



**AALBORG
UNIVERSITY**

MASTER'S THESIS

**The embodied carbon reduction potential of optimised
energy retrofits in the Danish building stock**

Jakub Jan Sulek

MD Tanveer Hasan Chowdhury

Supervisor – Kai Kanafani

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Abstract

This report evaluates the embodied carbon reduction potential of optimised energy retrofits in the Danish residential building stock. The focus is on single-family houses and apartment buildings constructed between 1890 and 1959 and 1960 and 1980, constituting a significant share of existing building stock. A life cycle assessment approach is applied, combining component-level calculations of embodied carbon with upscaling to the national level. Renovation strategies for roofs, ceilings, external walls, ground floors, and floors above ventilated crawl spaces are evaluated using common practice, low-carbon and hybrid material solutions. The results show that embodied carbon impacts vary by component and material choice. Roofs and external walls offer the greatest potential for embodied carbon reduction through optimal cladding choice, while ground floors represent the largest source of embodied emissions. Combined with operational energy savings, integrated renovation strategies can reduce total life-cycle emissions, especially in buildings constructed before 1960.

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1. Introduction

1.1 Background

The building sector accounts for nearly 39% of global greenhouse gas emissions with 28% coming from building energy use and 11% from the production of building materials (World Green Building Council, 2022). While new buildings will face stricter regulations starting in 2025, renovations (despite representing nearly half of the sector's revenue) remain largely unregulated. A rising challenge is that many renovation strategies still focus mainly on reducing operational energy consumption, even though embodied emissions from construction materials also contribute to the total climate impact. This shift is becoming increasingly crucial as Denmark's energy supply relies more heavily on renewable sources, reducing the carbon intensity of operational energy use. Consequently, the importance of embodied carbon will continue to rise. As a result, identifying renovation approaches that reduce total life-cycle emissions becomes more complex. Research indicates that renovating existing buildings can significantly reduce emissions, but most studies focus on specific building types or small-scale measures, leaving the potential at the national level unclear. This project aims to bridge that gap by evaluating renovation strategies from both operational and embodied carbon perspectives, therefore contributing to Denmark's 2030 goal of reducing greenhouse gas emissions by 70% compared to 1990 levels, as well as its long-term ambition of achieving climate neutrality by 2050 (Ministry of Foreign Affairs of Denmark, 2023).

1.2 Literature review

Effective building renovation requires a life-cycle perspective that considers both operational energy use and embodied carbon emissions from construction materials. National studies demonstrate that focusing solely on energy efficiency is insufficient to achieve meaningful greenhouse gas reductions, particularly as the carbon intensity of energy supply decreases (Kanafani et al., 2021).

Life-cycle assessment-based methods have been proposed to evaluate the climate efficiency of different renovation types and component-level interventions, enabling comparisons between energy savings and material-related impacts (Kanafani et al., 2021). Complementary cost-optimal analyses based on national building data indicate that renovation strategies should balance long-term energy savings with investment costs to ensure both environmental and economic feasibility (Kragh et al., 2025).

International academic literature supports these findings, showing that renovation measures such as insulation upgrades can substantially reduce operational energy demand but may increase embodied emissions if material choices and renovation sequencing are not carefully optimized (Kanafani et al., 2021). Studies focusing on the Danish building stock further indicate that deep renovation of dwellings constructed before 1980 offers significant emission reduction potential, but only when embodied carbon and material efficiency are explicitly addressed alongside operational savings (Kragh et al., 2025).

1.3 Research questions

The main research question of this study is:

How can embodied carbon reduction strategies be integrated with building envelope energy retrofitting to improve the life-cycle sustainability performance of existing residential buildings?

To address this, the following sub-questions are investigated:

1. Which embodied carbon reduction strategies most effectively complement building envelope energy retrofitting across representative residential building typologies?
2. How do material choices and envelope retrofit design approaches influence both operational energy demand and embodied carbon emissions over the building life cycle?
3. How does the integration of energy retrofitting and embodied carbon reduction strategies affect total life-cycle greenhouse gas emissions for buildings from different construction periods?

4. To what extent can integrated energy and embodied carbon reduction strategies in building renovation contribute to national climate mitigation targets?

2. Methodology

This study combines building energy performance calculations with life-cycle assessment (LCA) to evaluate the climate impacts of building envelope renovation. Energy modelling quantifies reductions in heat loss and operational carbon emissions, while LCA captures the embodied carbon associated with renovation materials and processes. Together, these methods enable a consistent life-cycle comparison of renovation strategies across building components, typologies and construction periods.

In this study, energy retrofitting refers specifically to interventions on the building envelope, excluding windows, to reduce heat loss and lower operational energy demand. Previous research shows that improving insulation levels significantly reduces heat loss and contributes to lower operational and life-cycle carbon emissions (Dodoo et al., 2010). The research, therefore, focuses on identifying insulation-focused retrofit strategies and material choices that minimize both operational and embodied carbon emissions over the building life cycle.

2.1 Research approach

Findings from the literature review inform the development of the research framework by identifying common retrofit measures, typical material compositions across historical construction periods and approaches for evaluating both operational and embodied carbon. Quantitative analysis assesses carbon impacts using LCA calculations, while qualitative insights support the interpretation and validation of the results.

2.2 Selection of time frames and building typologies

69% of the heated buildings and 68% of the heated floor area are in buildings constructed before 1979, when energy requirements for new buildings were less stringent. Heating consumption in these buildings, therefore, accounts for approximately 77% of the total heating consumption in heated buildings (Kragh et al., 2025). Further research into this study provided information on the total heated area among main building types, from the

time frame before 1890 to 1979, with the two biggest contributors being apartment buildings with 38% and detached single-family houses with 33%.

Typology	Total heated area in the energy level database (m ²)						Total (m ²)	Share (%)
	-1890	1890-	1930-	1950-	1960-	1973-1979		
Farmhouse	1 451 549	2 131 685	510 883	173 372	201 151	150 836	4 619 476	3
Detached house	3 350 604	9 843 561	6 599 948	5 486 847	15 756 648	8 071 508	49 109 117	33
Terraced house	478 315	902 831	1 095 348	1 082 253	2 354 572	1 735 137	7 648 455	5
Apartment building	3 956 119	16 239 525	12 623 743	6 840 105	12 338 977	4 199 708	56 198 177	38
Business	1 821 766	3 958 220	1 735 862	1 592 595	6 111 067	2 973 534	18 193 043	12
Institution	422 438	1 871 171	1 384 132	1 910 087	4 410 168	2 423 487	12 421 482	8

Table 1: Total heated area in the energy level database 1890-1979 (m²). Adapted from: Kragh et al., 2025

Another key reason for analysing the periods 1890-1959 and 1960-1980 separately is that they represent different construction practices, material use and levels of thermal performance. The introduction of the first Danish Building Regulations in 1961 marks a regulatory boundary between these periods,

2.3 Life cycle assessment (LCA)

Embodied carbon impact

Embodied carbon impact is assessed using the Life Cycle Assessment (LCA) method in accordance with the EN 15978 framework. LCA is used to quantify the environmental impacts of a building component over its entire life cycle, from material production to end-of-life stages. It provides a framework for evaluating the combined effects of operational energy use and embodied impacts. It is subsequently used to identify payback time and enable consistent comparison between renovation scenarios.

Stage	Product			Construction process		Use stage							End of life				Beyond system
Module	Raw material supply	Transport	Manufacturing	Transport	Construction installation	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction demolition	Transport	Waste processing	Disposal	Reuse, recovery, recycling potential
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D

Table 2: Stages considered in the life cycle assessment

The analysis considers carbon emissions across different life-cycle stages seen in Table 2. As required by BR18, the stages examined in this report include A1-A3, B2, B4, B6 and C3-C4, which cover material production, retrofit implementation, replacement, operational energy use and end-of-life impacts. Each building typology and construction period is evaluated using LCA for the two renovation methods.

Environmental data for materials are primarily based on the generic dataset provided in BR18, which represents average climate impacts for common construction materials. If a relevant material is not available in the generic dataset, specific environmental product declarations (EPDs) are used. The assessment is based on a 50-year reference study period. Further in the study, an average embodied impact is calculated at the component level. For apartment buildings, this average is based on four components: roof, ceiling, external wall and ground floor slab. For single-family houses, five components are included (with the addition of the floor above a ventilated crawl space). These averaged component impacts are then used in the upscaling calculations, both to determine the annual embodied impact per square metre of heated floor area (building level) and the embodied emissions with a fixed annual renovation rate.

To ensure that this averaging approach is accurate, components are assessed separately by construction period and, for the 1960-1980 period, by the building regulations

in force at the time of construction. Renovation methods are also divided consistently across components. The resulting component-specific divisions and assumptions are described in detail in the results analysis.

Operational carbon impact

Operational carbon impact is assessed by calculating the reduction in space-heating demand resulting from improved thermal performance of building envelope components after renovation.

For each building typology and construction period, typical envelope components (roof, ceiling, external wall, ground floor and floor above crawl space, where applicable) are defined. U-values are calculated for each component in its existing condition and after renovation. The difference between pre- and post-renovation U-values represents an improvement in thermal performance.

Component heat savings are calculated using 3,765 heating degree days per year and an indoor reference temperature of 20°C, representing Danish climatic conditions (Mortensen et al., 2018). Annual transmission heat savings per square meter of component are calculated as:

$$\Delta\Phi_{\text{construction}} = (U_{\text{before}} - U_{\text{after}}) \times 90.36 \text{ [kWh/m}^2\text{/year]}$$

For each typology and time frame, average heat savings are calculated by averaging the results of the typical components. These average values are then used for building-level and national-level calculations. Operational energy savings are converted to CO₂e using the relevant emission factor for delivered heating energy.

Upscaling to the national level

National operational carbon savings are estimated by upscaling component-level results using representative building stock data. Average component heat savings are multiplied by the total unrenovated component area at the national level for each building typology and construction period. An annual renovation rate of 2% is applied over a 50-year reference study period, corresponding to an average renovation rate of 1/50 per year. This approach accounts for the varying service lives of building envelope components, which are

renovated incrementally rather than simultaneously. Employing a constant rate enables consistent comparison of operational and embodied carbon impacts throughout the entire life cycle. While actual renovation schedules differ among buildings, this assumption offers a transparent and robust foundation for national-level assessments.

Carbon payback time

Carbon payback time is calculated to assess how quickly operational carbon savings offset the embodied carbon emissions of renovation.

Total embodied carbon emissions are obtained from the life-cycle assessment of each renovation measure. Annual operational carbon savings are calculated as described above. Carbon payback time is calculated as:

$$\text{Carbon payback time} = \frac{\text{Embodied carbon (kg CO}_2 \text{ e)}}{\text{Annual operational carbon savings (kg CO}_2 \text{ e/year)}}$$

This calculation is performed at the component level for all renovation scenarios, enabling direct comparison of climate effectiveness across components, building typologies and construction periods.

2.4 Component renovation

This section outlines the renovation methods analysed for representative building typologies. The renovation methods presented form the basis for the U-Value improvement calculations and LCA. As mentioned above, renovation measures are evaluated based on whether they lead to a net reduction in climate impact over the assessment period, rather than focusing solely on energy savings.

It is important to note that in Danish renovation practice, exposed masonry façades are often considered to have architectural or heritage value and are typically kept visible. For this reason, real-life energy renovation of walls focuses on cavity insulating or insulating from the inside, which preserves the original facade. External insulation covering the masonry facade is less common and is often avoided for aesthetic and conservation reasons. In this study, these conventions are deliberately put aside to explore the performance potential of

externally insulating masonry facades. This approach is used as an atypical scenario to evaluate the maximum energy savings and their climate impacts. The intention is not to propose a generally applicable solution, but to quantify the potential benefits.

