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Challenges in benchmarking whole-life GHG emissions from renovation cases: Evidence from 23 real-life cases

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ABSTRACT

While political initiatives focus on energy efficiency to reduce greenhouse gas emissions (GHGe), there is currently a lack of knowledge about GHGe from energy-efficiency measures versus other renovation measures. Recognizing the multitude of purposes and functions in play within real-life renovations is central to the ongoing development in benchmarking and regulating the life-cycle GHGe of building projects, to ultimately limit emissions from the growing number of renovation projects. This study therefore investigates lifecycle-based GHGe from the multitude of changed functions in 23 real-life cases of renovation and considers how the results contribute to discussions on benchmarking renovation projects. The results show that, from a lifecycle perspective, energy efficiency actions in renovation produced operational savings of around 50 % from 13.5 kg CO_2-eq/m^2/year to 7.0 kg CO_2-eq/m^2/year on average, indicating the significance of reducing the energy demand of buildings. The material-related, embodied GHGe contributed to an average of 2.8 kg CO_2-eq/m^2/year in the 23 renovation cases. A remarkable 54 % of these lifecycle-embodied impacts from the renovation cases are associated with other functions than energy efficiency, such as spatial adjustments, changes in interior layout, or the construction of balconies. The results contribute to discussions of three benchmarking approaches suggested in literature. First, single benchmarks for the whole building. This approach does not encompass the large variation in impacts and functions that are showcased in the renovation cases. Second, benchmarks on a smaller scale, such as building elements. This approach can be explored further, and the study provides pointers to the significance of different elements. Finally, benchmarks based on GHGe "savings" from energy reductions. The approach only considers one function and not the significance of the multitude of other functions added in renovation projects.

1. Introduction

In Europe buildings contribute to 40 % of final energy consumption and account for almost the same share of energy-related greenhouse gas emissions (GHGe) [1]. For that reason, initiatives such as the "renovation wave" in Europe have been developed with the goal of reducing the operational energy use of existing buildings [2]. The renovation follows the circular economy principles by 2030, resulting in 35 million buildings being renovated by this time. Thus, the revised Energy Performance of Buildings Directive (EPBD) includes initiatives to reduce the energy needs of existing buildings [1]. The initiative is related to the European "green deal" and the European climate law, which aims to achieve a climate-neutral EU by 2050 [3,4].

However, optimizing the energy performance of existing buildings will entail additional embodied emissions, thereby reducing the remaining global carbon budget outlined by the IPCC. These embodied emissions are related to the manufacture, transport, replacement, etc. of the materials added in renovation projects. The revised EPBD suggests including whole-life carbon declarations from new constructions and renovations, thus considering both embodied and operational emissions over the building's life-cycle [1]. Whole-life carbon is typically determined through the standardized life-cycle assessment (LCA), which is commonly used to assess the environmental impacts of buildings [5]. A growing number of scientific publications have been focusing on the LCA of building renovations, usually with a focus on improving their energy performance [6,7]. In case studies where LCA is carried out, the improved energy performance typically results in net environmental and GHGe savings over the building's life-cycle [7–11]. These GHGe savings

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have shown to be possible for a variety of existing types of energy performance and building [12]. The most significant GHGe savings have been found by improving the thermal insulation level of the building envelope [13]. To optimize the performance of insulation, the material types and thickness of insulation in renovation has been studied in the existing literature [14–17]. Furthermore, upgrades of the heating system have shown significant savings [18,19]. A change in the heating system can significantly influence the operational impacts, and thus the overall performance of the renovation project [15,18,19]. Several other research studies have investigated the life-cycle efficacy of GHGe reductions in large-scale roll-outs of building stock renovations on the urban [20–22], national [23,24] and European scales [25–27]. These stock-based studies typically investigate the technical options for improving the energy efficiency of the building stocks under investigation.

However, an important limitation on the transferability of these studies into real life is that building renovations are typically characterized by a multitude of additional criteria and desired functions aside from the technical focus on energy performance [28,29]. For instance they may be related to accessibility, spatial organization, or aspects of comfort other than thermal comfort [28,30]. Previous studies have indicated the significance of these emissions. For example, the contribution from fitting out offices has been shown to contribute 12–15 % of the initial embodied impacts [31], and in a larger renovation case study, Hasik et al. [32] found that finishes contributed to 40 % of GHGe, mostly from new access floors inside the building. However, the lack of knowledge about the life-cycle impacts of energy-efficiency measures versus measures for these other functions in real-life renovations constitutes a research gap for informed decision- and policy-making.

In parallel to the increased focus on renovations, ongoing policy development deals with performance evaluations and the benchmarking of buildings. Benchmarking whole-life carbon for new construction and renovation is recommended as a way to achieve net zero emissions [33]. Lifecycle-based GHGe have already become a part of building regulation in countries such as Denmark, France, Sweden and Finland, where some countries use benchmarks as minimum requirements in regulation [34]. Benchmarks can be based on either a bottom-up approach from, for instance, statistically derived data from selected buildings, or follow a top-down approach based on, for example, political targets [35]. Benchmarks related to renovation are less frequent than in new construction and have been defined as both a value equal to new construction, and a different lower value [36]. For renovation projects, it has also been suggested that benchmarks be used for building elements instead of whole building projects, and to make the benchmarks based on the relation between the project's embodied emissions and operational savings [37].

1.1. *Aim of study*

Benchmarking renovation can be complicated due to the different renovation actions and the functional qualities of renovation projects. While the focus in most policy initiatives is on energy-efficiency actions, the nature of adapting existing buildings is not solely related to energy efficiency, but also to, for example, structure, interior design, occupant comfort etc. [30]. However, little is known about the actual impacts from a larger number of renovation cases, and what emissions are related to energy reduction and other added functions. Therefore, the aim of this study is to investigate the lifecycle-based GHGe from the multitude of renovation actions in a larger sample of real-life cases of renovation, using the Danish context as an example. Specifically, this study investigates:

1. What is the contribution of life-cycle embodied and operational GHGe in real-life cases of renovation?
2. How much of the life-cycle embodied GHGe is caused by renovation actions specifically to reduce operational energy consumption in real-life renovations? And which building elements are of greater significance?
3. How do the insights from the cases contribute to discussions about different types of life-cycle GHGe benchmarks?

2. Methods

This study of the GHGe of different renovation actions is based on 23 real-life cases in Denmark. The renovation actions are categorized into different provided functions, resulting in a unique overview of which functions the renovation actions contribute to and the lifecycle GHGe associated with providing these functions.

2.1. *Renovation cases*

For the study, 23 cases of renovation have been collected with the purpose of showcasing the variation in GHG emissions of real-life renovation cases. The selection of cases is random, which therefore avoids systematic biases [38]. However, due to their sources, the cases represent a renovation subgroup of mainly larger renovations. The cases originate from three different sources: the sustainable certification scheme used in the Danish construction industry "DGNB" [39], cases collected from social housing projects, and other larger renovation projects that have been collected. Out of 23 cases, 21 of them are considered major renovations based on the building directive that defines major renovation as a change in more than 25 % of the surface of the building envelope [1]. This is because certification is typically only done on large renovation cases.

The cases represent a variation of building types and types of intervention in renovations, which are described in Table 1. They vary from complete conversions of the function of the building to only smaller energy-reduction actions. Details of the renovation actions are listed in Table 1. The cases consist of fifteen residential buildings, four offices, and one each in the categories of culture, hotel, hospital and institution.

2.2. *LCA procedure*

The LCA has been performed in compliance with the standards for LCA on buildings, EN 15978 [5]. Impacts from new materials are included in the assessment, following the burden-free approach for existing materials [40]. The lifecycles stages included are production (A1-3), replacements (B4), and waste-processing and disposal (C3 and C4). Emissions from replacements are based on the service lives of buildings [41], with a reference study period of fifty years. The assessment is focused on the impact category of "global warming potential" due to political awareness.

