw}).

3.2 Award based on environmental LCC

In addition, the GHG emissions savings potential when awarded according to eLCC was investigated based on the 37 scenarios. Figure 4 shows three different eLCCs based on three different shadow prices, i.e., 50 €/tCO_2eq, 200 €/tCO_2eq, and 400 €/tCO_2eq. The results show that at a shadow price of 50 €/tCO_2eq (in yellow on the graph), the cheapest scenario according to eLCC is the scenario with 50-cm brick construction, no insulation material, and heat pump system (B_{50}-0-H_{gw}). Compared to the award according to conventional LCC (see Fig. 3), the award according to eLCC at this defined shadow price does not bring any change in the award decision, and thus no further GHG emissions savings potential. However, if a shadow price of 200 €/tCO_2eq (in green) or 400 €/tCO_2eq (in blue) is set and awarding according to eLCC is used, the scenario with 36.5 cm wood-concrete construction, no insulation material, and heat pump system ($Wc_{36,5}$–0-H_{gw}) is awarded the contract. This means that a further reduction in GHG emissions of around 12% is possible.

Comparing the cost of awarding according to eLCC at a shadow price of 200 €/tCO_2eq and 400 €/tCO_2eq with awarding according to conventional LCC results in additional

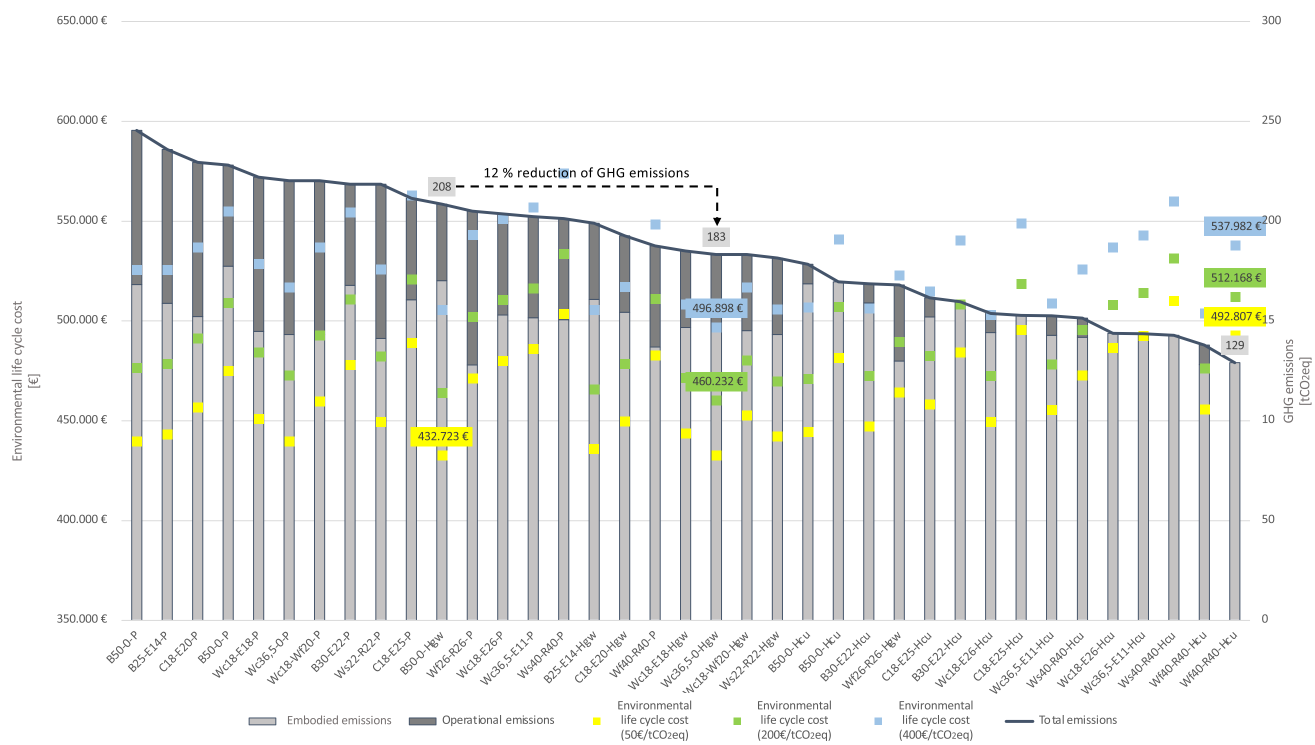

Fig. 4 Comparison of awarding according to eLCC by applying, three different shadow prices (50 €/tCO_2eq, 200 €/tCO_2eq, 400 €/tCO_2eq) and illustrating the GHG emissions reduction potential