Two renovation methods are considered:

- Common practice renovation
- Low-carbon renovation

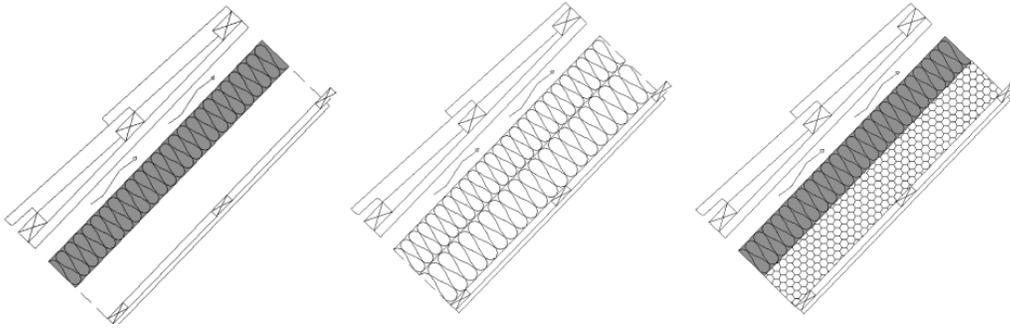


Figure 1: Roof renovation. Renovation methods are as follows: Existing condition, common practice, low-carbon practice.

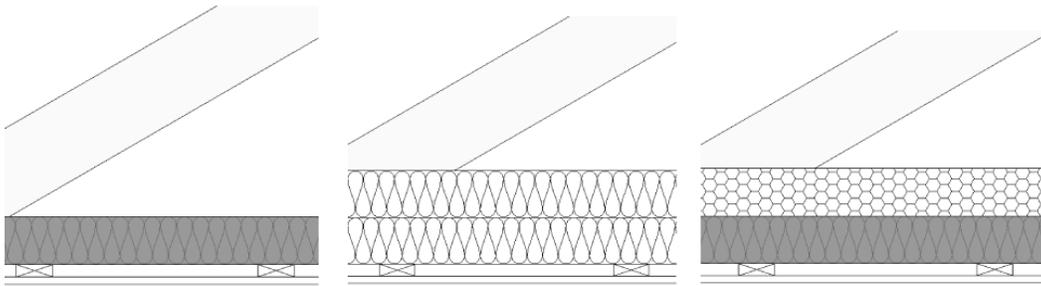


Figure 2: Ceiling renovation. Renovation methods are as follows: Existing condition, common practice, low-carbon practice

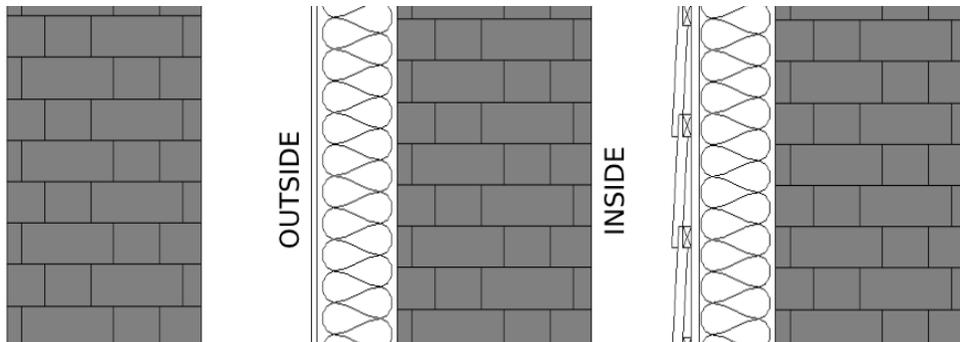


Figure 3: Solid masonry wall renovation. Renovation methods are as follows: Existing condition, common practice, low-carbon practice.

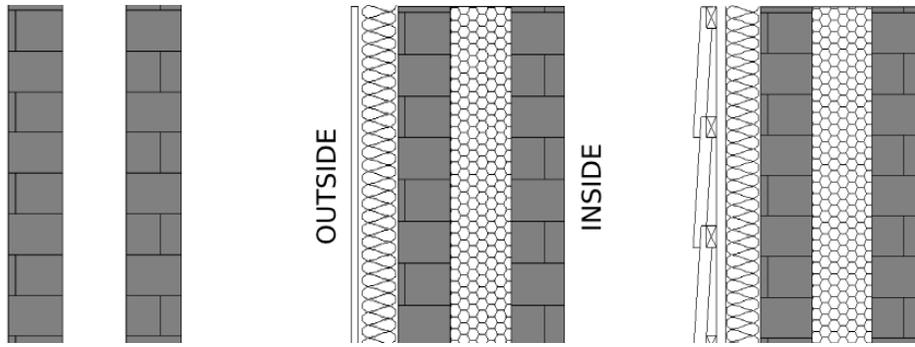


Figure 4: Cavity wall renovation. Renovation methods as follows: Existing condition, common practice, low-carbon practice.

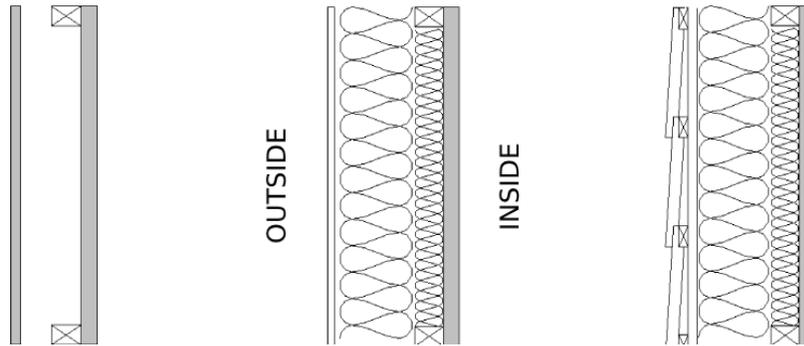


Figure 5: Lightweight wall renovation. Renovation methods as follows: Existing condition, common practice, low-carbon practice.

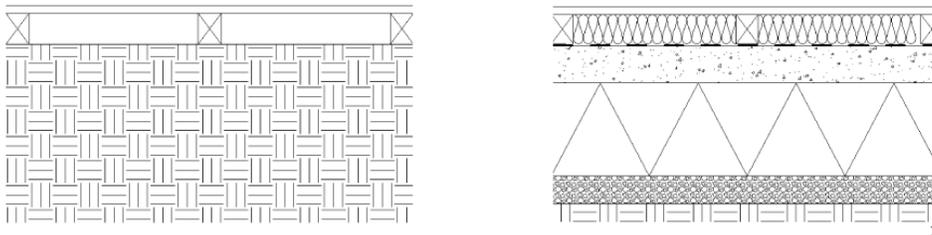


Figure 6: Ground floor slab renovation. Renovation methods as follows: Existing condition, EPS addition.

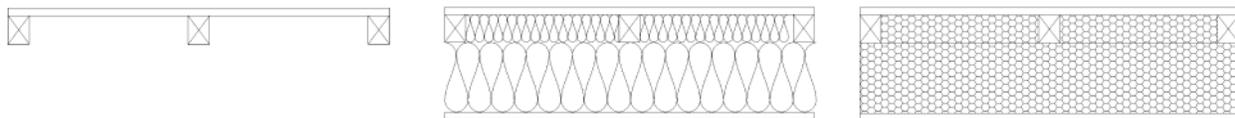


Figure 7: Floor above ventilated crawl space renovation. Renovation methods as follows: Existing condition, common practice, low-carbon practice.

The drawings above are simplified and intended for reference only, as insulation thickness varies depending on building typology, construction period and renovation method. Existing insulation is indicated using a darker shade.

The low-carbon approach is further split into two sub-methods depending on the type of biobased insulation product - wood fibre and cellulose. The renovation methods differ depending on the building envelope materials. For roofs and external walls, this includes the choice of cladding. Moreover, common practice in Denmark uses mineral wool insulation as it is the most widely used and available insulation material. Low-carbon scenarios use biobased insulation materials to explore their potential to reduce embodied carbon. Insulation types are selected according to the building component - blown-in insulation for cavities in walls, roofs and ceilings; batts for roofs where applicable; insulation boards for facades and rigid EPS for floor slabs.

2.5 Data analysis and integration

The study relies on secondary data sources rather than site-specific measurements. Data for renovated building components and heated floor areas by typology and construction period are derived from existing research databases and spreadsheets (BUILD, 2025). Typical component areas, component build-up and the ratio of typical component area to heated floor area per time frame, per typology are obtained from Danish reference building data provided by the *TABULA* database (TABULA Project, 2012).

The ratio calculations, found in Appendix A, are used to scale up total typical component stock in the absence of data for the total component stock at the national level per time frame, per typology, which the study required. In addition, *Håndbog for energikonsulenter* (Energistyrelsen, 2023) is used as support in calculating U-values of existing components, considering representative construction dimensions.

2.6 Delimitation

While this research provides a structured and comprehensive assessment of embodied carbon and energy retrofitting, several limitations should be acknowledged.

Technical building systems are intentionally excluded from this study, as they fall outside the defined methodological boundaries. The analysis focuses specifically on energy renovation of building envelope components and the associated trade-offs between operational energy savings and embodied carbon impacts, rather than on system-level optimization. Factors such as heat losses from technical systems, air infiltration due to airtightness and ventilation-related performance are not included, as their assessment would require whole-building energy modelling beyond the fabric-focused scope adopted in this study. In the case of U-value ground floor slab calculations, the potential case of underfloor heating is disregarded.

3. Results and analysis

3.1 Embodied carbon impact

3.1.1 Component level

While the analysis separates single-family homes from apartment buildings, the assumed construction build-ups, insulation levels for the respective time periods and cladding choices are the same for most of evaluated building components. As a result, the embodied carbon impacts for these components are the same across typologies within the same construction period. This means that both single-family houses and apartment buildings built from 1890 to 1960 result in the same embodied impact values for these components, with a similar pattern for those built between 1960 and 1980. Differences in embodied impact mainly come from the construction period rather than the building typology. The main exceptions are external walls, which differ between typologies and ground floors from 1960-1980, where the structural solution differs from that used in single-family houses from the same period. Therefore, for components that do not differ between typologies (roofs, ceilings and ground floor slabs from the 1890-1959 period) results are presented without typological distinction, as separate graphs would show identical values.

Roof

In the case of the roof, differences in embodied carbon between common renovation practice and low-carbon renovation come from both cladding and insulation choices. Information on the roof cladding of the existing stock of single-family houses for selected time frames was obtained from *Danmarks Statistik, 2025*. It was used to account for the end-of-life stages of the existing cladding. The available data indicates the share of different roof claddings from each period, but does not differentiate between renovated and unrenovated roofs for each specific cladding. As it is therefore not possible to determine how many renovated roofs originally had fibre cement plates or roof tiles, the most common roof cladding for the relevant construction period is selected as a representative for the analysis.