Results are shown in the same unit, as is standard in climate declarations for new constructions and current practice for renovation projects [42] nationally. This is done to showcase the results in the conditions in which they are currently being evaluated and compared. The unit is "kg CO_2-eq/m^2/year" with reference to the fifty-year reference study period. The area used is the gross floor area for embodied impacts and the heated gross floor area for operational impacts. For cases where the area is added or removed during renovation, the area after renovation is used, in compliance with current practice.

2.2.1. *Inventory for cases*

The data reported by the data provider has been used for the building inventory such as drawings and descriptions or final inventories. The building parts included in the inventory consist of foundations, the ground floor slab, external walls, roofs, windows and doors, internal walls, floor decks, stairs and ramps, columns and beams, balconies and building services (water, ventilation, heating and cooling). This scope is respected across all the building cases, ensuring consistent comparison.

The operational energy used is made up of the energy-demand calculations from the buildings from heating, cooling, ventilation and hot

Table 1
Description of renovation cases.

Code	Building type	Decade of original construction	Gross floor area [m^2] (span)	Conversion*	Description
C1	Cultural house	1970	1000–5000	Conversion of production building into cultural building for sports, music etc.	Change of interior layout. Insulation of part of the ground floor slab and roof. Replacing and adding windows.
O1	Office	1960	0–200	Conversion of production building into office	Change of interior layout. Insulation of ground floor slab, roof, and external walls. Adding new windows. Adding new building services for heating and water.
O2		1960	5000–10,000		Change of interior layout. Insulating roof and some external walls, replacing and adding new windows. Outside terrace. New building services for heating and cooling
O3		1950	10,000–20,000	Conversion of education building into offices and retail	Change of interior layout. New façade, and insulation of roof. New roof terrace. New building services for water and ventilation.
O4		1970	10,000–20,000	Conversion of a post office into offices and sport facilities	Change of interior layout. Adding new floor area and terrace on the roof. Insulation of external walls and roof. Adding new windows.
H1	Hotel	1880/1960	10,000–20,000	Conversion of production building into hotel	Adding floor area and terrace on top of the existing building. New interior layout. Insulation of roof. Replacing and adding windows. Structural support of the building. Replacing and adding building services for water, heating, and ventilation.
Hos1	Hospital	1980	5000–10,000		Change of interior layout, new roof, and new double-skin façade. Adding windows. Replacing building services for heating and ventilation.
I1	Institution	1910	1000–5000	Conversion of an education building into childcare facilities	Change of interior layout, insulation of external walls and roofs, new ground floor slab, and replacement of windows. Adding roof terrace. Painting after sanitation. Replacing and adding building services for water, heating, and ventilation.
R1	Residential, single family	1960	0–200		Change of interior layout. Replacement of ground floor slab and some exterior walls. Insulation in the roof, and replacements of windows. Replacing and adding building services for water, heating, and ventilation
R2	Residential, terraced houses	1990	1000–5000		Some changes in interior layout. Replacement of windows. Replacing roofing material.
R3		1960	200–1000		Some changes in interior layout. Replacement of some of the foundation and columns in facade. Insulation of external walls, replacement of ground floor slab, and replacement of windows. Replacing and adding building services for water, heating, and ventilation
R4		1970	200–1000		Reducing the building area on the 1. floor. Combining apartments and changing layout. New balcony. Insulation of exterior walls and roof, and replacement of windows. New pergola outside. Replacing and adding building services for water, heating, and ventilation.
R5		1970	1000–5000		Changing layout in some apartments. Insulation of external walls, and replacements of windows. Replacements of balconies. Replacing roofing material. Replacing and adding building services for heating and ventilation.
R6		1980	200–1000		Changing some internal layout and modernization including fire sections. Replacement of ground floor slab. Replacing and adding building services for water and ventilation
R7	Residential, multifamily	2000	10,000–20,000	Conversion of an office building into student housing	Change of interior layout, new balconies, and replacement of windows. Replacing building services for water, heating, and ventilation.
R8		1940	1000–5000		Changing layout in some apartments, replacing balconies, insulation of end walls, and new windows. Replacing building services for heating and ventilation
R9		1990	1000–5000	Partial conversion: Conversion of garages into a common house.	Combining and changing sizes of apartments. Expansion of some balconies. Insulation of roof and external walls, New windows. New building services for heating and ventilation
R10		1972	>20,000**		Insulating external walls and roof and ceilings facing unheated area. New windows. Expansion of balconies. Increase acoustics in slabs. New open façade at staircases.
R11		1950	5000–10,000		Change of layout in some apartments. Insulation of external walls, and new windows. New balconies. Adding some building services for heating, and ventilation.
R12		1940	1000–5000		Combining apartments, insulating external walls and roof, and new windows. Replacing and adding building services for water, heating, and ventilation
R13		1930	200–1000	Conversion of attic into dwellings	Adding penthouses with balconies on top of the existing building. The renovation only considered the penthouses.
R14		1900	1000–5000	Conversion of a cultural building into a residential building	Change of interior layout. Replacing and adding windows to improve daylight. Adding PV panels.
R15		1890	1000–5000		Adding floor area on top and on one facade to expand existing apartments and improve daylight. Change of interior layout. New windows. Improving acoustics in floor slabs. Adding balconies.

* Changing the function of the building. Based on the definition in [30].

** Consists of several stand-alone buildings.

water following the Danish building regulations [43]. The energy demand for lighting is also included in all other buildings than residential ones. The energy demand after renovation has been available for fifteen of the 23 cases, whereas the energy demand before renovation has been available for seven cases. The energy demand is calculated based on the heated floor area after renovation. For the seven cases with data on energy demand before renovation, the same floor area was used.

2.2.2. Environmental data and calculation tool

For the calculations, the Danish national tool for LCA on buildings, “LCAbyg”, is used [44–47]. LCAbyg uses environmental data that is considered representative of Denmark. It consists of generic data from the German *Ökobaudat* database [48], and some environmental product declarations (EPDs). Additional EPDs for specific products have been added in each case. All data follow EN15804 [49]. Emissions from the Danish national energy system are used for the operational energy emissions [50], data that includes the projected decarbonization of the energy system based on political targets at the time they were created.

2.3. Categorizing functions in renovation

A renovation project can add new functions or provide improvements to existing functions, such as improving the thermal insulation properties of the building to reduce energy use. Though energy reduction can be a large focus in renovation cases, new materials are also installed to provide other functions than energy efficiency. The categorization can therefore be used to show whether there are significant emissions from other functions than energy reduction in real-life renovation cases. The trends found in the Danish cases will likely be similar in many other settings where buildings require upgrades in functionality.

Table 2 lists the functions used in this study to categorize the emissions from the different renovation actions in the different cases. The list is based on functional demands from the Danish building code [43]. Additionally, the list also includes the functions *spatial* and *balcony*. The first is added to show the emissions from increasing or reducing the building floor area, while the latter is added to show emissions from adding balconies, as this was included in several of the cases.

Table 2
List of functions added in the renovation.

Renovation function	Description
Spatial	Components that are added to increase or reduce the floor area of the building.
Layout	Components that are added or changed due to changes in the interior layout. Includes new floor and ceilings even if this could be due to the end of service life, for aesthetic reasons etc.
Energy reduction	When a component in the building envelope is replaced or insulated or, e.g., ventilation systems are replaced to reduce energy use and the hot water tank is also replaced.
Indoor climate	E.g. introducing mechanical ventilation or floor heating, if this was not there before.
Fire	Components added or changed to comply with the building code on fire safety.
Structural	Components added or changed to comply with the building code on load-bearing structures.
Contamination	Components added or changed, with the main focus being to remove contaminated materials.
Acoustics	Components added or changed, with the main focus being to increase the building’s acoustic properties.
Daylight	Components added or changed in relation to daylight, e.g. increasing façade openings to enhance daylight.
Outside areas	Components added or changed outside the building.
Elevators	Components added or changed when an elevator is added where there were none before.
Balconies	Components added or changed when a balcony is added where there was none before.
Local energy production	Energy production on site, such as PV panels.
Replacements and repairs	Replacements or repairs with no significant added or improved function, such as replacing water and waste piping.