cost of 8% and 15%, respectively. Comparing the cost within the eLCC award, there is about 6% additional cost between eLCC at a shadow price of 50 €/tCO_2eq to eLCC at a shadow price of 200 €/tCO_2eq. In order to execute the scenario with 40-cm wood-frame construction, 40-cm rock wool insulation, and heat pump system (Wf_{40}-R_{40}-H_{cu}) with the lowest total emissions, and therefore achieve a GHG emissions reduction of around 38%, an additional cost of 12% is incurred at a shadow price of 50 €/tCO_2eq and when awarded according to eLCC. The additional cost between the award to the lowest eLCC scenario at a shadow price of 200 €/tCO_2eq. and the award to the most environmental scenario with 40-cm wood-frame construction, 40-cm rock wool insulation, and heat pump system (Wf_{40}-R_{40}-H_{cu}) amount to 10% at an achieved GHG emission reduction of 30%. The additional cost between the award to the lowest eLCC scenario at a shadow price of 400 €/tCO_2eq. and the award to the most environmental scenario with 40-cm wood-frame construction, 40-cm rock wool insulation, and heat pump system (Wf_{40}-R_{40}-H_{cu}) amount to 13% also at an achieved GHG emission reduction of 30%.

3.3 Award based on Paris-compatible cost scenarios

In order to reduce the shadow price and still achieve a further GHG emissions reduction, the awarding according to PCC scenarios was introduced. This means that the LCA-based bonus/malus system is additionally applied to the calculated environmental LCC. Figure 5 shows the PCC scenarios at three different shadow prices and carbon prices for the RBCF approach, i.e., 50 €/tCO_2eq. (in yellow), 200 €/tCO_2eq. (in green), and 400 €/tCO_2eq. (in blue).

The results show that awarding by PCC scenarios at a shadow price and RBCF carbon price of 50 €/tCO_2eq results in a different award decision (scenario with 36.5-cm wood-concrete construction, no insulation material, and heat pump system; $Wc_{36,5}$–0-H_{gw}) than awarding by eLCC at a shadow price of 50 €/tCO_2eq. (scenario with 50-cm brick construction, no insulation material, and heat pump system; B_{50}-0-H_{gw}).

Thus, already at this set shadow price and by applying the RBCF approach, i.e., GHG emissions bonus, the further 12% GHG emission savings are achievable. While no further GHG emissions reduction can be achieved with an awarding according to PCC scenarios at 200 €/tCO_2eq, a further GHG emissions reduction of around 25% can be reached with a shadow price and RBCF carbon price of 400 €/tCO_2eq. In this case, the scenario with 40-cm wood-frame construction, 40-cm rock wool insulation, and heat pump system (Wf_{40}-R_{40}-H_{cu}) is awarded the contract.

Comparing the cost of awarding according to PCC scenarios at a shadow price and RBCF carbon price of 50 €/tCO_2eq with awarding according to conventional LCC results in additional

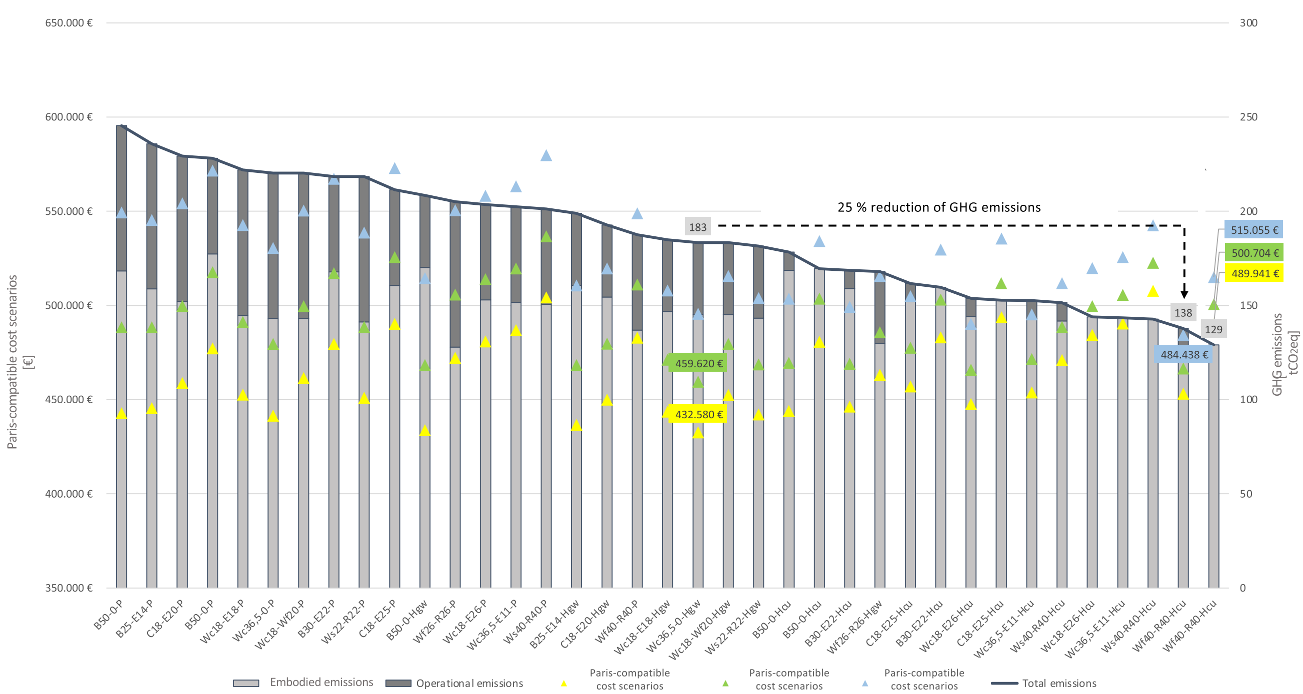

Fig. 5 Comparison of awarding according to Paris-compatible cost scenarios by applying, three different shadow prices and RBCF carbon prices (50€/tCO_2eq, 200€/tCO_2eq, 400€/tCO_2eq) and illustrating the GHG emissions reduction potential