Time	Bitumen felt	Fibre cement (inc. absestos)	Concrete tile	Clay tile	Thatched roof
Before 1900	983	34094	6959	16704	15151
1900-1904	504	17076	4308	7425	1146
1905-1909	236	8334	2776	4966	175
1910-1914	238	9737	3940	8093	166
1915-1919	218	5497	2328	6546	151
1920-1924	391	7855	3611	11081	175
1925-1929	563	8746	4779	16444	177
1930-1934	3151	8217	5289	19260	114
1935-1939	4916	7185	4565	16870	96
1940-1944	1035	4917	2638	9028	52
1945-1949	1143	7283	3603	14128	80
1950-1954	1687	13206	3830	23982	63
1955-1959	2557	24590	2957	10641	50
TOTAL	17622	156737	51583	165168	17596

Table 3: Roof cladding types, single-family house (1890-1959)

Time	Bitumen felt	Fibre cement (inc. absestos)	Concrete tile	Clay tile	Thatched roof
1960-1964	4991	53123	4664	9065	144
1965-1969	3206	67314	6893	17955	172
1970-1974	2391	81284	13729	22646	190
1975-1979	1690	53145	26707	14272	156
TOTAL	12278	254866	51993	63938	662

Table 4: Roof cladding types, single-family house (1960-1979)

Tables 3 and 4 show the numbers of single-family houses constructed in time frames 1890-1959 and 1960-1980 with their roof cladding types. The roof cladding chosen as the representative existing cladding for single-family houses built between 1890-1959 is clay tile and 1960-1980 is fibre cement plate.

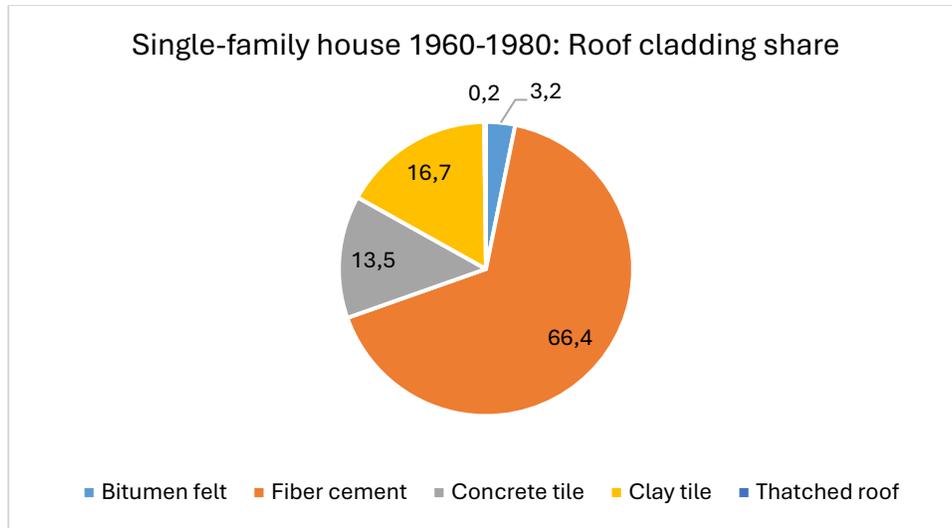


Figure 8: Roof cladding shares, single family house (1960-1980)

Almost 70% of single-family houses built between 1960-1980 used fibre cement plates with asbestos. The plates from this period are still found on many Danish houses, since their use in construction started being gradually phased out by restrictions in the 1980s. Due to health risks associated with asbestos when plates are damaged or removed, replacement is often necessary during renovation.

For apartment buildings, the roof cladding assumptions follow the same time period distribution as for single-family houses. Buildings constructed between 1890-1959 are assumed to have clay roof tiles, while those from 1960-1980 are assumed to have fibre-cement roof plates.

Time	Bitumen felt	Fibre cement (inc. absestos)	Concrete tile	Clay tile	Thatched roof
Before 1900	947	7455	533	6916	87
1900-1904	483	4238	554	2681	3
1905-1909	231	2168	378	1735	1
1910-1914	100	1527	388	2357	1
1915-1919	67	767	218	2029	1
1920-1924	99	755	253	2209	0
1925-1929	92	644	244	2740	1
1930-1934	536	806	267	3859	1
1935-1939	1048	1033	218	3761	1
1940-1944	275	584	98	1571	0
1945-1949	122	540	156	1939	0
1950-1954	136	772	72	2315	1
1955-1959	291	1127	20	962	0
TOTAL	4427	22416	3399	35074	97

Table 5: Roof cladding types, apartment building (1890-1959)

Time	Bitumen felt	Fibre cement (inc. absestos)	Concrete tile	Clay tile	Thatched roof
1960-1964	267	1226	37	483	1
1965-1969	400	1108	85	398	0
1970-1974	499	1025	147	209	0
1975-1979	207	420	117	157	0
TOTAL	1373	3779	386	1247	1

Table 6: Roof cladding types, apartment building (1960-1979)

For buildings constructed between 1890 and 1960, the roof construction is assumed to have no existing insulation. In 1961 the Danish Building Regulations were first introduced. For roofs constructed when BR61 until BR72 was binding, the existing insulation level is assumed to be 80 mm of mineral wool, reflecting the minimum energy performance requirements at the time. For roofs constructed under BR77, the existing insulation level is assumed to be 210 mm of mineral wool. Therefore, two embodied carbon calculations are

carried out for this period - one represents renovation of roofs constructed under BR61-72 and the other represents renovation of roofs constructed under BR77, reflecting differences in energy performance requirements at the time of construction.

Furthermore, for buildings constructed between 1960-1980, the existing mineral wool insulation is assumed to be removed and disposed of (with new mineral wool installed) in the common renovation practice. In reality, renovation conditions vary and it is not possible to predict how much existing insulation can be kept in place in each case. In the low-carbon renovation scenarios, the existing mineral wool is therefore assumed to remain. Additional insulation is added using wood fibre insulation and cellulose insulation. This assumption was made in order to explore the potential for embodied carbon reduction by minimising material replacement.

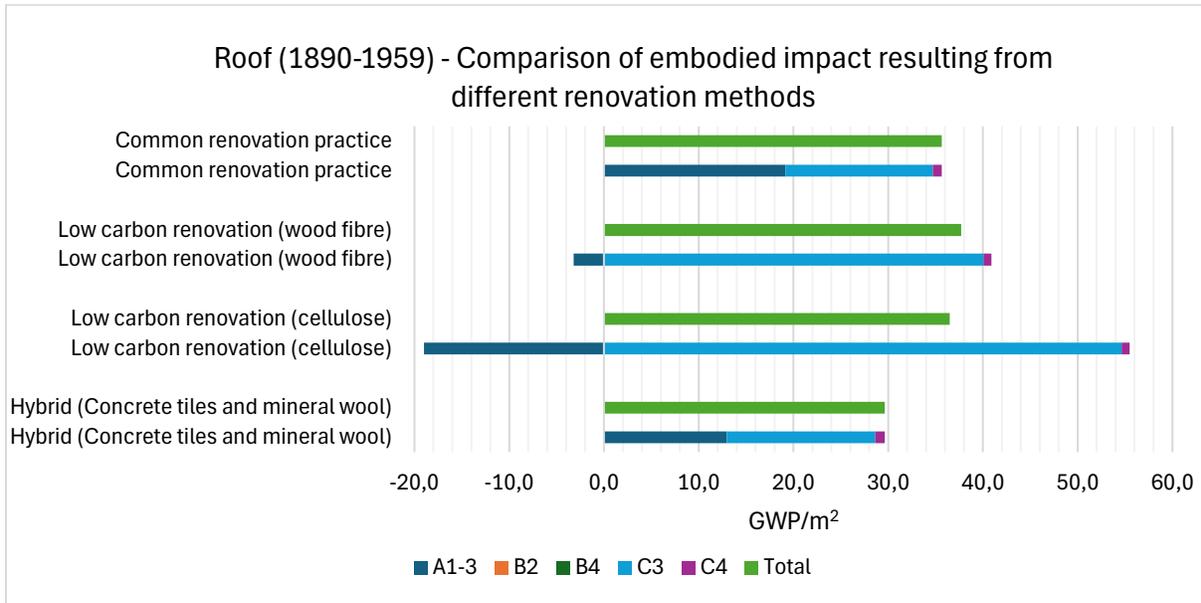


Figure 9: Embodied impact from different methods of roof renovation (1890-1959)

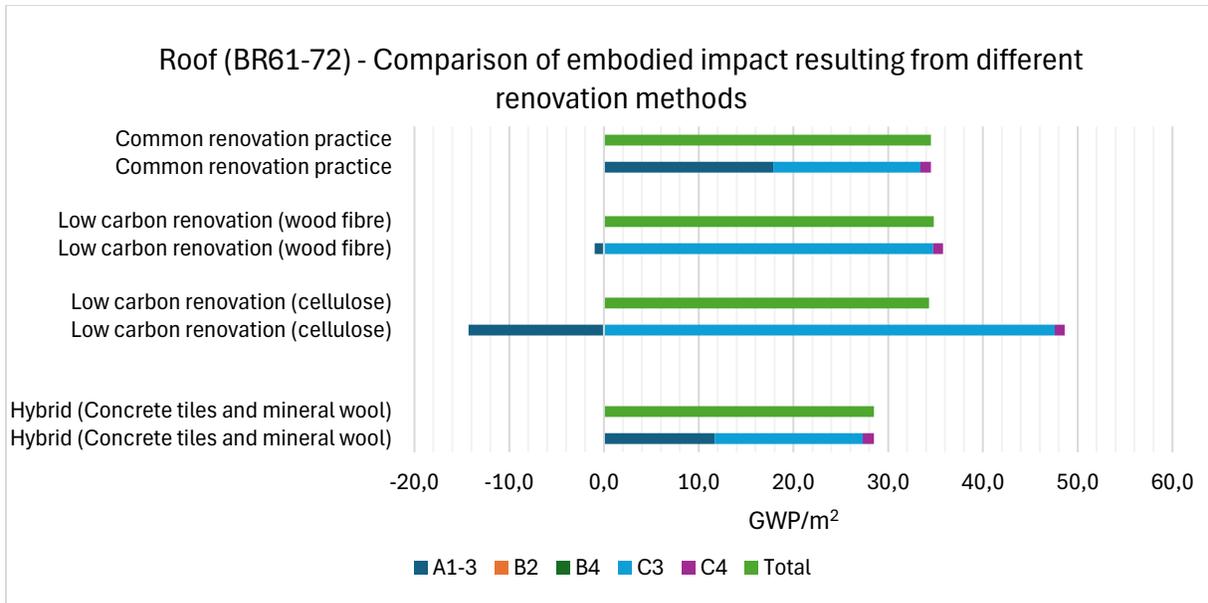


Figure 10: Embodied impact from different methods of roof renovation (BR61-72)

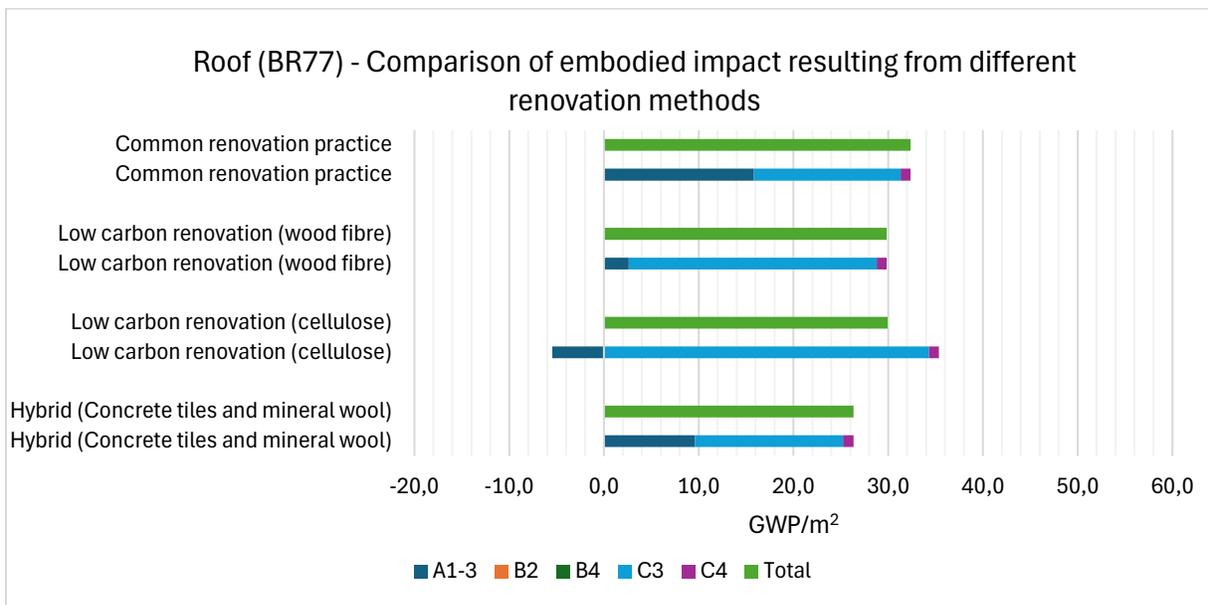


Figure 11: Embodied impact from different methods of roof renovation (BR77)

After analysing the initial renovation methods, it was found that mineral wool insulation resulted in a lower embodied carbon impact than the blown-in biobased insulation materials, based on data from the generic dataset in BR18. To explore this result, a third renovation method was introduced for roof renovation only. In this hybrid scenario, the low-carbon cladding choice (concrete roof tiles) is combined with mineral wool

insulation. The hybrid method results in the lowest embodied carbon impact among the analysed roof renovation scenarios.