Table 3 shows which cases are related to the different provided functions. The table shows that most cases change the interior layout and include actions to reduce energy use. Five cases include an extension, and one case removed some building area, which are all categorized in the *spatial* function. The *indoor climate* function includes emissions from ventilation and floor-heating systems that have been implemented. This applies to several of the residential buildings where implementing ventilation is part of the renovation, as well as to buildings that are converted to a different use. Terraces and balconies are added to the *balcony* function, which is added in eleven of the projects.

The functions from renovation actions will in some cases overlap. For instance, *fire* and *acoustics* are considered in many building products that are added in renovation, though the categories have not been used much in this study. This is because the categorization only considers the primary function of the renovation action based on what the purpose of the renovation action was. This is determined based on the available knowledge of the project. Considering acoustic ceilings, they will often be categorized with the *layout* function because the ceilings are changed together with other interior elements as part of the change in layout. Furthermore, while windows are associated with daylight, the majority of new windows have not been categorized in *daylight*, but rather in the *energy reduction* category, because they contribute to significant energy reductions. The *daylight* category is only used when daylight is added by making new openings in the building where there were none before. Building services have been categorized into several different categories, such as *indoor climate*, when ventilation and floor heating are introduced, although this also has an influence on the building’s energy use. Building services are categorized in the *spatial* category when they are related to building extensions.

3. Results

The results section shows GHGe from the 23 renovation cases with a focus on the contribution from *energy reduction* versus other functions provided in the building. This information is crucial to understand the nature of real-life renovation projects and how they can be benchmarked to limit emissions.

3.1. Embodied and operational impacts

The GHGe from renovation projects are shown in Fig. 1, with the table at the bottom showing the data going into the graph. The contributions from operational energy use are shown both before (“no renovation”) and after renovation. “No renovation” considers a scenario where the building is not renovated, thus the energy demand of the existing building is considered over the RSP. In the seven cases for which data was available both before and after renovation, a potential impact savings can be considered. The average values for these cases are 13.5 kg CO_2-eq/m^2/year and 7.0 kg CO_2-eq/m^2/year before and after renovation. The savings in GHGe for operational energy use are thus approximately 50 %, but for the individual projects, savings are between 20 % and 65 %.

Fig. 1 shows a large variation in the operational emissions. This reflects the variation of the energy performance of the buildings both before and after renovation. Furthermore, in some cases there is also a difference in the thermal energy technology. For heating, most cases are supplied by district heating, the incineration of waste and biomass in combined heat and power plants being large contributors to district heating in Denmark [51]. However, for cases I1 and R1, the heating is supplied solely by natural gas, which has significantly higher emissions per kWh.

Embodied emissions over the lifecycle of the renovation are shown in Fig. 1 for all 23 cases. The embodied emissions also vary but have an

Table 3
Categorization of the renovation cases.

Code	Spatial	Layout	Energy reduction	Indoor climate	Fire	Structural	Contamination	Acoustics	Daylight	Outside areas	Elevators	Balconies	Local energy production	Replacements and repairs
C1		X	X						X		X			
O1		X	X	X					X					
O2		X	X						X	X				X
O3		X	X					X			X	X		X
O4	X	X	X						X		X	X		
H1	X	X	X	X		X			X		X			X
Hos1		X	X						X					X
I1		X	X	X			X					X		
R1		X	X	X										X
R2		X	X											X
R3		X	X	X		X								X
R4	X	X	X	X						X		X		X
R5		X	X	X										X
R6		X	X	X	X									X
R7		X	X					X			X	X		X
R8		X	X								X	X		
R9		X	X	X							X	X		X
R10			X					X	X			X		X
R11		X	X	X							X	X		X
R12		X	X	X							X			X
R13	X											X		
R14		X	X						X		X		X	X
R15	X	X	X					X	X			X		

average value of 2.8 kg CO_2-eq/m^2/year, which is lower than the operational emissions and savings. The reason for the variance in embodied emissions will be investigated in the next section.

The average total emissions, from operational and embodied emissions after renovation, are 8.7 kg CO_2-eq/m^2/year, though emissions range from 5.4 to 19.1 kg CO_2-eq/m^2/year over a fifty-year reference study period.

3.2. *Embodied impacts from provided functions*

To understand the variation in embodied impacts introduced in section 3.1, this section investigates the source of emissions, in terms of the functions provided to the building from the renovation actions. This is presented in Fig. 2 for the case buildings. The figure illustrates which embodied impacts come from *energy reduction* actions and which are due to other added functions.

Fig. 2b shows that the median and average emissions are highest for the functions *spatial*, *layout* and *energy reduction*. However, *spatial* only appears in five of the 23 cases, whereas *layout* and *energy reduction* appear in almost all cases (21 and 22 cases, respectively). Therefore, considering the emissions across all cases, *spatial* only contributes 8 %, on average, whereas *energy reduction* contributes 43 % (46 % including PV panels) followed by 18 % from *layout*. Other function categories that appear with high frequency and substantial emissions are *indoor climate*, *daylight*, *elevator*, *balconies* and *replacements or repairs*. *Local renewable energy supply* (in this case PV panels) only appears in one case but has a significant influence on emissions.

Though *energy reduction* contributes the largest emissions on average, Fig. 2a shows that some of the cases mainly have emissions from other functions. This relates to cases where conversion of the interior building function results in higher emissions from *layout* (H1, R7), or in cases where a completely new area has been added to the existing structure, thus having higher emissions from the *spatial* category (R13, R15). The renovation actions in R14 are mainly related to a change in layout, but PV panels are also added, which have a significant influence on embodied emissions.

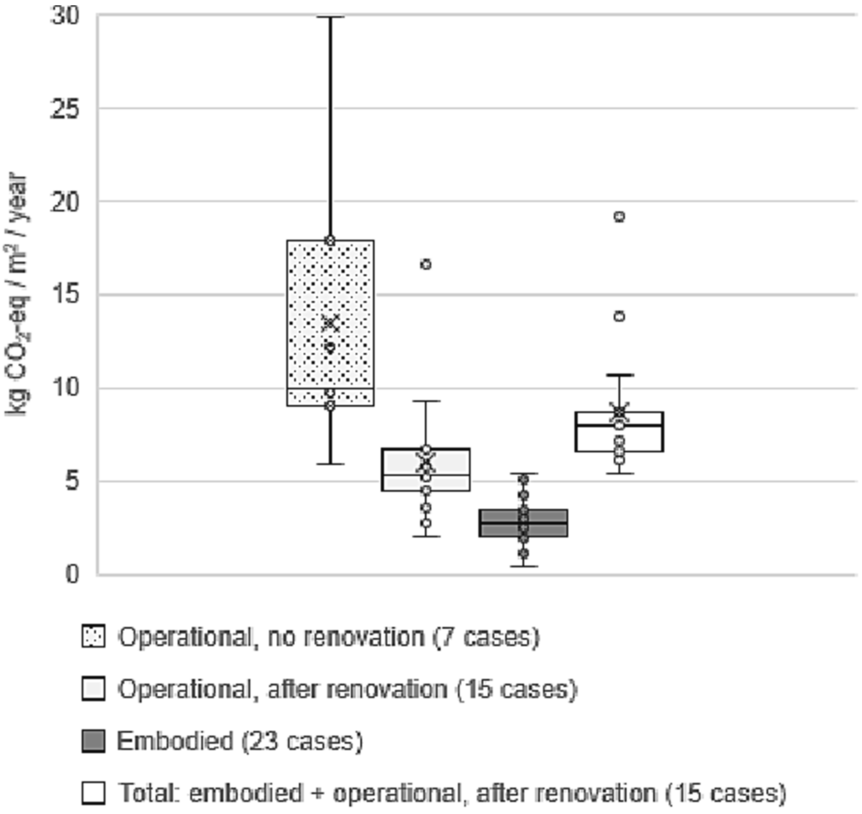
The five cases behind the most profound embodied emissions (>3.5 kg CO_2-eq/m^2/year) are cases O1, I1, R3, R4 and R13. However, these cases have different building typologies and functions: three of the five buildings have converted the building's use, for instance, from production to office space. For one of the conversions, most emissions go to the *spatial* category, as a dwelling area has been added by constructing an entirely new roof (R13). The remaining two cases (R3 and R4) are residential buildings renovated for energy and interior layout.