cost of around 2%. Thus, awarding by PCC scenarios at a shadow price and RBCF carbon price of 50 €/tCO_2eq (the scenario with 36.5-cm wood-concrete construction, no insulation material, and heat pump system; $Wc_{36,5}$–0-H_{gw}) compared to awarding by eLCC at a shadow price of 200 €/tCO_2eq (the scenario with 36.5-cm wood-concrete construction, no insulation material, and heat pump system; $Wc_{36,5}$–0-H_{gw}) is about 6% less costly for awarding authorities.

Comparing the cost within the PCC scenarios award, there is about 11% additional cost between PCC scenarios at a shadow price and RBCF carbon price of 50 €/tCO_2eq to PCC scenarios at a shadow price and RBCF carbon price of 400 €/tCO_2eq for achieving a GHG emissions reduction of 25%. Between PCC scenarios award at a shadow price and RBCF carbon price of 200 €/tCO_2eq. and PCC scenarios at a shadow price and RBCF carbon price of 400 €/tCO_2eq, there are additional cost of 5% for the GHG emissions reduction of 25%. In order to execute the scenario with 40-cm wood-frame construction, 40-cm rock wool insulation, and heat pump system (Wf_{40}-R_{40}-H_{cu}) with the lowest total emissions and thus achieve a further GHG emissions reduction of around 7%, an additional cost of 6% is incurred at a shadow price and RBCF carbon price of 400 €/tCO_2eq. When awarded according to PCC scenarios at a shadow price and RBCF carbon price of 50 €/tCO_2eq, an additional cost of 12% is incurred for a GHG emission saving potential of 3%. When awarded according to PCC scenarios at a shadow price and RBCF carbon price of 200 €/tCO_2eq, an additional cost of 7% is incurred also for a GHG emission saving potential of 30%.

The detailed cost calculations for conventional LCC, eLCC, and PCC scenarios can be found in the Supplementary Materials.

3.4 Environmental break-even point and enhancement strategies for residential buildings

The results presented so far were based on the three defined shadow prices and RBCF carbon prices, i.e., 50 €/tCO_2eq, 200 €/tCO_2eq, and 400 €/tCO_2eq. In order to examine the impact of the shadow prices and the RBCF carbon prices in detail, environmental break-even points were identified for the 37 scenarios. The environmental break-even point is the level of the shadow price and RBCF carbon price at which the award decision, i.e., the scenario, changes, and therefore a further GHG emissions reduction, is achieved. For the determination of the environmental break-even point, the shadow price and RBCF carbon price was chosen from 0 €/tCO_2eq to 400 €/tCO_2eq in 1€ increments and applied to both the awarding according to eLCC and the awarding according to PCC scenarios.

Table 1 shows the awarded scenarios by (i) construction cost, (ii) conventional LCC, (iii) eLCC, and (iv) PCC scenarios. For the eLCC and PCC scenarios, the environmental break-even points are highlighted.

For the PCC scenarios awarding, this means that the first environmental break-even point is at a shadow price and RBCF carbon price of 26 €/tCO_2eq. At this price, the award decision changes from the scenario with 50-cm brick construction, no insulation material, and heat pump system

Table 1 Awarded scenarios by (i) construction cost, (ii) conventional life cycle cost, (iii) environmental life cycle cost, and (iv) Paris-compatible cost scenarios. For the environmental life cycle cost and the Paris-compatible cost scenarios, the environmental break-even points are highlighted and their GHG emissions reduction potentials are described[1]

Awarding based on	Cost [€]	Carbon price [€/tCO_2eq]	Scenario	Compared to scenario	Total GHG emissions	GHG emissions reduction potential	Enhancement strategies
Construction cost	338.933		B25-E14-P		236		
LCC	422.298		B50-0-H	B25-E14-P	208	12%	50-cm brick, no EPS insulation, heat pump
eLCC	432.580	50	B50-0-H		208		
eLCC	432.760	51	Wc36,5–0-H	B50-0-H	183	12%	36.5-cm wood-concrete
eLCC	524.947	553	Wc36,5–0-H		183		
eLCC	525.085	554	Wf40-R40-H	Wc36,5–0-H	129	30%	40-cm wood-frame, 40-cm rock wool insulation
PCC	428.063	25	B50-0-H		208		
PCC	428.253	26	Wc36,5–0-H	B50-0-H	183	12%	36.5-cm wood-concrete
PCC	473.320	276	Wc36,5–0-H		183		
PCC	473.455	277	Wf40-R40-H	Wc36,5–0-H	129	30%	40-cm wood-frame, 40-cm rock wool insulation

(B_{50}-0-H_{gw}) to the scenario with 36.5 cm wood-concrete construction, no insulation material, and heat pump system ($Wc_{36,5}$–0-H_{gw}). The second environmental break-even point is at a shadow price and RBCF carbon price of 277 €/tCO_2eq. At this price, the award decision changes from the scenario with 36.5-cm wood-concrete construction, no insulation material, and heat pump system ($Wc_{36,5}$–0-H_{gw}) to the scenario with 18-cm wood-concrete construction, 26-cm EPS insulation material, and heat pump system (Wc_{18}-E_{26}-H_{cu}).