The biobased insulation materials show a higher total GWP than the common practice solution when using the generic data. Certain life-cycle stages contribute relatively high impacts, which increase the overall result. Wood fibre insulation has a thermal conductivity similar to mineral wool and therefore requires a comparable thickness, but results in a higher embodied impact in the LCA. Cellulose insulation has a higher thermal conductivity, requiring greater thickness to achieve the same thermal performance, which further increases its life-cycle carbon impact. Detailed LCA calculations and construction build-ups for all scenarios are provided in Appendix B.

Ceiling

In the case of the ceiling, the renovation scenarios differ only in the choice of insulation, as the existing structural components are unchanged. As mentioned above, the embodied impact based on generic data shows that mineral wool results in lower emissions than the biobased insulation. Since it is the only material added in the ceiling build-up, the choice of insulation determines the embodied carbon outcome. Therefore, the common renovation practice using mineral wool insulation represents the most beneficial method in terms of embodied carbon for ceiling renovation.

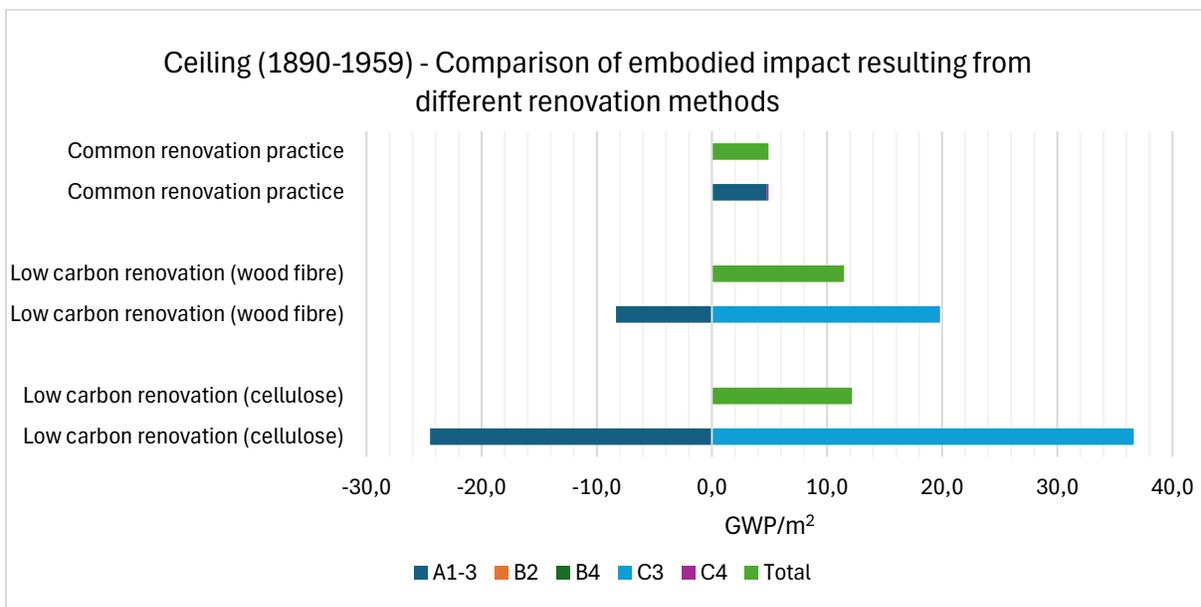


Figure 12: Embodied impact from different methods of ceiling renovation (1890-1959)

An additional scenario including the installation of a vapour barrier within a suspended ceiling structure was also assessed. This option required an aluminium frame, which has a relatively high embodied carbon impact. As a result, this scenario shows the highest embodied emissions among the ceiling renovation options. It was therefore included as a test case only and is not considered further for other building typologies or construction periods

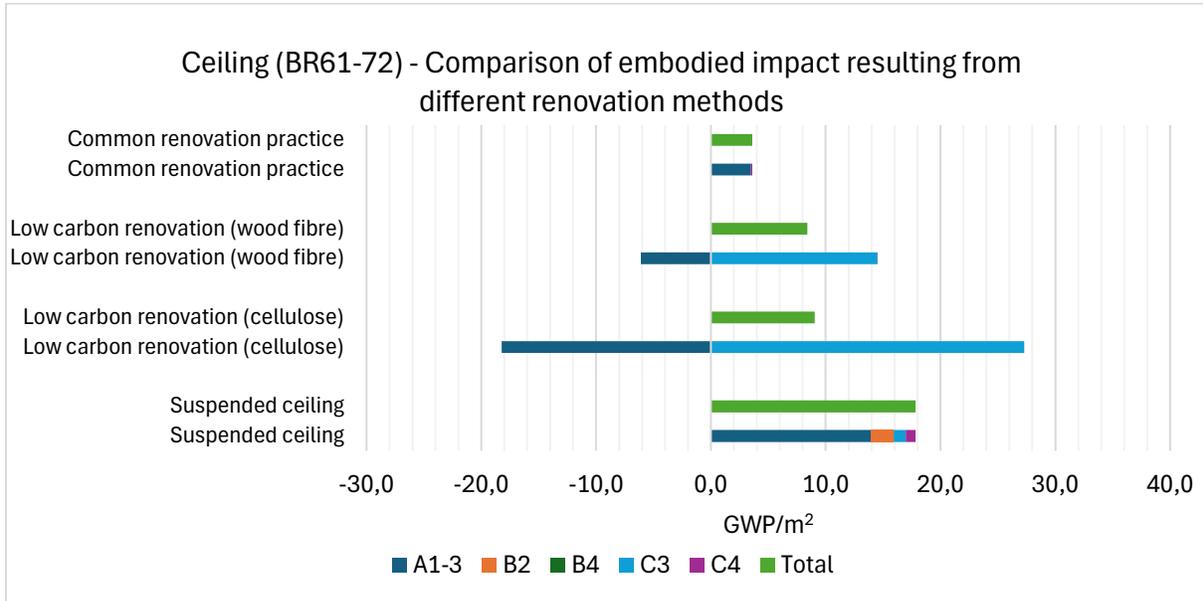


Figure 13: Embodied impact from different methods of ceiling renovation (BR61-72)

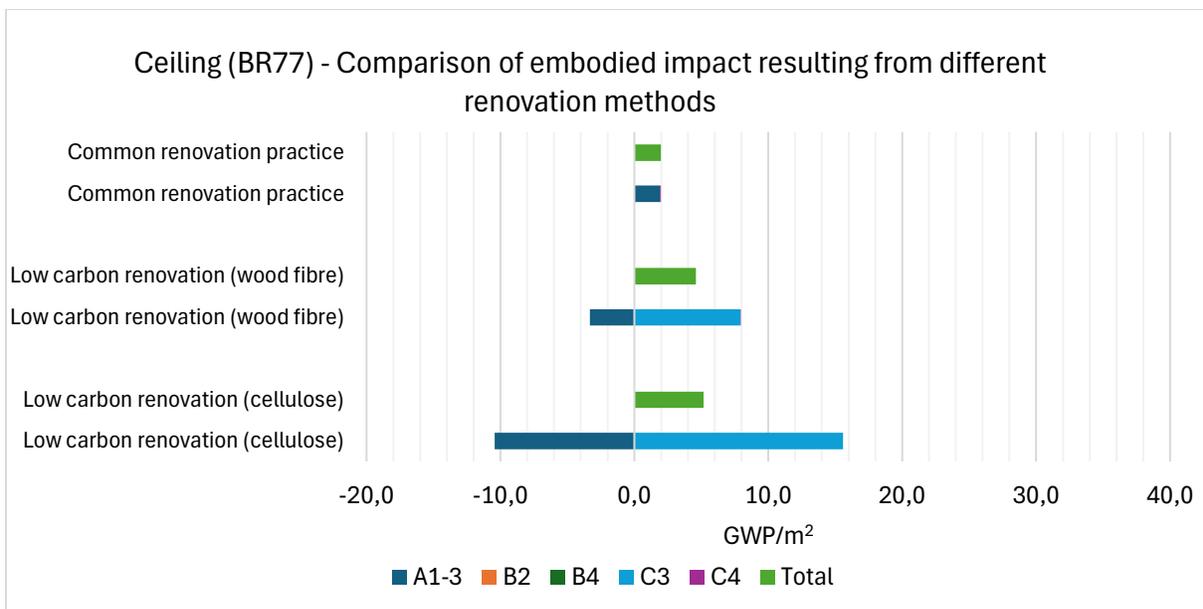


Figure 14: Embodied impact from different methods of ceiling renovation (BR77)

For the time frame 1960-1980, the approach follows the same logic as for roof constructions. Ceilings constructed under BR61-72 are assumed to contain 100 mm of existing mineral wool insulation. For ceilings constructed under BR77, the existing insulation level is assumed to be 200 mm of mineral wool.

External walls: Single-family house 1890-1959

External walls are grouped into three wall types: solid masonry walls, cavity walls and lightweight walls. For buildings constructed between 1890 and 1960, it is assumed that no existing insulation is present in any of these wall types.