The cases with lowest embodied emissions (<1.5 kg CO_2-eq/m^2/year) are cases O2, O4, R2, and R8. These cases had limited interventions in the building envelope, for instance, due to architectural considerations (O2), acceptable existing energy-use conditions (O4) or minor scope in general for the renovation.

3.3. *Energy reduction measures: building element level*

To provide more insights into embodied GHGe from renovation measures, this section investigates the emissions on the building-element level.

Section 3.2 showed that the category of *energy reductions* is the main contributor to the embodied emissions, with 43 % on average between the cases. Fig. 3 shows the contributions from *energy reduction* to the renovation cases and the building elements these emissions are attributed to. The figure shows that "windows, doors and glazing systems" contribute to almost a third of the total emissions, with contributions from most of the cases (20 out of 23 cases), and emissions mainly derived from replacing windows. Only nine cases have emissions from the ground-floor slab, though these renovation actions were more emissions-intense per case. This is because insulating the ground-floor slab typically requires the entire element to be replaced, thus



	C1	O1	O2	O3	O4	H1	Hos1	I1	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15
⊡				9.9					29.9		17.9		9.0	5.9				9.7		12.1			
□			5.3	3.6			5.2	9.2	16.5		6.8		5.8	4.7	4.5	6.7	4.5	6.2		5.5	2.0	2.7	
■	2.0	5.4	1.2	2.5	1.1	2.8	3.0	4.6	2.6	0.4	3.9	4.2	2.4	2.0	2.0	1.3	2.7	2.2	3.0	3.1	5.1	2.7	3.5
□			6.6	6.1			8.2	13.8	19.1		10.6		8.2	6.7	6.5	8.0	7.2	8.4		8.7	7.1	5.4	

Fig. 1. Embodied and operational GHGe for the renovation cases over fifty years. The figure also shows the operational emissions over fifty years if the building had not been renovated ("no renovation"). The boxplot shows the median and mean values, upper and lower quartiles, minimum and maximum, and all data points in the dataset. The table shows the datasets that are included in the plot.

contributing high emissions from new concrete and rigid insulation materials. Significant overall emissions also come from external walls and roofs, where emissions primarily come from a change in the existing element. This typically comes from adding insulation and associated materials such as cladding.

Fig. 4 shows the difference between building element's GHGe from *energy reduction* measures (4a) and emissions from all renovation measures (4b). The boxplots show that average emissions from windows, ground-floor slabs, roofs and external walls are similar between the two plots, meaning that the vast majority of emissions from these elements are associated with the function of *energy reduction*. Most significant for these elements is the change in average value for ground-floor slabs between the plots. In Fig. 4b the average emissions are lower, which is related to less emission-intense renovation actions such as new flooring etc., associated with other functions such as *layout*.

For other building elements such as internal walls, floor decks, balconies and building services, the emissions are related to other renovation measures than *energy reduction*. For instance, building services have a significant influence, their emissions being ascribed to several different function categories, such as *energy reduction*, *elevators*, *indoor climate*, *spatial*, *replacement and repair* and *local renewable energy*.

4. Discussion

The results show how renovation projects contribute to a multitude of new functions in renovation and which building elements contributed to largest emissions. This is important information for future policy-making, given if, and how, the different functions and elements can be evaluated in the assessment of GHGe. Though the cases in this study do not represent all types of renovation, the emissions related to different functions and elements provide insights into the possible hotspots which can be addressed in future design and legislation. For instance, the results from these real-life cases show that, if legislation focuses solely on energy reduction actions, then a significant part of embodied emissions in renovations will be unaccounted for.

Furthermore, the results showed that energy-reduction actions resulted in net savings, given both the embodied and operational impacts given large operational savings, which is consistent with findings in the existing literature [7]. However, the results from this study also showed that renovation activities for energy reductions contribute a significant part of the total embodied emissions. A multitude of existing literature shows that savings in embodied emissions are possible by considering material choices and design in energy-reduction actions