For the eLCC awarding, the environmental break-even points are higher. This means that the first environmental break-even point is at a shadow price of 51 €/tCO_2eq. At this shadow price, the award decision changes from the scenario with 50-cm brick construction, no insulation material, and heat pump system (B_{50}-0-H_{gw}) to the scenario with 36.5-cm wood-concrete construction, no insulation material, and heat pump system ($Wc_{36,5}$–0-H_{gw}). The second environmental break-even point is at a shadow price of 554 €/tCO_2eq. At this shadow price, the award decision changes from the scenario with 36.5-cm wood-concrete construction, no insulation material, and heat pump system ($Wc_{36,5}$–0-H_{gw}) to the scenario with 40-cm wood-frame construction, 40-cm rock wool insulation, and heat pump system (Wf_{40}-R_{40}-H_{cu}).

Based on the results of the calculations, five different types of reduction potentials for residential buildings can be derived within the case study under investigation. Within the first reduction potential in the tender documents, the awarding according to conventional LCC must be mandatory. In this case, it is not necessary to define a shadow price or RBCF carbon price because no external cost are considered within the conventional LCC. With this approach, savings in GHG emissions of approximately 12% can be achieved. Looking at the awarded scenario from a technical point of view, it is evident that in terms of the construction material, there is a change from a 25-cm brick construction with 14-cm EPS insulation material to a 50-cm brick construction without additional insulation material. Regarding the technical building equipment, a change from pellet heating to a heat pump system takes place.

Within the second reduction potential in the tender documents, the awarding according to PCC scenarios must be mandatory. In order to reach the first environmental break-even point, a shadow price and RBCF carbon price of 26 €/tCO_2eq must also be specified. With this approach, savings in GHG emissions of approximately 12% can be achieved. Looking at the awarded scenario from a technical point of view, it is evident that in terms of the construction material, a change from brick to wood-concrete takes place. Regarding the insulation material also in this scenario, no insulation material is necessary. Within the third reduction potential, also the awarding according to PCC scenarios must be allowed. Within this case and in order to reach the second environmental break-even point, a shadow price and RBCF carbon price of 277 €/tCO_2eq must be specified. With this approach, savings in GHG emissions of approximately 25% can be achieved. Looking at the awarded scenario from a technical point of view, the implementation of 40-cm wood-frame construction instead of 36.5-cm wood-concrete construction, the implementation of 40-cm additional rock wool insulation, and also the implementation of heat pump is required.

Within the fourth reduction potential in the tender documents, the awarding according to eLCC must be mandatory. In order to reach the first environmental break-even point, a shadow price of 51 €/tCO_2eq must also be specified. With this approach, savings in GHG emissions of approximately 12% can be achieved. Looking at the awarded scenario from a technical point of view, it is evident that in terms of the construction material, a change from 50-cm brick to 36.5-cm wood-concrete takes place. Regarding the insulation material in this scenario, also no insulation material is necessary. Within the fifth reduction potential, also the awarding according to eLCC must be allowed. Within this case and in order to reach the second environmental break-even point, a shadow price of 554 €/tCO_2eq must be specified. With this approach, savings in GHG emissions of approximately 25% can be achieved. Looking at the awarded scenario from a technical point of view, the implementation of 40-cm wood-frame construction instead of 36.5-cm wood-concrete construction, the implementation of 40-cm additional rock wool insulation, and also the implementation of heat pump is required.

3.5 Tendering and awarding according to Paris-compatible cost scenarios

Table 2 shows the results for each cost type, i.e., conventional LCC, eLCC, and PCC scenarios and its impact on the award decision at a defined shadow price and RBCF carbon price of 277 €/tCO_2eq.

Awarding according to PCC scenarios have implications for the awarding authority not only in terms of the scenario executed, but also in terms of the bid price. However, the additional cost incurred does not have to be covered entirely by the awarding authority, but is subsidized by the GHG emissions bonus if the award is made to a more environmentally friendly scenario. Setting a shadow price and RBCF carbon price of 277 €/tCO_2eq, awarding according to PCC scenarios, would result in a bid price of 486.903 € for the scenario with 40-cm wood-frame construction, 40-cm rock wool insulation, and heat pump system (Wf_{40}-R_{40}-H_{cu}). The bid price is always the price according to environmental LCC, as the PCC scenarios only represent fictitious bid prices for the Paris-compatible vision award.