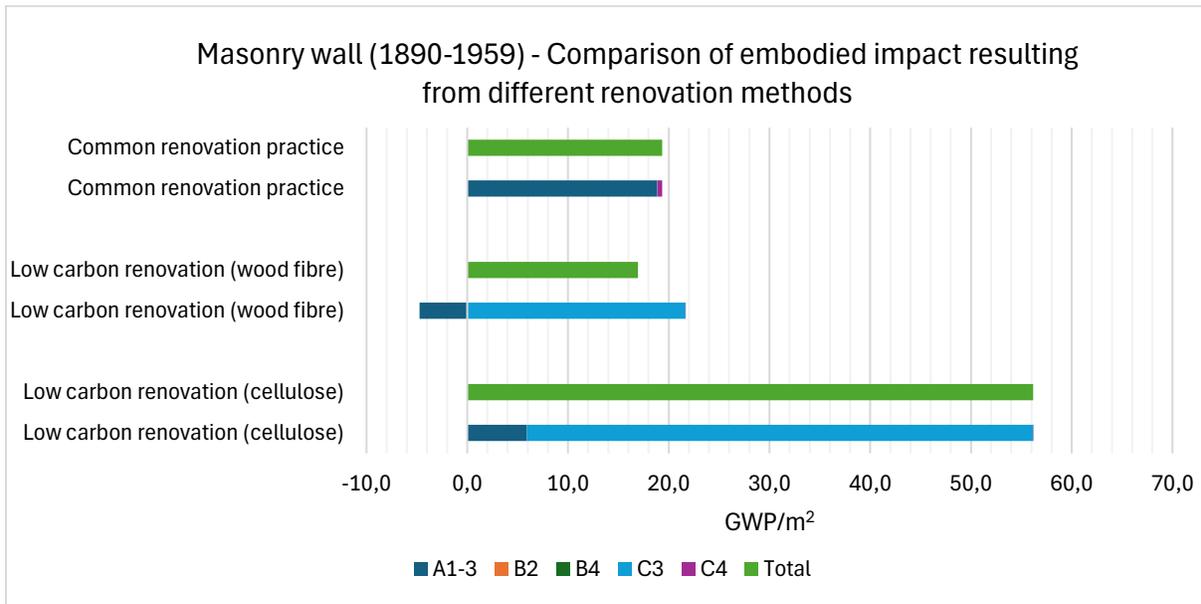


Figure 15: Embodied impact from different methods of masonry wall renovation (1890-1959)

For solid masonry walls, in the common renovation practice, mineral wool insulation boards are installed on the exterior masonry façade and finished with lime-cement plaster as cladding. In the low-carbon renovation scenarios, the façade is insulated using wood fibre boards or cellulose insulation boards with a screen brick tile (*skærmtegl*) cladding mounted on a timber frame.

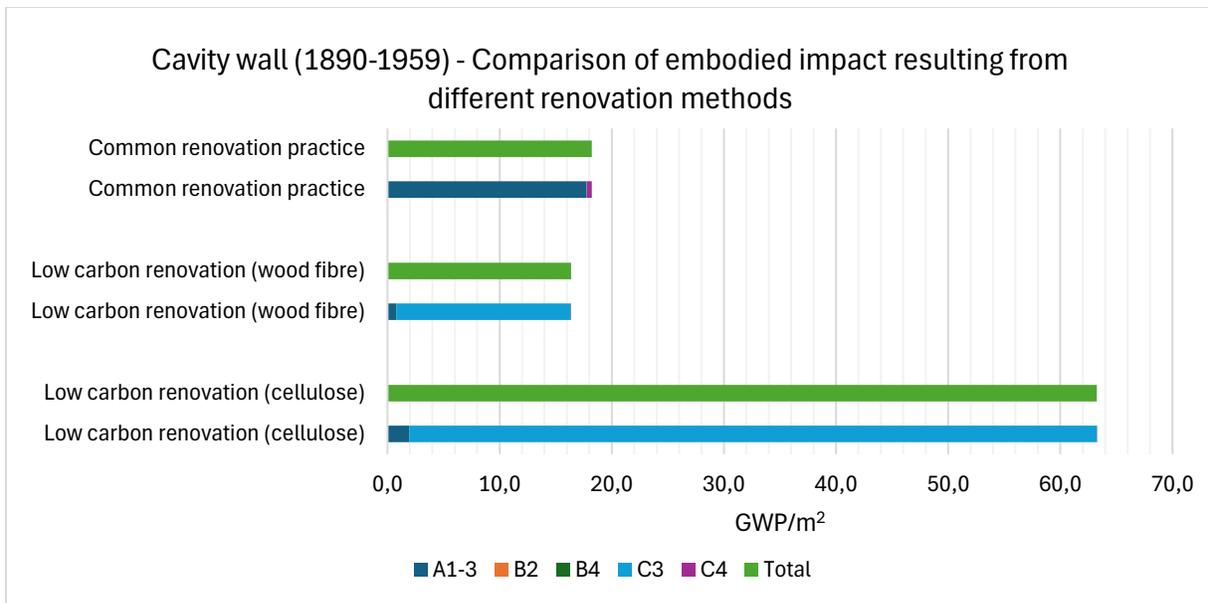


Figure 16: Embodied impact from different methods of cavity wall renovation (1890-1959)

For cavity walls, the renovation build-up follows the same external insulation solutions as for solid masonry walls, with the addition of blown-in insulation filling the existing cavity.

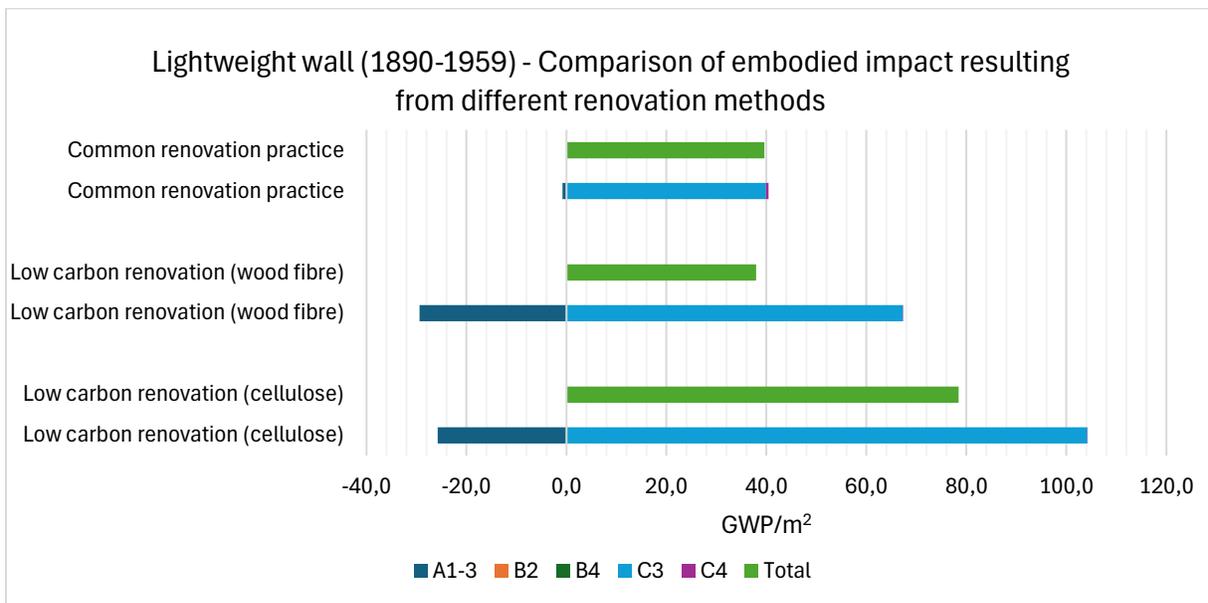


Figure 17: Embodied impact from different methods of lightweight wall renovation (1890-1959)

For lightweight walls, the cladding solutions correspond to those used for the other wall types, while the insulation thickness is adjusted to reflect the structural characteristics and thermal requirements of lightweight constructions.

External walls: Single-family house 1960-1980

In the period 1960-1980, external walls are subject to different energy performance requirements, resulting in varying insulation levels. Within solid masonry and cavity walls, distinctions are made between buildings constructed under BR61-67, BR72 and BR77. Within lightweight walls, distinctions are made between buildings constructed under BR61-72 and BR77.

			Total GWP/m ²
Masonry wall	BR61-67	Common renovation practice	18,1
		Low carbon renovation (wood fibre)	17,1
		Low carbon renovation (cellulose)	54,7
	BR72	Common renovation practice	18,1
		Low carbon renovation (wood fibre)	16,5
		Low carbon renovation (cellulose)	54,7
	BR77	Common renovation practice	16,0
		Low carbon renovation (wood fibre)	15,0
		Low carbon renovation (cellulose)	40,0
Cavity wall	BR61-67	Common renovation practice	17,3
		Low carbon renovation (wood fibre)	16,5
		Low carbon renovation (cellulose)	50,0
	BR72	Common renovation practice	18,1
		Low carbon renovation (wood fibre)	16,5
		Low carbon renovation (cellulose)	51,8
	BR77	Common renovation practice	15,8
		Low carbon renovation (wood fibre)	14,9
		Low carbon renovation (cellulose)	40,8
Lightweight wall	BR61-72	Common renovation practice	17,0
		Low carbon renovation (wood fibre)	15,8
		Low carbon renovation (cellulose)	48,1
	BR77	Common renovation practice	15,0
		Low carbon renovation (wood fibre)	13,8
		Low carbon renovation (cellulose)	33,4

Table 7: Embodied impact from different methods of external wall renovation (Single-family house 1960-1980)

It must be noted that, for cavity walls, the embodied impact of renovations under BR72 is higher than under BR61-67. In the BR61-67 case, the renovation assumes that the existing 100 mm cavity is uninsulated and is therefore filled with blown-in insulation,

allowing a thinner layer of insulation boards to be installed on the façade. For buildings constructed under BR72, the cavity is assumed to contain insulation already, resulting in the use of a thicker layer of insulation boards on the façade during renovation. Since insulation boards have a higher embodied impact than blown-in insulation, this leads to the difference in embodied carbon between the two cases.

External walls: Apartment building 1890-1959

Masonry external walls are evaluated under two assumptions here. The first assumes no existing insulation, following the same logic applied to single-family house masonry walls from the same period. Additionally, an alternative case with 50 mm of internal insulation is considered, based on findings from the *TABULA* database (TABULA Project, 2012), which documented a real case where masonry walls in an apartment building were insulated from the inside. Although the share of insulated masonry walls in apartment buildings from this period is unknown, this scenario is included to account for such cases. In the case of cavity wall renovation for apartment buildings from this period, it is identical to that of the corresponding single-family house case, as the construction build-up is the same.