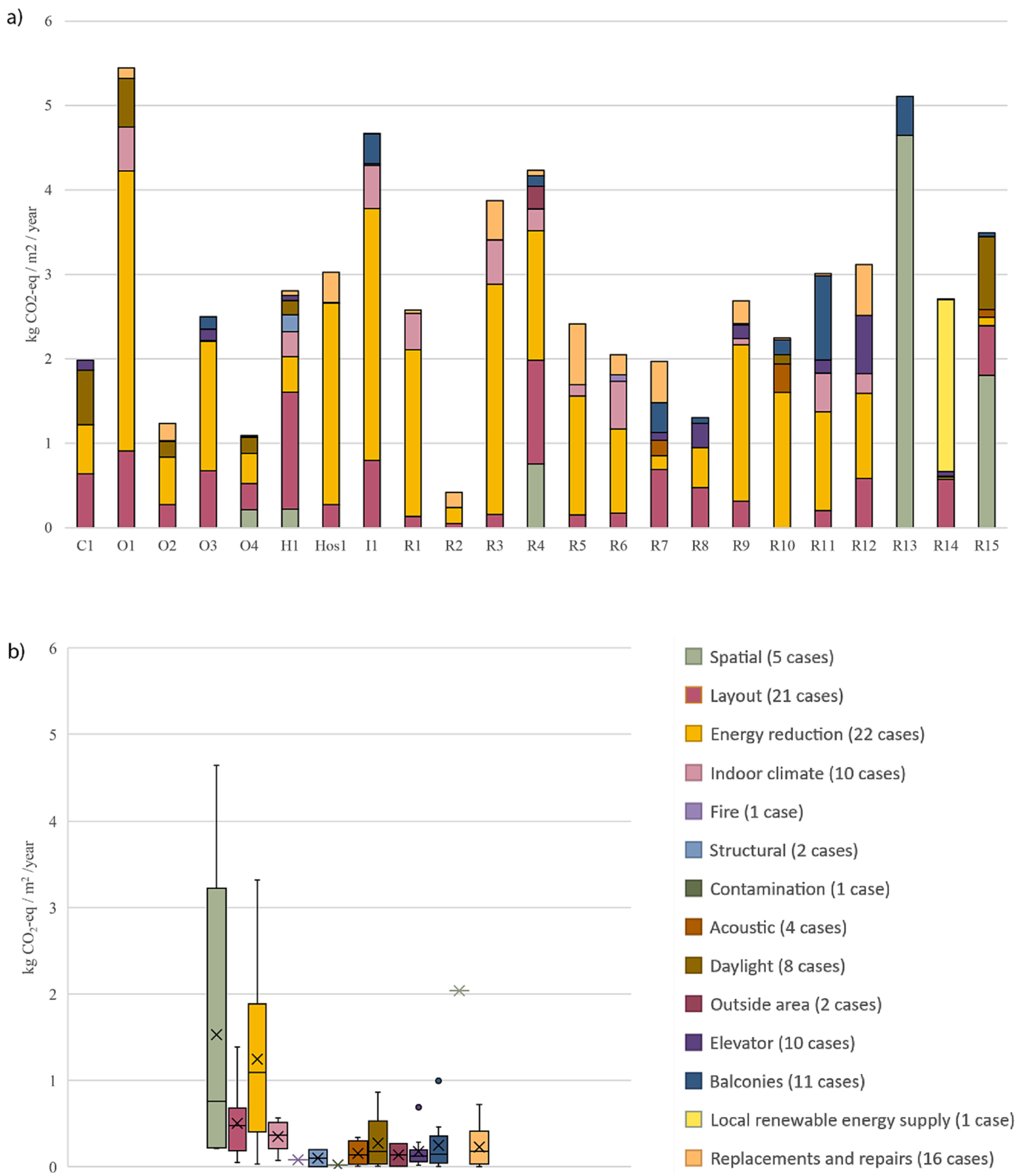


Fig. 2. A) Embodied emissions from cases of renovation divided into contributions from functions. b) Variance of function in embodied emissions described through a boxplot that shows the median and mean values, upper and lower quartiles, minimum and maximum, and outliers in the dataset.

[16,52–56]. Together, the results of this study and the findings of previous studies point to the necessity of considering emissions from energy renovations in future policy-making.

4.1. *Operational emissions and savings*

The results also showed that operational energy emissions had a significant impact on the renovation projects' GHGe savings and future emissions. Emissions from operational energy can vary a lot depending on different factors, such as local climate conditions, energy sources and assumptions for future scenarios. For instance, the results showed significantly larger emissions from the buildings supplied with natural gas for heating than the buildings using district heating. Energy technologies are largely dependent on national energy strategies, which are expected to decarbonize GHGe for operational energy in Europe in the coming years [2]. Savings in GHGe from operational energy in renovation projects may therefore become less significant in future renovation projects, while embodied emissions gain much more in importance. However, overarching scenarios for future energy mixes and uses are complex and inherently uncertain, for instance depending on global temperature rises and the energy demand responses to this, e.g. increased use of cooling systems. The systemic background changes are rarely addressed in LCA modelling, although recent research initiatives, such as 'premise' [57] have facilitated the coupling between global-scale

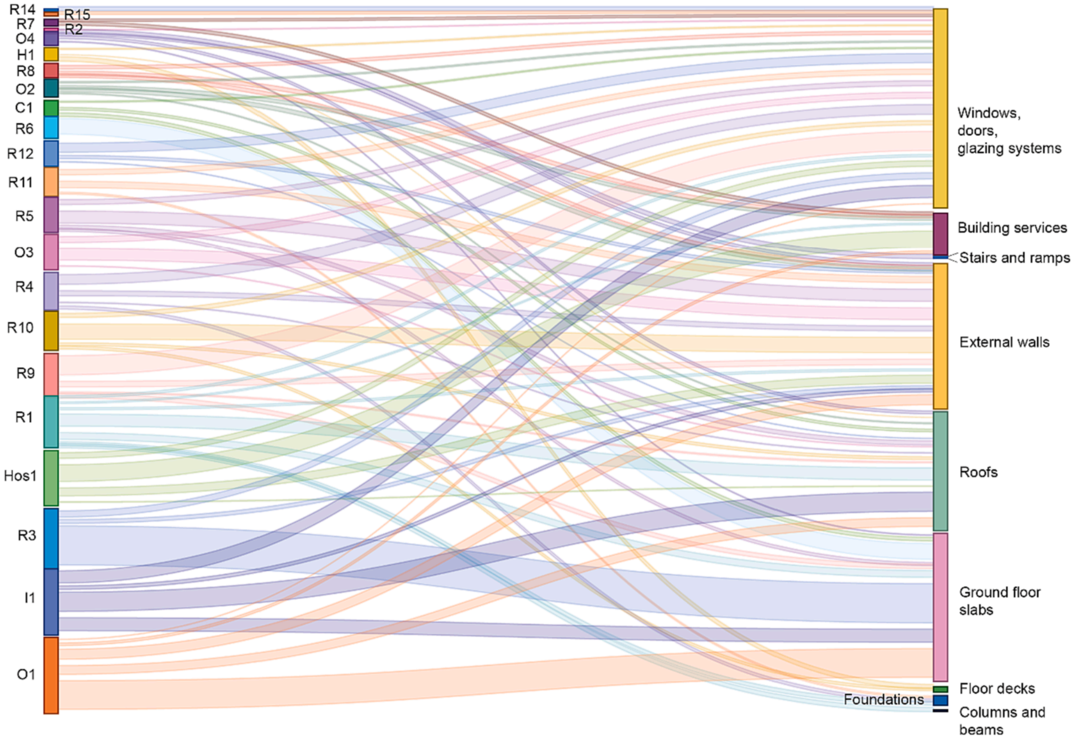


Fig. 3. Embodied GHGe related to energy-reduction measures from cases and building elements.

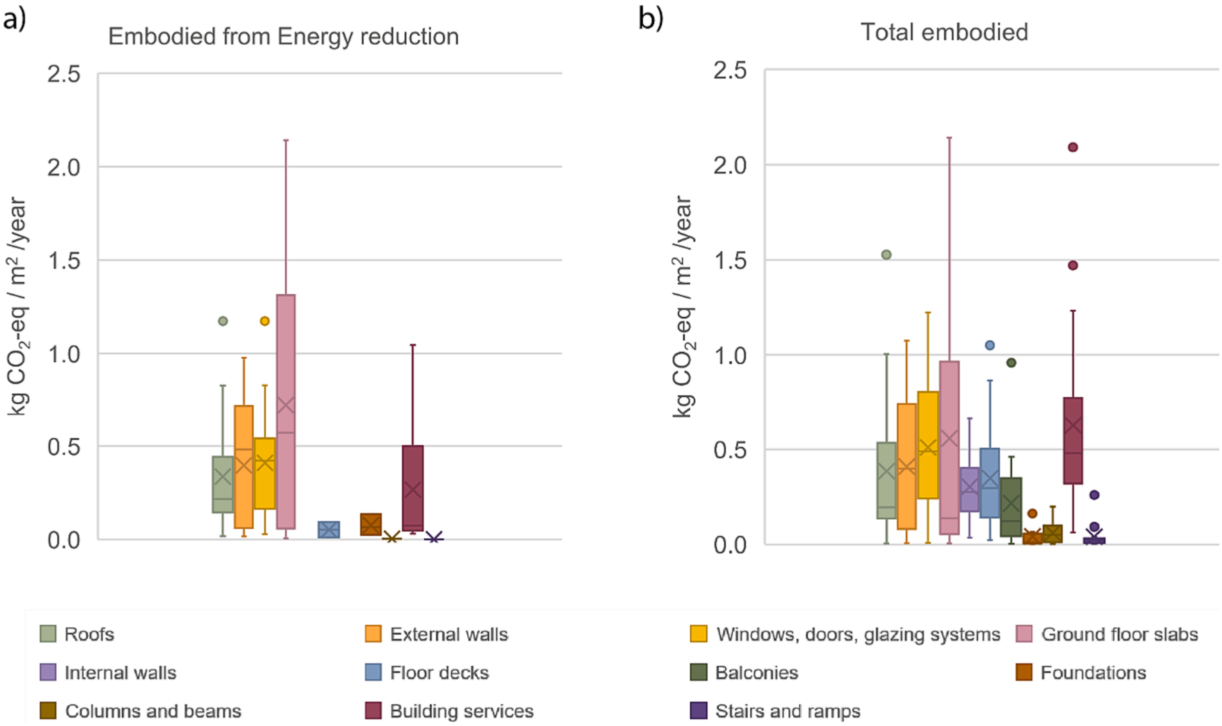


Fig. 4. Embodied GHG emissions from building elements for a) energy reduction measures and b) all renovation measures.

integrated assessment models and LCA modelling.