Table 2 Award decision in case of PCC scenarios awarding based on the LCA-based bonus/malus system at a fixed shadow price and RBCF carbon price of 277 €/tCO_2eq

	Life cycle assessment[b] [tCO2eq]	Conventional life cycle cost[1] [€]	Environmental life cycle cost [€]	GHG emissions bonus/malus [€]	Paris-compatible cost scenarios [€]
B50-0-P	245	431.312 €	496.657 €	13.715 €	510.372 €
B25-E14-P	236	427.549 €	495.537 €	16.358 €	511.896 €
C18-E20-P	229	445.297 €	508.824 €	11.897 €	520.721 €
B50-0-P	228	463.686 €	526.878 €	11.561 €	538.439 €
Wc18-E18-P	222	439.759 €	501.229 €	9.839 €	511.068 €
Wc36,5–0-P	220	428.817 €	489.836 €	9.389 €	499.225 €
Wc18-Wf20-P	220	448.814 €	509.830 €	9.386 €	519.215 €
B30-E22-P	218	467.021 €	527.543 €	8.892 €	536.435 €
Ws22-R22-P	218	438.550 €	499.060 €	8.880 €	507.940 €
C18-E25-P	211	478.419 €	536.974 €	6.925 €	543.898 €
B50-0-Hgw	208	422.298 €	480.050 €	6.121 €	486.171 €
Wf26-R26-P	205	461.045 €	517.841 €	5.165 €	523.006 €
Wc18-E26-P	204	469.867 €	526.270 €	4.772 €	531.042 €
Wc36,5-E11-P	202	476.025 €	532.073 €	4.417 €	536.490 €
Ws40-R40-P	201	493.416 €	549.167 €	4.121 €	553.288 €
B25-E14-Hgw	199	426.061 €	481.169 €	3.478 €	484.647 €
C18-E20-Hgw	193	440.046 €	493.411 €	1.735 €	495.146 €
Wf40-R40-P	188	473.439 €	525.410 €	341 €	525.751 €
Wc18-E18-Hgw	185	434.509 €	485.741 €	-398 €	485.344 €
Wc36,5–0-Hgw	183	423.567 €	474.349 €	-848 €	473.500 €
Wc18-Wf20-Hgw	183	443.563 €	494.342 €	-851 €	493.491 €
Ws22-R22-Hgw	181	433.336 €	483.609 €	-1.357 €	482.252 €
B50-0-Hcu	178	435.509 €	484.912 €	-2.228 €	482.684 €
B50-0-Hcu[a]	170	473.141 €	520.114 €	-4.657 €	515.457 €
B30-E22-Hcu	169	438.842 €	485.576 €	-4.897 €	480.679 €
Wf26-R26-Hgw	168	455.758 €	502.317 €	-5.072 €	497.245 €
C18-E25-Hcu	162	450.241 €	495.007 €	-6.864 €	488.143 €
B30-E22-Hcu[a]	160	476.476 €	520.705 €	-7.401 €	513.305 €
Wc18-E26-Hcu	154	441.690 €	484.304 €	-9.016 €	475.288 €
C18-E25-Hcu[a]	153	487.874 €	530.210 €	-9.293 €	520.917 €
Wc36,5-E11-Hcu	153	447.847 €	490.106 €	-9.372 €	480.734 €
Ws40-R40-Hcu	151	465.238 €	507.201 €	-9.667 €	497.533 €
Wc18-E26-Hcu[a]	144	479.322 €	519.178 €	-11.774 €	507.404 €
Wc36,5-E11-Hcu[a]	144	485.480 €	525.235 €	-11.875 €	513.360 €
Ws40-R40-Hcu[a]	143	502.871 €	542.404 €	-12.097 €	530.307 €
Wf40-R40-Hcu	138	448.721 €	486.903 €	-13.448 €	473.455 €
Wf40-R40-Hcu[a]	129	486.353 €	522.106 €	-15.877 €	506.229 €
	Mean value	Minimum value	Minimum value		Minimum value
	186	422.298 €	474.349 €		473.455 €
Award decision		B_{50}-0-H_{gw}	$Wc_{36,5}$–0-H_{gw}		Wf_{40}-R_{40}-H_{cu}

[a]Scenario is designed in the energetic standard “plus-energy house standard” [b]The detailed LCA and LCC results can be found in the supplementary materials of Scherz et al. (2022b)

As a result, not the bidder with the scenario with 50-cm brick construction, no insulation material, and heat pump system (B_{50}-0-H_{gw}) with the lowest conventional LCC would get the award, but the bidder with the scenario with 40-cm wood-frame construction, 40-cm rock wool insulation and heat pump system (Wf_{40}-R_{40}-H_{cu}). This would subsequently lead to additional cost for the awarding authority of 13% and a GHG emissions reduction of 34% (208 tCO_2eq to 138 tCO_2eq). However, this bid price is reduced due to the application of the LCA-based bonus/malus system. Because the fictitious bid price according to the PCC scenario is 473.455 €, a GHG emissions bonus in the amount of 13.448 € is paid to the awarding authority by a climate fund (RBCF approach), reducing the additional cost to 11%. If the scenario with 50-cm brick construction, no insulation material, and heat pump system (B_{50}-0-H_{gw}) was to be awarded the contract, the bid price to be paid would be 480.050 € at a shadow price and RBCF carbon price of 277 €/tCO_2eq. In addition, the awarding authority would have to pay a GHG emissions malus in the amount of 6.121 € to the climate fund.