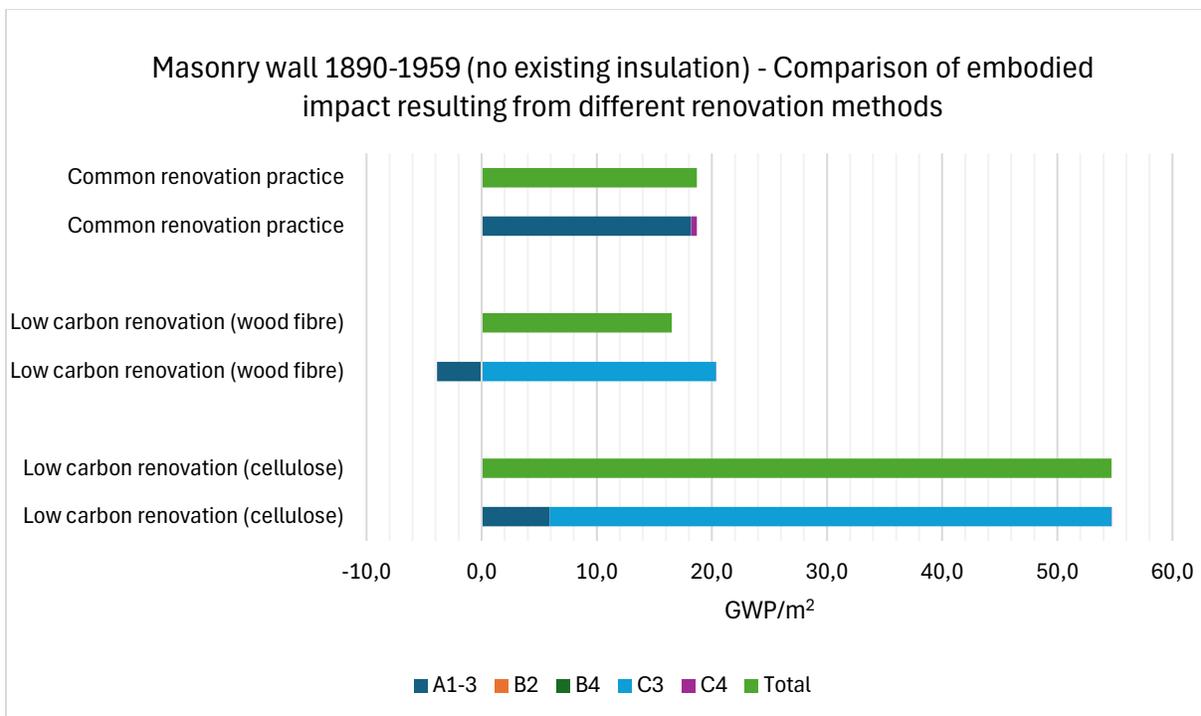


Figure 18: Embodied impact from different methods of masonry wall renovation with no existing insulation (Apartment building 1890-1959)

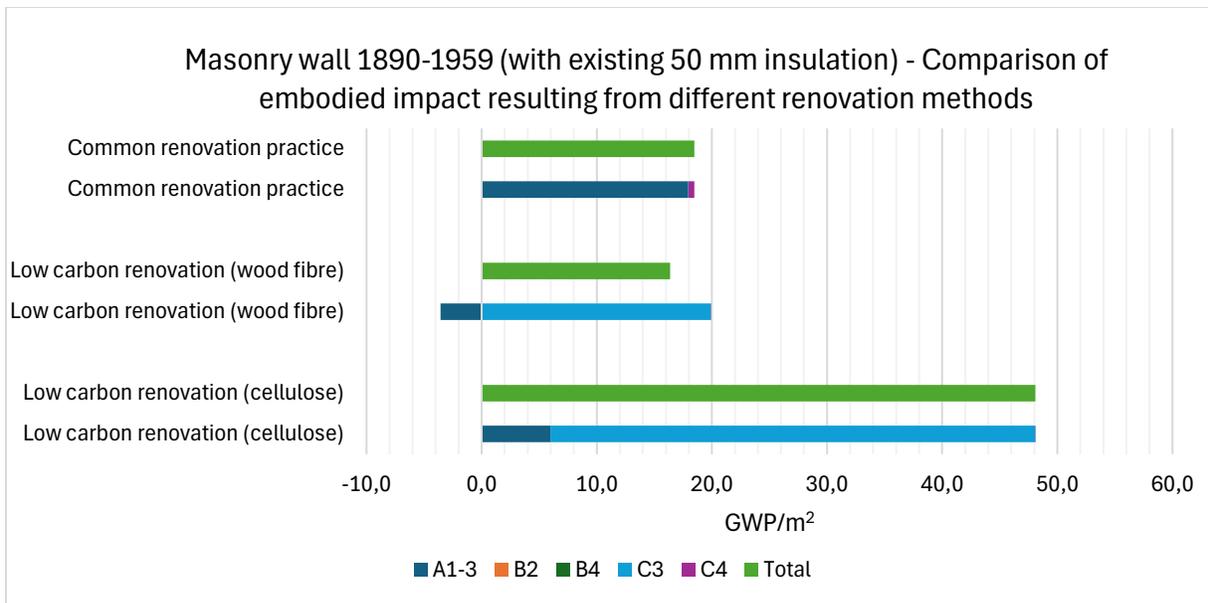


Figure 19: Embodied impact from different methods of masonry wall renovation with existing insulation (Apartment building 1890-1959)

External walls: Apartment building 1960-1980

Three types of external walls are considered, based on documented cases from the TABULA database (TABULA Project, 2012). These include a masonry wall constructed under BR77, a cavity wall constructed under BR77 and a lightweight wall constructed under BR61-72.

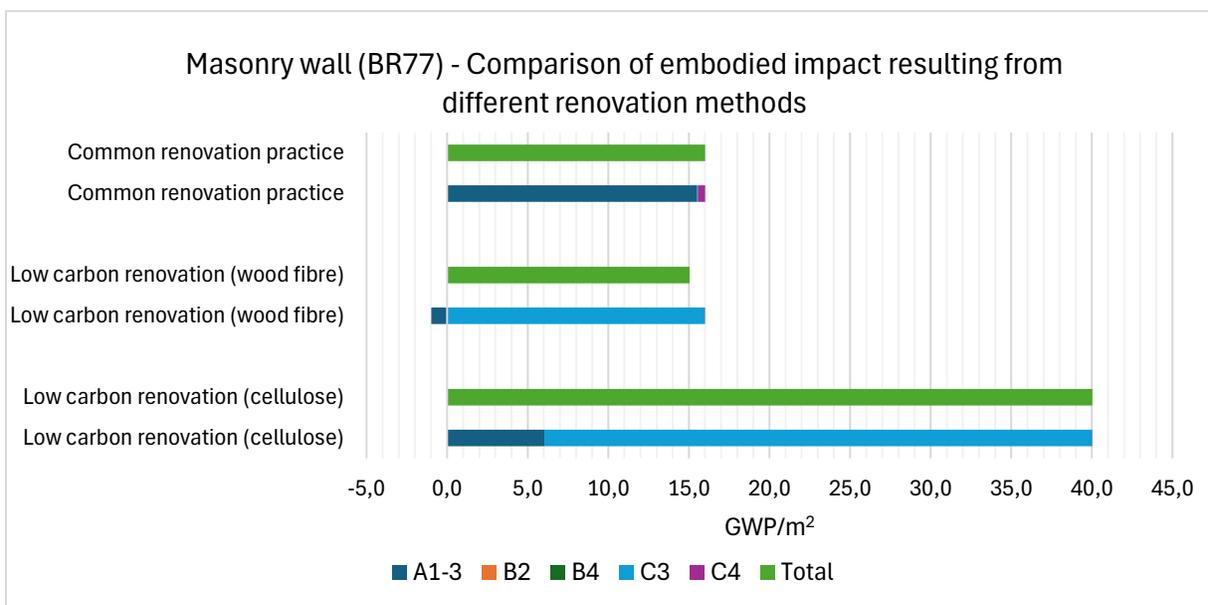


Figure 20: Embodied impact from different methods of masonry wall renovation (Apartment building, BR77)

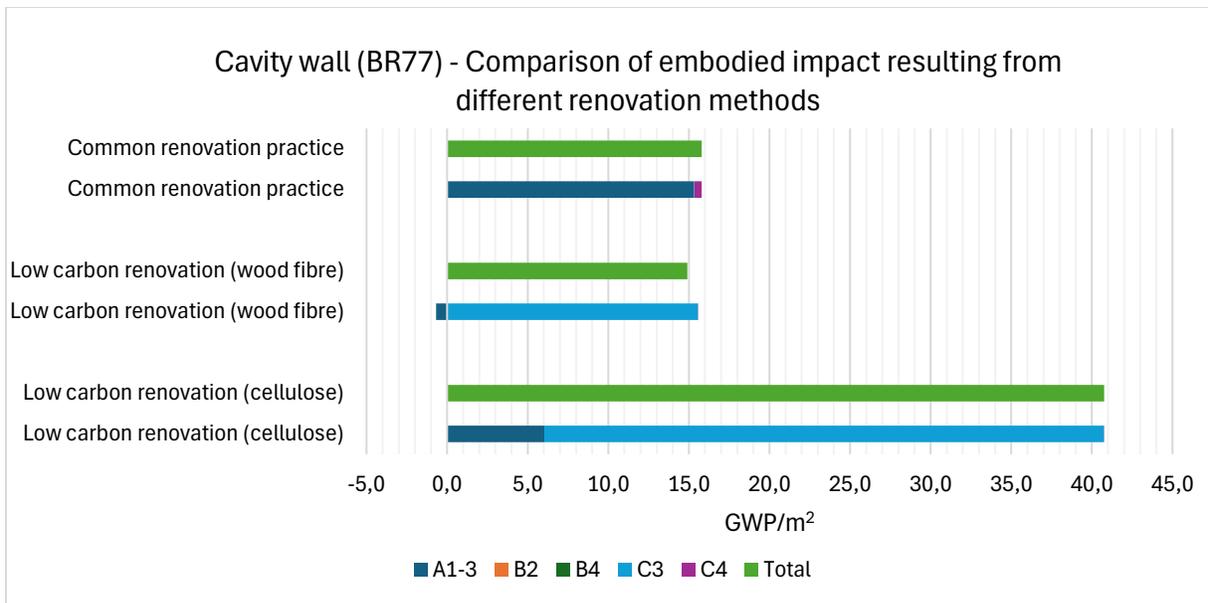


Figure 21: Embodied impact from different methods of cavity wall renovation (Apartment building BR77)

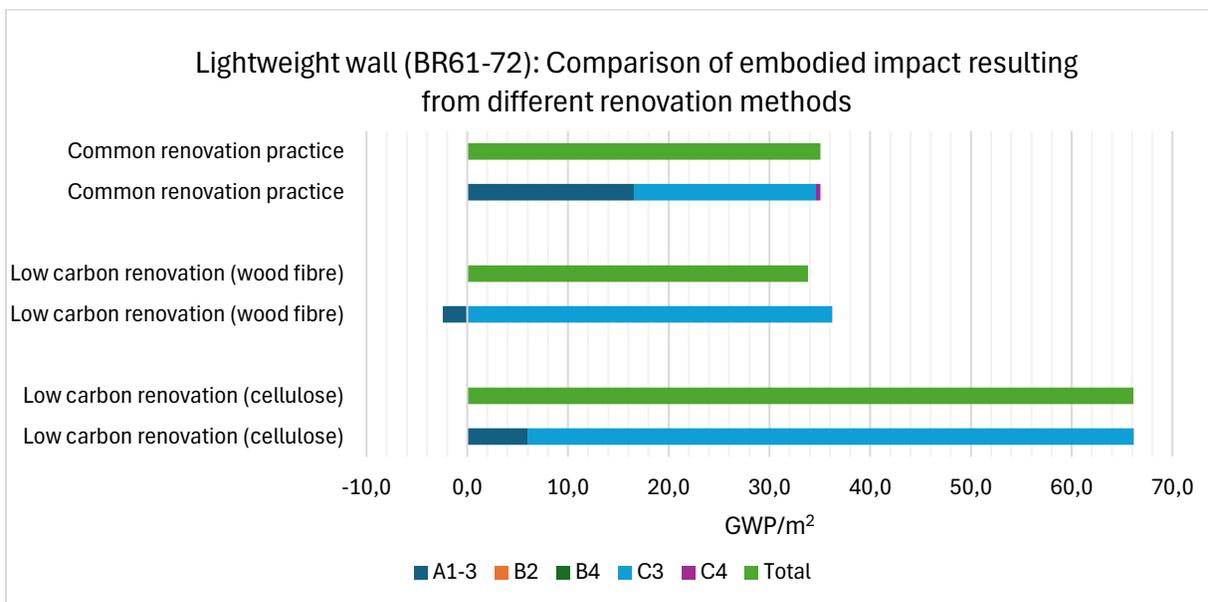


Figure 22: Embodied impact from different methods of lightweight wall renovation (Apartment building BR61-72)

Ground floor: 1890-1959

Similar to the case of roof and ceiling, ground floor constructions from the period 1890-1959 follow the same patterns regarding existing structures and renovation build-ups for both single-family houses and apartment buildings. However, specifically in the case of ground floors, a common renovation practice is evaluated with only a single low-carbon renovation method. The low-carbon method uses recycled EPS insulation, proposed as an

alternative to conventional EPS. Information on recycled EPS is taken from the specific product EPD, as this material is not represented in the generic data provided in BR18.