Furthermore, it is important to consider the temporal differences between upfront embodied emissions and operational energy reductions, where emissions happen over the building's service life [58]. Reducing upfront emissions is important in order to stay within our carbon budget and keep temperature rises well below two degrees Celsius, as stated in the Paris Agreement [59].

For future policy-making, it is therefore relevant to consider the uncertainties and take into account the temporal aspects of the operational impacts of renovation projects.

4.2. *Considerations for benchmarks*

The results of this study showed large variations in emissions in renovation projects due to differences in renovation actions. The differences were visible, even though 21 of 23 cases are considered a major renovation, following the definition based on changes in the building envelope in the EPBD [1]. This is caused by differences in the existing condition of the building and the plans for its future use. Consequently, different functions are provided within the projects.

Benchmark values for renovation have been suggested in the form of a) a single benchmark for the whole renovation project, b) for building elements, or c) based on the relationship between embodied emissions and operational savings in the project [37]. Benchmark a) for the entire renovation project is commonly used for new construction, though renovation projects are highly unique due to the different initial conditions and the variety of scale and functions provided in a renovation project. This makes them difficult to benchmark on the building level using a single value. An exception to this is building extensions, which are similar to new construction and contributed significant impacts on several of the cases from the *spatial* category. The building extensions pose a methodological challenge in terms of what area emissions are allocated to. The results in this study reflect the new functional equivalent, where emissions are normalized to the floor area *after* renovation, including both the extension and the existing building. However, if building extensions are to be benchmarked separately from the existing building, embodied and operational emissions would have to be allocated to the new area.

Benchmark values can also be defined on a smaller scale such as the building elements or product scale (suggestion b), where the function is similar to new construction e.g. emissions per m^2 of wall. The results showed that some of the elements that contributed the most to embodied GHGe in the renovation projects were from building envelope elements, followed by building services, internal walls, floor decks and balconies. In the renovation actions, the windows and ground-floor slabs were mainly replaced. They are therefore entirely new elements, where element benchmarks can be considered similar to new construction, whereas the renovation measure for roofs and external walls are mainly changes in existing elements, making it more difficult to set generic benchmarks. One drawback is that benchmarks for building elements do not give any indication of how the entire project performs.

A benchmark that considers the relationship between embodied emissions and operational savings in the renovation project (suggestion c) can be relevant when considering the emissions related to energy reductions. However, the results of this study showed that a majority of embodied emissions did not come specifically from energy reductions but contributed to several other new functions in the building. Evaluating the renovation actions related to *energy reduction* makes it possible to evaluate other individual functions in renovation projects. Most radically, benchmarks can help limit emissions to functions that are truly necessary. Deciding what is truly necessary can be based on, e.g. the fulfilment of human needs [60]. For instance, building expansions can solve an immediate need to provide shelter for people. On the other hand, they can also be used to expand the living area for the current inhabitants, thus continuing the rise in living area per person in Denmark [61]. Emissions that consider other functions such as layout can provide for the social (comfort, aesthetic etc.) and economic sustainability of the building [30], thus future-proofing the building in relation to, e.g., demolition. Improvements in the indoor climate, daylight, and balconies also contribute to the well-being of the inhabitants. For emissions related to these functions, it can therefore be relevant to consider other benchmarks focused on, e.g., human and social needs.

4.3. Limitations of the study

This study was carried out in the Danish context for building renovations, taking a diverse collection of cases into account. For purposes of generalization, the number of cases is still limited, especially due to the varied nature of renovation projects and the different building types. However, general trends are visible across all building types, such as the significance of considering embodied emissions from “other functions” than energy reduction. The general trends shown for the Danish context of real-life renovations would likely be similar in other comparable settings: for instance, the larger part of building stock in European countries with a significant amount of such stock erected in the 1960s and 1970s needing upgrading in several aspects of their functionality. This could be investigated in future studies of real-life renovations from other geographical contexts and could examine if this applies to other contexts as well. Further, the significance of types of building and renovation could be further explored in future studies.

The results were calculated over a reference study period (RSP) of fifty years, reflecting the current practice for the Danish context, which uses the same RSP for new construction and renovation. For the calculation, the required/estimated service life of the renovation projects are assumed to be identical to the RSP. However, this approach is debatable, as the service life of renovation projects can depend on the condition of the building, the type of renovation etc. [62].

5. Conclusions

The findings from this study show that, in the renovation cases where before- and after-energy demand were reported, lifecycle GHGe-savings of around 50 % were obtained, reducing operational emissions from 13.5 kg CO_2-eq/m^2/year to 7.0 kg CO_2-eq/m^2/year on average. Despite uncertainties and variations between the cases, these numbers from the real-life renovation cases suggest, like other studies before them, that substantial reductions in operational emissions can be achieved in a lifecycle perspective on renovations. The energy and emissions savings are an important part of fulfilling the goals of the Renovation Wave under the European Green Deal. However, this study expands the existing knowledge about lifecycle GHGe of renovations by systematically assessing the building functions that were improved or established in renovations conducted in Denmark. In the 23 renovation cases examined here, an average of 2.8 kg CO_2-eq/m^2/year is ascribed to the material-related, embodied GHGe. A remarkable 54 % of these lifecycle embodied impacts from the renovation cases are associated with functions that are not related to improving energy efficiency, but to other aspects such as spatial adjustments, interior layout changes or the establishment of balconies. Of the 43 % embodied GHGe associated with improved energy efficiency, almost a third came from the renovation of windows and glazing systems, a renovation action that all modelled cases employed. Less frequent, in only six cases, was the renovation of ground-floor slabs. However, on a per-case basis, this renovation action was notably emissions-intense, typically representing around 30 %–70 % of the embodied GHGe associated with the energy efficiency measures of the cases in question.

The growing interest in benchmarking and regulating the lifecycle GHGe from renovations makes it more important to recognize the multitude of purposes and functions at play within real-life renovations. Literature has suggested three main approaches to benchmarking renovation projects. These approaches are each challenged by the complex characteristics of renovations, as indicated by the results of this study:

1. A single benchmark for the whole building. The results of this study showed that projects varied significantly in their embodied and operational emissions, even though 21 out of the 23 cases are considered major renovations following the EPBD definition. This means that it will be very difficult to find a common benchmarking system to encompass the variation.
2. Benchmarks on a smaller, material scale, such as the building-element level. This study provides pointers to the significance of these elements in the building envelope for further exploration. However, this approach does not take into account the performance of the entire project.

3. Benchmark of renovations based on their GHGe "savings" from energy reductions. The results of this study clearly show that renovation projects contribute to a multitude of functions other than energy reduction. In theory, a system of allocating emissions in accordance with functions, as is done in this study, could tackle this. However, a such categorization would be difficult to integrate into practice, due to the high requirements for documentation.

Despite large variations across real-life cases of renovation, the study clearly demonstrates the significance of embodied emissions related to a variety of new functions beyond energy efficiency across the cases. This knowledge is important for the future benchmarking of renovation projects, in support of the efforts towards drastic reductions in GHGe from buildings.

Declaration of Competing Interest

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

Data availability

The data that has been used is confidential.

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References

[1] E. Commission, Proposal for a Directive of the European Parliament and of the Council on the energy performance of buildings (recast), Off. J. Eur. Union 0426 (2021) 10–27. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0802&qid=1641802763889.

[2] E. Commission, Renovation Wave for Europe - greening our buildings, creating jobs, improving lives, Off. J. Eur. Union (2020) 26. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1603122220757&uri=CELEX:52020DC0662.