4 Discussion

Although the EU directive (European Parliament 2014) and the Federal Procurement Act in Austria (Federal Procurement Act 2018) allow the awarding based on the most economically advantageous tender (MEAT) and also explicitly mention the implementation of LCC and external cost based on LCA. However, in practice, building procurement is still based on price (Cheng et al. 2018). The results of this study show that with an adapted tendering and awarding procedure, GHG emissions can be reduced. By awarding contracts on the basis of conventional LCC instead of construction cost, up to 12% of GHG emissions can be reduced in the first step within the analyzed case study. This GHG emissions saving is achieved within the 37 scenarios with the application of heat pump systems instead of pellet heating systems. This is a reasonable strategy and therefore seems to be advisable for future residential buildings as well (Borge-Diez et al. 2022; Nematchoua et al. 2022). Nevertheless, it has to be mentioned that this result however strongly depends on the carbon content of the local electricity mix. However, the literature shows that the mandatory requirements of conventional LCC calculation in the tender as well as the awarding according to the lowest conventional LCC in the award phase are not applied in the current procurement practice. In this context, only a few studies analyze the implementation of conventional LCC in the building procurement process (Khalil et al. 2021; Lim et al. 2018; Dragos and Neamtu 2013).

Further GHG emissions reduction potential can be achieved by awarding contracts according to eLCC. Depending on the level of the shadow price (i.e., 50 €/tCO_2eq, 200 €/tCO_2eq, 400 €/tCO_2eq), GHG emissions savings of up to 23% compared to the awarding according to construction cost can be achieved within the 37 scenarios considered. In addition to the prerequisite that the awarding of contracts according to the lowest eLCC must be anchored in the tender documents, the implementation of LCA (calculation of embodied and operational emissions) must also be required, as the GHG emissions of the building scenarios are necessary for the calculation of the external cost. For this purpose, all calculation principles and databases to be used must also be specified in the tender documents (Lützkendorf 2021). It seems necessary to consolidate sustainability assessment experts, i.e., LCA and LCC experts, in order to be able to check the offers correctly. It has to be mentioned that solely the involvement of sustainability assessment experts does not solve the problem, but we are convinced that this measure is a necessary important step to implement and ensure more environmentally friendly procurement of buildings in the future. Similar to LCC implementation, there are only a few studies on the implementation of LCA in current procurement practices (Francart et al. 2019; Vidal and Sánchez-Pantoja 2019; Fuentes-Bargues et al. 2017; Ng 2015; Du et al. 2014). This is also confirmed by a recent study commissioned by the European Commission, which analyzed 207 tenders and 16 court cases for the application of LCA-based criteria in the procurement process (Schreiber et al. 2021). Moreover, the literature identified obstacles to its implementation. These obstacles were classified into five categories, (i) methodological obstacles, (ii) organizational obstacles, (iii) economic obstacles, (iv) legal obstacles, and (v) political obstacles, in a review article on LCA implementation in procurement of buildings (Scherz et al. 2022a).

Finally, a shadow price must also be determined for the calculation of the eLCC. In this context, the literature discusses starting values for carbon prices or ranges for carbon prices (Rennert et al. 2022; Arendt et al. 2020; Schneider-Marin and Lang 2020; De Nocker and Debacker 2017; Allacker and De Nocker 2012). In this context, particular attention must be paid to a precise use of terms within the carbon pricing instruments (carbon tax, ETS, crediting mechanism, RBCF, shadow price, internal carbon fee) and to the avoidance of double-accounting. As mentioned in the introduction section the eLCC is based on shadow prices. For instance, the World Bank Group has signaled intentions to implement shadow prices, in consistence with the high-level commission recommendations on carbon prices, on relevant investment projects (Carbon Pricing Leadership Coalition 2018). Additionally, besides to the shadow prices within the LCA-based bonus/malus system, a RBCF approach is applied. The shadow prices and the RBCF carbon prices assumed in this study are based on literature values (CCCA-Experten 2020) as well as on the European Union average value of carbon prices (The World Bank 2021).

The results show that the application of the defined shadow price range and RBCF carbon price range lead to a change in the award decision. A detailed examination by calculating the environmental break-even points shows that these values fit well into the existing literature (Rennert et al. 2022; The World Bank 2021). Although the defined shadow prices also lead to a change in the scenarios when allocated according to eLCC, they are in the upper range compared to the literature values. For this reason, the LCA-based bonus/malus system was developed. By combining this RBCF approach, i.e., the GHG emissions bonus/malus, and the eLCC, an approach to calculate so-called PCC scenarios is demonstrated. A bonus (lower GHG emissions than the mean value of all GHG emissions of the submitted scenarios) is deducted, or a malus (higher GHG emissions than the mean value of all GHG emissions of the submitted scenarios) is added to the eLCC. The same GHG emissions reduction, i.e., 12% or 25%, can be achieved with the awarding according to PCC scenarios, but at a lower shadow price and RBCF carbon price, i.e., at 26 €/tCO_2eq and 277 €/tCO_2eq.