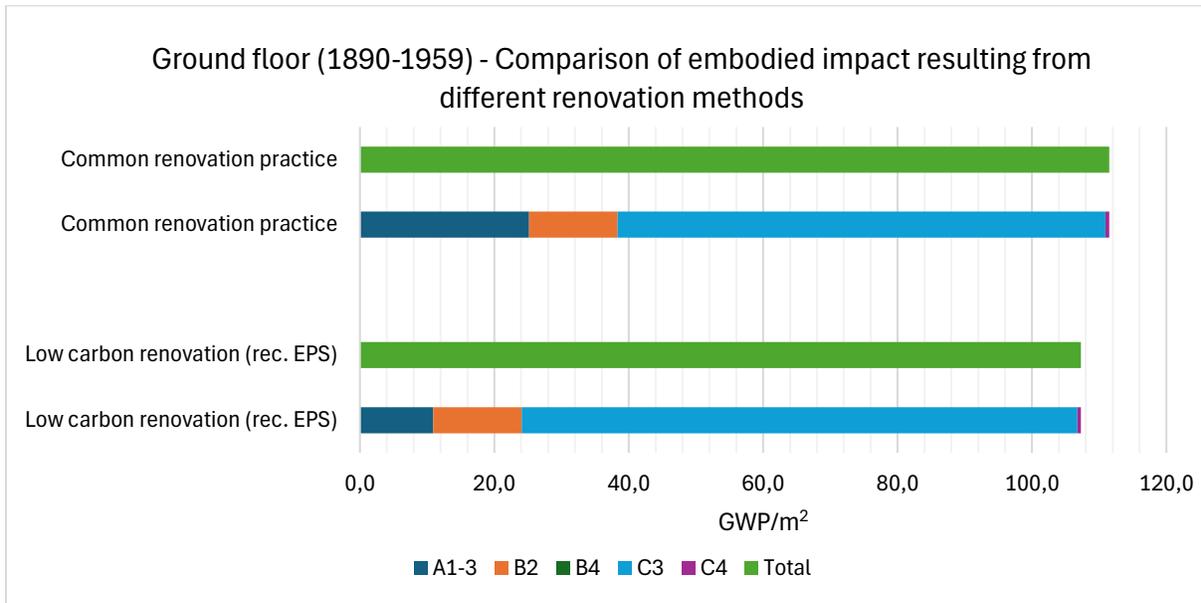


Figure 23: Embodied impact from different methods of ground floor slab renovation (1890-1959)

Ground floor: 1960-1980

As mentioned at the beginning of the chapter, assumptions about existing ground floor structures differ between apartment buildings and single-family houses for the period 1960-1980, therefore producing different results in embodied carbon assessments of their renovation. The build-ups follow the same construction logic as for the 1890-1959 period, with differences in insulation thickness. In common renovation practice, existing mineral wool between the floor joists is assumed to be removed and disposed of before installing new insulation. In the low-carbon renovation scenarios, the existing mineral wool is to be reused.

			Total GWP/m ²
Single family house	BR61-72	Common renovation practice	116,8
		Low carbon renovation (rec. EPS)	113,5
	BR77	Common renovation practice	116,8
		Low carbon renovation (rec. EPS)	112,3
Apartment building	BR61-72	Common renovation practice	142,5
		Low carbon renovation (rec. EPS)	139,9
	BR77	Common renovation practice	145,9
		Low carbon renovation (rec. EPS)	136,2

Table 8: Embodied impact from different methods of ground floor slab renovation (Both typologies, 1890-1959)

As can be seen in Table 8, ground floor contributes more significantly to embodied emissions in apartment buildings for this period. In apartment buildings, the ground floor includes a thicker reinforced concrete layer, which is assumed to be disposed of during renovation with a new concrete layer poured. This results in higher embodied carbon impacts compared to single-family houses, where lighter structural solutions are used.

Floor above ventilated crawl space

The floor above a ventilated crawl space is a construction specific to single-family houses and is not considered for apartment buildings. For the period 1890-1959, a timber floor construction is assumed, following building practice at the time. Two variants are considered: a timber floor without infill and a timber floor with clay infill (*lerindskud*), which was used to regulate moisture, but provided limited thermal insulation.

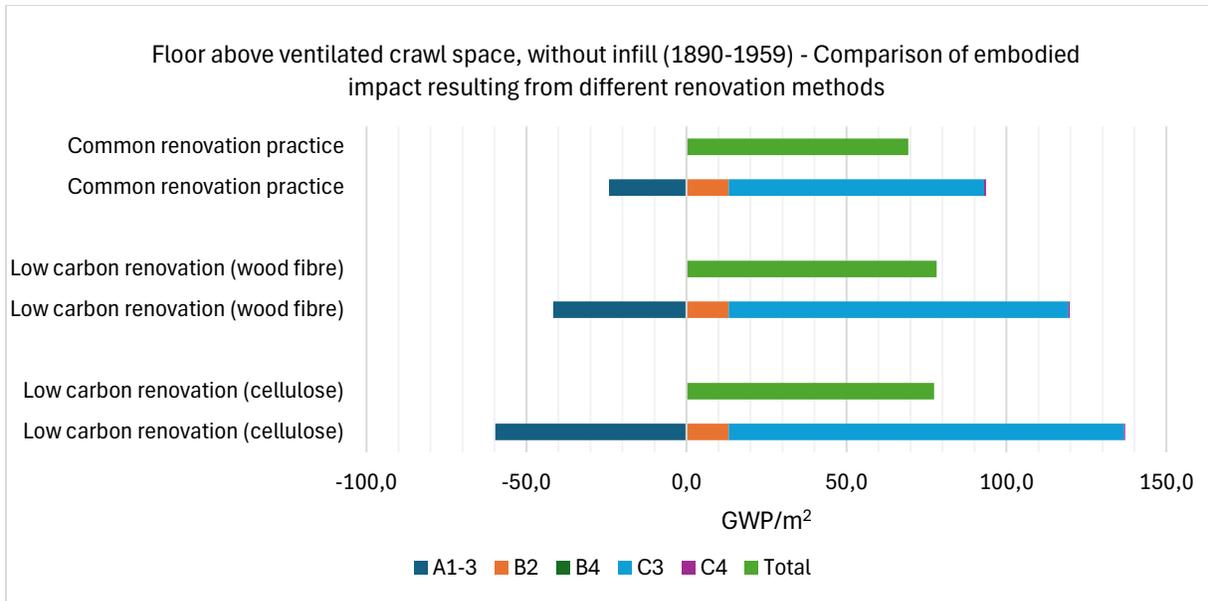


Figure 24: Embodied impact from different methods of floor above crawl space renovation (Without infill 1890-1959)

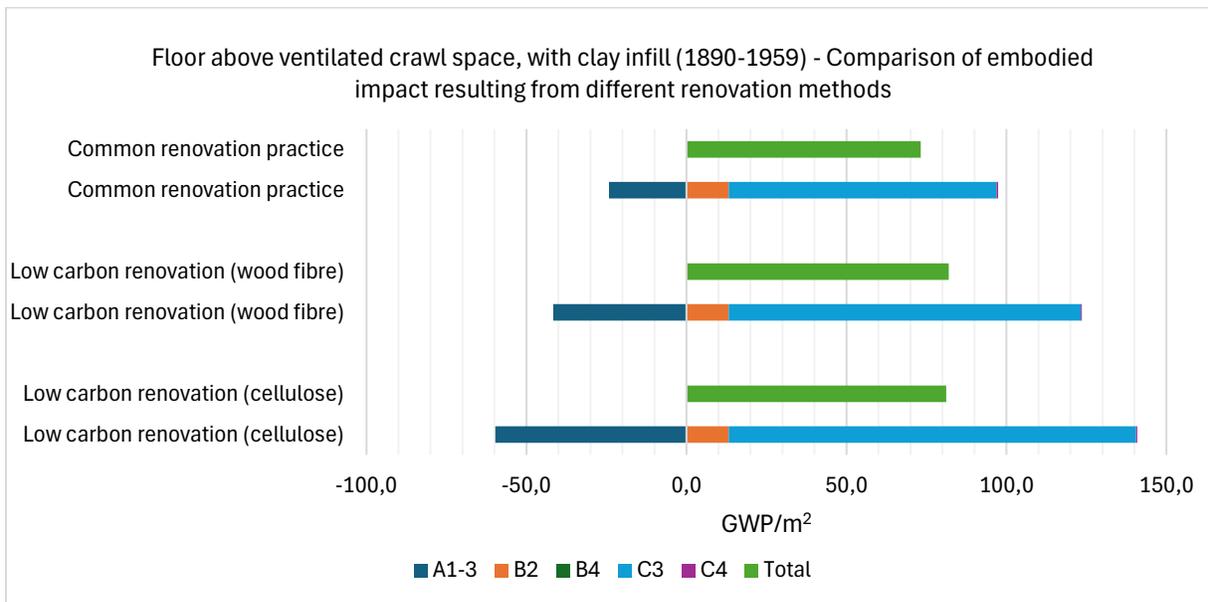


Figure 25: Embodied impact from different methods of floor above crawl space renovation (With clay infill 1890-1959)

As the renovation of this component mainly involves adding new insulation, the choice of insulation material is the dominant contributor to embodied carbon. Under these conditions, the common renovation practice using mineral wool batts results in a lower embodied carbon impact than the biobased blown-in wood fibre and cellulose insulation options. This case is similar to the one observed in the ceiling renovation, which relies heavily on adding insulation.

For the period 1960-1980, two variants of this component are considered: a solid concrete floor and a timber floor. Energy performance requirements remained consistent from BR61 through BR77. Under the common renovation practice, the existing mineral wool insulation between floor joists is assumed to be removed and replaced with new insulation. In the low-carbon renovation scenarios, the existing mineral wool insulation is assumed to remain in place and be reused.