[3] European Commission, European Green Deal, 2019. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en#documents.

[4] European Commission, European Climate Law, 2021. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021R1119.

[5] CEN, EN 15978: Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method, 2012. https://www.en-standard.eu/din-en-15978-sustainability-of-construction-works-assessment-of-environmental-performance-of-buildings-calculation-method/.

[6] O. Fahlstedt, A. Temeljotov-Salaj, J. Lohne, R.A. Bohne, Holistic assessment of carbon abatement strategies in building refurbishment literature — A scoping review, Renew. Sustain. Energy Rev. 167 (2022), 112636, https://doi.org/10.1016/j.rser.2022.112636.

[7] A. Vilches, A. Garcia-Martinez, B. Sanchez-Montañes, Life cycle assessment (LCA) of building refurbishment: A literature review, Energ. Buildings 135 (2017) 286–301, https://doi.org/10.1016/j.enbuild.2016.11.042.

[8] G. Bin, P. Parker, Measuring buildings for sustainability: Comparing the initial and retrofit ecological footprint of a century home - The REEP House, Appl. Energy 93 (2012) 24–32, https://doi.org/10.1016/j.apenergy.2011.05.055.

[9] O. Pombo, K. Allacker, B. Rivela, J. Neila, Sustainability assessment of energy saving measures: A multi-criteria approach for residential buildings retrofitting - A case study of the Spanish housing stock, Energ. Buildings 116 (2016) 384–394, https://doi.org/10.1016/j.enbuild.2016.01.019.

[10] B. Wrålsen, R. O'Born, C. Skaar, Life cycle assessment of an ambitious renovation of a Norwegian apartment building to nZEB standard, Energ. Buildings 177 (2018) 197–206, https://doi.org/10.1016/j.enbuild.2018.07.036.

[11] M. Österbring, É. Mata, L. Thuvander, H. Wallbaum, Explorative life-cycle assessment of renovating existing urban housing-stocks, Build. Environ. 165 (2019), 106391, https://doi.org/10.1016/j.buildenv.2019.106391.

[12] S. Seo, G. Foliente, Carbon footprint reduction through residential building stock retrofit: A metro melbourne suburb case study, Energies 14 (2021), https://doi.org/10.3390/en14206550.

[13] N. Mirabella, M. Röck, M.R.M. Saade, C. Spirinckx, M. Bosmans, K. Allacker, A. Passer, Strategies to improve the energy performance of buildings: A review of their life cycle impact, Buildings 8 (2018) 1–18, https://doi.org/10.3390/buildings8080105.

[14] F. Montana, K. Kanafani, K.B. Wittchen, H. Birgisdottir, S. Longo, M. Cellura, E. R. Sanseverino, Multi-objective optimization of building life cycle performance. A housing renovation case study in Northern Europe, Sustainability. 12 (2020), https://doi.org/10.3390/SU12187807.

[15] C. Favi, I. Meo, E. Di Giuseppe, M. Iannaccone, M. D'Orazio, M. Germani, Towards a probabilistic approach in LCA of building retrofit measures, Energy Procedia 134 (2017) 394–403, https://doi.org/10.1016/j.egypro.2017.09.584.

[16] B. Nicolae, B. George-Vlad, Life cycle analysis in refurbishment of the buildings as intervention practices in energy saving, Energ. Buildings 86 (2015) 74–85, https://doi.org/10.1016/j.enbuild.2014.10.021.

[17] S. Tadeu, C. Rodrigues, A. Tadeu, F. Freire, N. Simões, Energy retrofit of historic buildings: Environmental assessment of cost-optimal solutions, J. Build. Eng. 4 (2015) 167–176, https://doi.org/10.1016/j.jobe.2015.09.009.

[18] H. Zhang, K. Hewage, T. Prabatha, R. Sadiq, Life cycle thinking-based energy retrofits evaluation framework for Canadian residences: A Pareto optimization approach, Build. Environ. 204 (2021), 108115, https://doi.org/10.1016/j.buildenv.2021.108115.

[19] A. Galimshina, M. Moustapha, A. Hollberg, P. Padey, S. Lasvaux, B. Sudret, G. Habert, What is the optimal robust environmental and cost-effective solution for building renovation? Not the Usual One, Energy Build. 251 (2021), 111329 https://doi.org/10.1016/j.enbuild.2021.111329.

[20] E. Verellen, K. Allacker, Life cycle assessment of clustered buildings with a similar renovation potential, Int. J. Life Cycle Assess. 27 (2022) 1127–1144, https://doi.org/10.1007/s11367-022-02095-0.

[21] X. Yang, M. Hu, C. Zhang, B. Steubing, Key strategies for decarbonizing the residential building stock: Results from a spatiotemporal model for Leiden, the Netherlands, Resour. Conserv. Recycl. 184 (2022), 106388, https://doi.org/10.1016/j.resconrec.2022.106388.

[22] N. Cihan Kayacetin, A. Versele, A Circular and Bio-based Renovation Strategy for Low-income Neighbourhoods, IOP Conf, Ser. Earth Environ. Sci. 1078 (2022), https://doi.org/10.1088/1755-1315/1078/1/012080.

[23] K. Kertsmik, K. Kuusk, K. Lylykangas, T. Kalamees, Evaluation of renovation strategies: cost-optimal, CO_2e optimal, or total energy optimal, or total energy optimal, Energ. Buildings 287 (2023), 112995, https://doi.org/10.1016/j.enbuild.2023.112995.

[24] A. Lupíšek, T. Trubačík, P. Holub, Czech building stock: Renovation wave scenarios and potential for CO2 savings until 2050, Energies 14 (2021), https://doi.org/10.3390/en14092455.

[25] D.A. Pohoryles, C. Maduta, D.A. Bournas, L.A. Kouris, Energy performance of existing residential buildings in Europe: A novel approach combining energy with seismic retrofitting, Energ. Buildings 223 (2020), 110024, https://doi.org/10.1016/j.enbuild.2020.110024.

[26] K.N. Streicher, M. Berger, E. Panos, K. Narula, M.C. Soini, M.K. Patel, Optimal building retrofit pathways considering stock dynamics and climate change impacts, Energy Policy 152 (2021), 112220, https://doi.org/10.1016/j.enpol.2021.112220.

[27] F. Pittau, G. Habert, G. Iannaccone, A life-cycle approach to building energy retrofitting: bio-based technologies for sustainable urban regeneration, IOP Conf. Ser. Earth Environ. Sci. 290 (2019), https://doi.org/10.1088/1755-1315/290/1/012057.

[28] N. Galiotto, P. Heiselberg, M.-A. Knudstrup, Integrated renovation process: overcoming barriers to sustainable renovation, J. Archit. Eng. 22 (2016) 1–12, https://doi.org/10.1061/(asce)ae.1943-5568.0000180.

[29] P.A. Jensen, E. Maslesa, J.B. Berg, Sustainable building renovation: Proposals for a research agenda, Sustain. 10 (2018), https://doi.org/10.3390/su10124677.

[30] S. Shahi, M. Esnaashary Esfahani, C. Bachmann, C. Haas, A definition framework for building adaptation projects, Sustain. Cities Soc. 63 (2020), 102345, https://doi.org/10.1016/j.scs.2020.102345.

[31] A. Ghose, S.J. McLaren, D. Dowdell, R. Phipps, Environmental assessment of deep energy refurbishment for energy efficiency-case study of an office building in New Zealand, Build. Environ. 117 (2017) 274–287, https://doi.org/10.1016/j.buildenv.2017.03.012.

[32] V. Hasik, E. Escott, R. Bates, S. Carlisle, B. Faircloth, M.M. Bilec, Comparative whole-building life cycle assessment of renovation and new construction, Build. Environ. 161 (2019), 106218, https://doi.org/10.1016/j.buildenv.2019.106218.