The importance of this research direction is also underlined by the development of the Carbon Risk Real Estate Monitor (CRREM). This tool assists real estate owners in reducing operational emissions from existing properties (Wein et al. 2022). Similar to the concept of the LCA-based bonus-malus system, the idea of CREEM is to provide Paris-compatible pathways to achieving our climate goals. While CREEM focuses on the current building stock and takes into account operational emissions, the proposed LCA-based bonus/malus system aims to encourage more environmentally friendly procurement decisions for new buildings based on a whole life cycle perspective, i.e., embodied and operational emissions. However, it can also be used for tendering and awarding refurbishment projects.

4.1 Critical remarks

Awarding contracts according to conventional LCC, eLCC, or PCC scenarios requires mandatory consideration and implementation of LCA and LCC in the tendering and awarding phase of buildings. However, the use of these two methods at this early stage of projects involves a number of obstacles. On the side of the awarding authorities, the complete and transparent specification of all requirements for the implementation of LCA and LCC in the tender documents has to be stated. Furthermore, it is necessary to ensure the correct verification of the offers in order to guarantee the comparability of the offers. In this context, and also for the preparation of the tender documents, sustainability assessment experts will have to be consulted in the future. While the choice of a functional performance specification allows bidders to include their own innovative ideas into projects, the choice of a constructive performance specification must allow alternative offers in order to generate GHG emissions reduction potential. On the bidder's side, the additional time and cost involved in preparing a bid have to be mentioned. In order to remain marketable and competitive in the adapted tendering and awarding process, know-how in the field of sustainability assessment must be generated.

Since the implementation of LCA and LCC in the tendering and awarding process is currently not mandatory, in this context, the next step towards Paris-compatible buildings must first be taken by the awarding authorities as well as the policy-makers. However, the application of the LCA-based bonus/malus system and thus the awarding of contracts according to PCC scenarios show promising GHG emissions reduction potential and thus represent an innovative and sustainable framework for an adapted procurement process. Due to a lack of data, i.e., emission pathways for different building types to achieve the Paris climate goals, it was not possible to show a detailed distance-to-target deviation in terms of GHG emissions from residential buildings. Therefore, the calculated PCC scenarios are only a first approach to determine future cost scenarios for Paris-compatible buildings and for the achievement of the Paris climate targets. To determine real PCC scenarios, detailed shadow prices and RBCF carbon prices based on specific emission pathways for individual building typologies must be implemented in the LCA-based bonus/malus system. A recent study modelled the embodied carbon cost of the domestic building stock and investigated carbon reduction interventions (Drewniok et al. 2023).

With regard to the different building typologies, it should be emphasized that the developed LCA-based bonus/malus system and thus the awarding according to eLCC or PCC scenarios can be used for all building typologies. In this study, we validated the LCA-based bonus/malus system only on a single-family house. However, the prerequisite for its application is that the Federal Procurement Act is used as the basis for the tendering and awarding process, and the willingness to pay for the GHG emissions based on shadow prices and RBCF carbon prices. For other building typologies, it is expected that the identified GHG emissions savings potentials, as well as the environmental break-even points, will be different than in the case study examined. Awarding based on PCC scenarios is particularly useful for awarding authorities that are also users of the buildings, as external cost based on GHG emissions are taken into account. It is also worth mentioning that prices for awarding authorities may increase. In this context, the investor-user dilemma should be pointed out. If the investor is not the user, the investor will endeavor to seek an award based on construction cost. If the investor is also the user, in the case study under consideration, there are no additional cost when awarding according to conventional LCC. Although the conventional LCC are 20% higher than the construction cost, this cost difference cannot be described as an additional cost, since the awarding according to construction cost does not take into account the operational cost over 50 years. When applying eLCC, the additional cost amount to 2 or 20% compared to awarding according to conventional LCC. When applying the LCA-based bonus/malus system and awarding according to PCC scenarios, the additional cost compared to conventional LCC amount to between 1 and 11%. However, even if the user is not the awarding authority, the abatement cost for more environmentally friendly buildings should be borne by both the awarding authority and the users, and not by the rest of society. Regarding the production and construction phase of buildings, it does not matter whether prefabricated buildings elements or on-site construction is used for the application of the LCA-based bonus/malus system. Emissions from both prefabricated and on-site construction must be taken into account. In the case of prefabricated building elements, this can be done with environmental product declarations (EPDs), which include the production process, or bidders who offer prefabricated building elements must evaluate their production processes accordingly within the offer.

Additionally, the implementation of the climate fund needs to be examined in detail. In particular, the start of the climate fund needs to be discussed, as there needs to be a starting amount before the climate fund is further filled with the GHG emission malus from projects.