[33] BPIE (Building Performance Institute Europe), Roadmap To Climate-Proof Buildings and Construction - How To Embed Whole-Life Carbon in the Epbd, 2022. https://www.bpie.eu/publication/roadmap-to-climate-proof-buildings-and-construction-.

[34] OneClickLCA, Construction Carbon Regulations In Europe, 2022. https://www.oneclicklca.com/construction-carbon-regulations-in-europe/.

[35] ISO, ISO 21678:2020 Sustainability in buildings and civil engineering works – Indicators and benchmarks – Principles, requirements and guidelines, 2021. https://www.iso.org/standard/71344.html.

[36] T. Lützkendorf, M. Balouktsi, Benchmarking and target-setting for the life cycle-based environmental performance of buildings, 2023. https://annex72.iea-ebc.org/Data/publications/EBC_Annex_72_Benchmarking_for Environmental_Performance_of_Buildings_2023.pdf.

[37] A. Lund, R. Zimmermann, J. Kragh, J. Rose, S. Aggerholm, H. Birgusdottir, Klimapåvirkning fra renovering: Muligheder for udformning af grænseværdier til LCA for renovering, 2022. https://vbn.aau.dk/en/publications/klimapåvirkning-fra-renovering-muligheder-for-udformning-af-græns.

[38] B. Flyvbjerg, Five misunderstandings about case-study research, Qual. Res. Pract. (2011) 390–404, https://doi.org/10.4135/9781848608191.d33.

[39] Rådet for bæredygtigt byggeri, DGNB, (2023). https://rfbb.dk/dgnb-certificering (accessed June 30, 2023).

[40] R.K. Zimmermann, F.N. Rasmussen, K. Kanafani, L.C. Malabi Eberhardt, H. Birgisdóttir, Reviewing allocation approaches and modelling in LCA for building refurbishment, IOP Conf. Ser. Earth Environ. Sci. 1078 (2022), https://doi.org/10.1088/1755-1315/1078/1/012095.

[41] K. Haugbølle, V. Mahdi, M. Morelli, H. Wahedi, BUILD Levetidstabel, Copenhagen, 2021. https://build.dk/Pages/BUILD-levetidstabel.aspx.

[42] S. Butera, A.A.W. Karl, T.F. Astrup, C. Collin, N.L. Rasmussen, J.R. Nielsen, L.H. H. Sørensen, Klimavenligt byggeri og LCA - Analyse af udvalgte landes tilgange til klimavenligt byggeri, LCA Og Samfundsøkonomi (2021). https://www.lifecyclecenter.se/wp-content/uploads/Analysis-of-other-countries-approach-to-building-LCA.pdf.

[43] Danish housing and planning authority, Danish Building Regulations, (2023). https://bygningsreglementet.dk/ (accessed February 28, 2023).

[44] F.N. Rasmussen, H. Birgisdóttir, Development of the LCAbyg tool: influence of user requirements and context, in: C. ZEBAU – Centre for Energy Architecture and the Environment GmbH (Ed.), 2016. 10.5445/IR/1000051699.

[45] K. Kanafani, R.K. Zimmermann, F.N. Rasmussen, H. Birgisdóttir, Learnings from developing a context-specific LCA tool for buildings—the case of lcabyg 4, Sustain. 13 (2021) 1–23, https://doi.org/10.3390/su13031508.

[46] R.K. Zimmermann, K. Kanafani, F. Nygaard Rasmussen, H. Birgisdóttir, Early design stage building LCA using the LCAbyg tool: comparing cases for early stage and detailed LCA approaches, IOP Conf. Ser. Earth Environ. Sci. 323 (2019), https://doi.org/10.1088/1755-1315/323/1/012118.

[47] K. Kanafani, R.K. Zimmermann, F.N. Rasmussen, H. Birgisdóttir, Early design stage building LCA using The LCAbyg tool: new strategies for bridging the data gap, IOP Conf. Ser. Earth Environ. Sci. 323 (2019), https://doi.org/10.1088/1755-1315/323/1/012117.

[48] Ökobaudat, Ökobaudat, (2023). https://www.oekobaudat.de/ (accessed June 7, 2023).

[49] CEN, EN 15804+A1 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products, 2012. https://webshop.ds.dk/en/standard/M254454/ds-en-15804-2012.

[50] The Danish building code, Emissions from electricity, district hearing, and natural gas, (2023). https://bygningsreglementet.dk/Bilag/B2/Bilag_2/Tabel_8#1f165e42-7a97-45dd-9f4d-5b6373522e23 (accessed June 7, 2023).

[51] COWI, Opdaterede emissionsfaktorer for el og fjernvarme, 2020. https://bpst.dk/da/Byggeri/Lister/Publikationsliste?theme=Indeklima.

[52] X. Su, Z. Luo, Y. Li, C. Huang, Life cycle inventory comparison of different building insulation materials and uncertainty analysis, J. Clean. Prod. 112 (2016) 275–281, https://doi.org/10.1016/j.jclepro.2015.08.113.

[53] J. Sierra-Pérez, J. Boschmonart-Rives, X. Gabarrell, Environmental assessment of façade-building systems and thermal insulation materials for different climatic conditions, J. Clean. Prod. 113 (2016) 102–113, https://doi.org/10.1016/j.jclepro.2015.11.090.

[54] M. Braulio-Gonzalo, M.D. Bovea, Environmental and cost performance of building's envelope insulation materials to reduce energy demand: Thickness optimisation, Energ. Buildings 150 (2017) 527–545, https://doi.org/10.1016/j.enbuild.2017.06.005.

[55] H. Huang, Y. Zhou, R. Huang, H. Wu, Y. Sun, G. Huang, T. Xu, Optimum insulation thicknesses and energy conservation of building thermal insulation materials in Chinese zone of humid subtropical climate, Sustain. Cities Soc. 52 (2020), 101840, https://doi.org/10.1016/j.scs.2019.101840.

[56] J. Carreras, D. Boer, G. Guillén-Gosálbez, L.F. Cabeza, M. Medrano, L. Jiménez, Multi-objective optimization of thermal modelled cubicles considering the total cost and life cycle environmental impact, Energ. Buildings 88 (2015) 335–346, https://doi.org/10.1016/j.enbuild.2014.12.007.

[57] R. Sacchi, T. Terlouw, K. Siala, A. Dirnaichner, C. Bauer, B. Cox, C. Mutel, V. Daioglou, G. Luderer, PRospective EnvironMental Impact asSEment (premise): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models, Renew. Sustain. Energy Rev. 160 (2022), 112311, https://doi.org/10.1016/j.rser.2022.112311.

[58] R.K. Zimmermann, Z. Barjot, F.N. Rasmussen, T. Malmqvist, M. Kuittinen, H. Birgisdottir, GHG emissions from building renovation versus new-build: incentives from assessment methods, Build, Cities 4 (2023) 274–291, https://doi.org/10.5334/bc.325.

[59] UN, The Paris Agreement, (2023). https://unfccc.int/process-and-meetings/the-paris-agreement.

[60] M. Heide, M.Z. Hauschild, M. Ryberg, Reflecting the importance of human needs fulfilment in absolute sustainability assessments: Development of a sharing principle, J. Ind. Ecol. 27 (2023) 1151–1164, https://doi.org/10.1111/jiec.13405.

[61] Statistics Denmark, Housing, (2023). https://www.dst.dk/en/Statistik/emner/borgere/boligforhold (accessed July 29, 2023).

[62] Y. Decorte, N. Van Den Bossche, M. Steeman, Guidelines for defining the reference study period and system boundaries in comparative LCA of building renovation and reconstruction, Int. J. Life Cycle Assess. (2022), https://doi.org/10.1007/s11367-022-02114-0.