Finally, it should be mentioned that when awarding contracts according to conventional LCC, eLCC, or PCC scenarios, only price has to be specified as an award criterion, which may be advantageous in future award procedures, since in practice the procurement of construction services is still based on price. Nevertheless, it is not our intention to limit the award of contracts to price alone. It is also possible to define and weight other award criteria in addition to price. For example, when awarding contracts according to conventional LCC, eLCC, or PCC scenarios, other award criteria can also be used, such as professional qualification of key personnel, optimization of the construction and/or operating phase, employees over 50 years of age and employment of trainees, reduction of transport kilometers and truck transports, and extension of warranty.

4.2 Limitations

Although the application of the LCA-based bonus/malus system and thus the calculation of PCC scenarios area feasible for all building types, it was only validated on the basis of the underlying case study. This means that it has currently only been applied to residential buildings and further investigation of multi-storey residential buildings, as well as non-residential buildings, is needed. This is of particular importance because private awarding authorities can currently use the process model only if they use the Federal Procurement Act as a basis for their contracts. However, in practice, private buyers in general do not use the Federal Procurement Act as a basis for their contracts. Nevertheless, the objective of the study was to validate the developed process model by means of a case study and to investigate how shadow prices and RBCF carbon prices have to be set in order to achieve a change in the awarding process. Since 37 tender variants were developed for the single-family house in the course of a research project, this case study corresponds to reality from the perspective of the practical process flow, which allowed the validation of the process model in the most appropriate way.

Additional strategies and emerging technologies, which could further reduce the GHG emissions towards Paris-compatible buildings, such as carbon capture and storage or fast-growing bio-based materials (Alaux et al. 2022), could also be included in future calculations.

Further limitations arise from a methodological point of view. The PCC scenarios consist of the eLCC and the LCA-based bonus/malus system. eLCC includes next to construction cost, operation cost, maintenance cost and end-of-life cost, and only external cost. Other cost types like non-construction cost and income, as suggested within WLC or other external cost as proposed within societal LCC, are not considered. In this context firstly, this study only considers external cost within the eLCC. Secondly, the external cost do not include all environmental indicators, but only the environmental indicator GWP in t/CO_2eq which is monetized with shadow prices. Thirdly, conventional LCC and eLCC calculations are based on assumed calculation parameters such as inflation rate, interest rate, price increase rates, or energy prices. These calculation parameters are dynamic over time and always subject to uncertainties. Especially in times of crisis, such as the COVID crisis and the Ukraine-Russia conflict, the parameters deviate strongly from literature values and expected developments. In this study, calculation parameters were assumed that were common before the aforementioned crises. Sensitivity and uncertainty analyses (e.g., with Monte Carlo Simulations) would provide even more detailed insights into the results and would minimize uncertainties in decision-making. However, in this study, we chose only fixed initial values for the calculation parameters within the conducted assessments and did not vary them in increments within a defined range.

5 Conclusions

Rising GHG emissions keep forcing climate change and are increasingly turning into a significant global challenge. For global warming to be kept below 1.5 °C by 2050, the amount of remaining carbon budget globally is estimated to be 400 billion tons of CO_2 (IPCC 2022). Contributing 37% of global GHG emissions, one of the leading emitters is the construction industry (UNEP 2021).

This negative trend is reinforced by increasing urbanization. Due to the increasing population in cities, about 60% of the buildings worldwide have to be built first. This implementation of new buildings must therefore be tendered and awarded, making an adaptation of the building procurement process an important lever for GHG emissions reduction. In this study, we therefore adapted the tendering and awarding process and analyzed the differences in the award decisions based on the awarding according to conventional LCC, eLCC, and PCC scenarios. By applying a developed LCA-based bonus/malus system, the applied level of shadow prices and RBCF carbon price was reduced. Finally, based on the changes in the award decisions, enhancement strategies for residential buildings were derived to contribute to the achievement of the Paris goals.

In summary, the findings show that an award based on conventional LCC results in a reduction of GHG emissions. This reduction in GHG emissions can be further increased by awarding contracts based on eLCC. The calculation of environmental break-even points has shown that the shadow prices used in the eLCC are too high compared to the literature. For this reason, the LCA-based bonus/malus system was applied to calculate PCC scenarios. By using PCC scenarios, the same GHG emissions reduction can be achieved as with the eLCC, but at a significantly lower shadow price and RBCF carbon price.

From a technical point of view, using wood-concrete and wood-frame construction instead of brick as construction material seems to have the most potential to reduce GHG emissions, among the residential building scenarios. In addition, it shows that the installation of heat pumps instead of pellet heating brings another environmental advantage.

In conclusion, it must be mentioned that the results of our study are of great importance for the further reduction of GHG emissions in the construction industry. Based on the case study under consideration, we show a GHG emissions reduction of 12 to 42% for residential buildings by adapting the procurement process. Taking into account the huge amount of newly constructed buildings, this reduction can be multiplied by a factor of several times.

Especially for awarding authorities, which can take an exemplary role in a first step, the application of eLCC and the LCA-based bonus/malus system is a good possibility to contribute to the achievement of the Paris climate goals. In a second step, the theoretical framework of the LCA-based bonus/malus system and the validation based on the case study will make policy-makers aware of necessary adjustments in the current procurement practice of buildings.

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

Declarations

Conflict of interest The authors declare no competing interests.

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