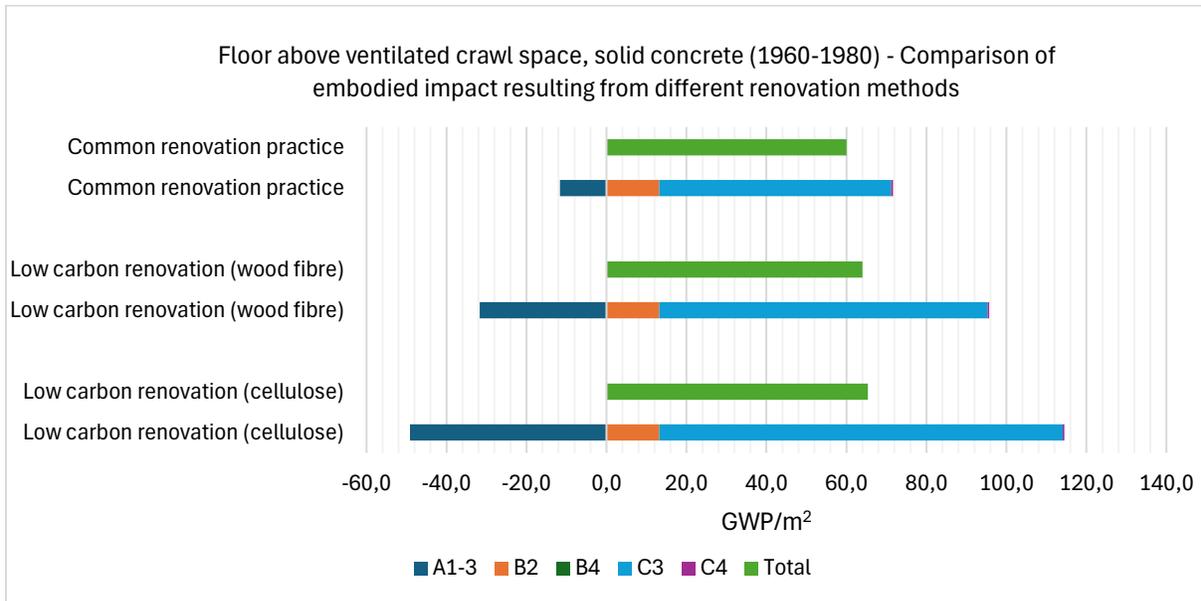


Figure 26: Embodied impact from different methods of floor above crawl space renovation (Solid concrete 1960-1980)

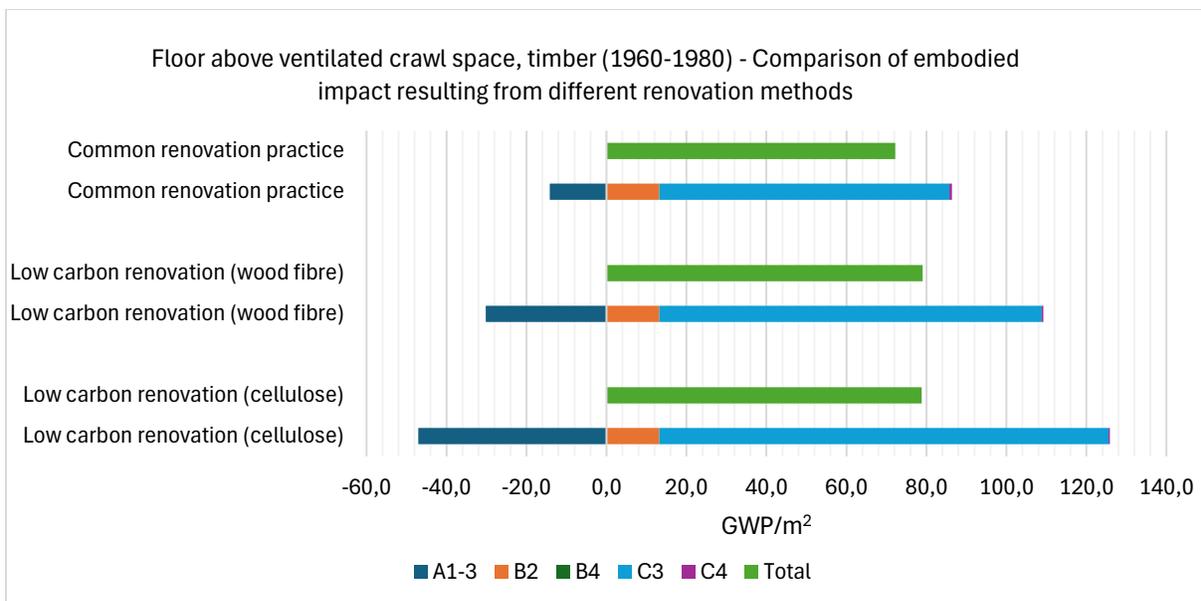


Figure 27: Embodied impact from different methods of floor above crawl space renovation (Timber 1960-1980)

Under the given assumptions, renovation of the concrete floor results in lower embodied carbon emissions than renovation of the timber floor. This is due to the lower insulation demand required to achieve the same thermal performance in a concrete floor construction.

Average embodied carbon impact - component level

As mentioned in the methodology chapter, the embodied impacts are summarised using average values at the component level. As detailed information on the distribution of specific component types within each construction period is not available, all relevant component variants for each time frame were assessed individually above. The resulting emissions are averaged to obtain a representative value per square metre of component per year. Averaged values are subsequently used to calculate the annual embodied impact per square metre of heated floor area and to estimate embodied emissions with annual renovation rate.

Single family house: 1890-1959					
Average embodied impact by component (kg CO₂e/m²/yr)					
Component	Common practice	Low carbon (wood fibre)	Low carbon (cellulose)	Low carbon (rec. EPS)	Hybrid (roof-only)
Roof	35,7	37,7	36,5	-	29,6
Ceiling	4,9	11,5	12,2	-	-
External wall	25,7	23,8	66,0	-	-
Ground floor	111,5	-	-	107,3	-
Floor (crawl space)	71,3	80,1	79,3	-	-
Single family house: 1960-1980					
Average embodied impact by component (kg CO₂e/m²/yr)					
Component	Common practice	Low carbon (wood fibre)	Low carbon (cellulose)	Low carbon (rec. EPS)	Hybrid (roof-only)
Roof	33,4	32,3	32,1	-	27,4
Ceiling	2,8	6,5	7,1	-	-
External wall	16,9	15,8	46,7	-	-
Ground floor	116,8	-	-	112,9	-
Floor (crawl space)	66,1	71,5	72,1	-	-
Apartment building: 1890-1959					
Average embodied impact by component (kg CO₂e/m²/yr)					
Component	Common practice	Low carbon (wood fibre)	Low carbon (cellulose)	Low carbon (rec. EPS)	Hybrid (roof-only)
Roof	35,7	37,7	36,5	-	29,6
Ceiling	4,9	11,5	12,2	-	-
External wall	18,5	16,4	55,4	-	-
Ground floor	111,5	-	-	107,3	-
Apartment building: 1960-1980					
Average embodied impact by component (kg CO₂e/m²/yr)					
Component	Common practice	Low carbon (wood fibre)	Low carbon (cellulose)	Low carbon (rec. EPS)	Hybrid (roof-only)
Roof	33,4	32,3	32,1	-	27,4
Ceiling	2,8	6,5	7,1	-	-
External wall	22,3	21,3	49,0	-	-
Ground floor	144,2	-	-	138,1	-

Table 9: Average embodied carbon impact by component

The results show that, depending on the construction period and typology, different renovation approaches are most effective in limiting embodied emissions. The renovation strategy with the lowest embodied impact for each component is highlighted in green in Table 9. For components where both the choice of cladding and insulation influence the outcome, such as roofs and external walls, there is clear potential to reduce embodied carbon through targeted material choices. However, for components where renovation primarily involves the addition of insulation and where insulation is the dominant contributor, the common renovation practice results in the lowest emissions. This suggests that biobased insulation does not necessarily lead to lower embodied carbon in all applications. The possible explanation is that the generic data used for biobased materials include relatively high impacts in certain life-cycle stages or that larger material quantities are required to achieve equivalent thermal performance compared to mineral wool, specifically in the case of cellulose insulation.

3.1.2 Building level

Building-level embodied carbon impacts are calculated to enable direct comparison between embodied and operational impacts. The building-level embodied impact is obtained by upscaling component-level results. For each building typology and construction period, the total unrenovated area of each building component is multiplied by the corresponding average embodied impact of its renovation presented above. The result is then divided by the total heated floor area for the given typology and time frame. For the total unrenovated area for each component, refer to Appendix B.

Single family house: 1890-1959					
Annual embodied impact per m2 heated floor					
Component	Common practice	Low carbon (wood fibre)	Low carbon (cellulose)	Low carbon (rec. EPS)	Hybrid (roof-only)
Roof	35,6	37,7	36,4	-	29,6
Ceiling	2,3	5,3	5,6	-	-
External wall	19,0	17,5	48,7	-	-
Ground floor	83,8	-	-	80,7	-
Floor (crawl space)	0,3	0,4	0,4	-	-
Single family house: 1960-1980					
Annual embodied impact per m2 heated floor					
Component	Common practice	Low carbon (wood fibre)	Low carbon (cellulose)	Low carbon (rec. EPS)	Hybrid (roof-only)
Roof	36,8	35,6	35,3	-	30,2
Ceiling	1,5	3,5	3,8	-	-
External wall	11,7	10,9	32,4	-	-
Ground floor	102,9	-	-	99,5	-
Floor (crawl space)	1,9	2,1	2,1	-	-
Apartment building: 1890-1959					
Annual embodied impact per m2 heated floor					
Component	Common practice	Low carbon (wood fibre)	Low carbon (cellulose)	Low carbon (rec. EPS)	Hybrid (roof-only)
Roof	10,7	11,3	10,9	-	8,9
Ceiling	0,6	1,5	1,5	-	-
External wall	10,1	9,0	30,4	-	-
Ground floor	32,2	-	-	31,0	-
Apartment building: 1960-1980					
Annual embodied impact per m2 heated floor					
Component	Common practice	Low carbon (wood fibre)	Low carbon (cellulose)	Low carbon (rec. EPS)	Hybrid (roof-only)
Roof	10,0	9,7	9,6	-	8,2
Ceiling	0,6	1,3	1,5	-	-
External wall	6,3	6,0	13,8	-	-
Ground floor	42,1	-	-	40,3	-

Table 10: Building-level embodied carbon impacts

The results show that roof and ground floor renovations contribute the largest embodied emissions per square metre of heated floor area. External wall renovations also account for a significant share, while ceilings and floors above ventilated crawl spaces contribute little, since their unrenovated areas are comparably small.

3.1.3 Impact with annual renovation rate

Impacts with annual renovation rate are calculated to reflect the overall climate impact of renovation activity at the building stock level. For each component, the average impact is multiplied by the unrenovated component area at the national scale and by the assumed annual renovation rate of 2%, resulting in annual embodied emissions associated with renovation.

Single family house: 1890-1959					
Embodied impact with annual renovation rate (ton CO2e/yr)					
Component	Common practice	Low carbon (wood fibre)	Low carbon (cellulose)	Low carbon (rec. EPS)	Hybrid (roof-only)
Roof	17 997	19 039	18 420	-	14 964
Ceiling	1 152	2 682	2 840	-	-
External wall	9 599	8 868	24 616	-	-
Ground floor	42 386	-	-	40 792	-
Floor (crawl space)	167	187	185	-	-
Single family house: 1960-1980					
Embodied impact with annual renovation rate (ton CO2e/yr)					
Component	Common practice	Low carbon (wood fibre)	Low carbon (cellulose)	Low carbon (rec. EPS)	Hybrid (roof-only)
Roof	17 941	17 350	17 241	-	14 716
Ceiling	734	1 708	1 868	-	-
External wall	5 723	5 335	15 802	-	-
Ground floor	50 221	-	-	48 556	-
Floor (crawl space)	949	1 026	1 034	-	-
Apartment building: 1890-1959					
Embodied impact with annual renovation rate (ton CO2e/yr)					
Component	Common practice	Low carbon (wood fibre)	Low carbon (cellulose)	Low carbon (rec. EPS)	Hybrid (roof-only)
Roof	8 328	8 810	8 523	-	6 924
Ceiling	486	1 132	1 198	-	-
External wall	7 893	7 019	23 675	-	-
Ground floor	25 064	-	-	24 122	-
Apartment building: 1960-1980					
Embodied impact with annual renovation rate (ton CO2e/yr)					
Component	Common practice	Low carbon (wood fibre)	Low carbon (cellulose)	Low carbon (rec. EPS)	Hybrid (roof-only)
Roof	3 187	3 082	3 063	-	2 614
Ceiling	182	424	463	-	-
External wall	2 003	1 909	4 401	-	-
Ground floor	13 390	-	-	12 821	-

Table 11: Embodied impacts with annual renovation rate by component

In the case of external walls for apartment buildings constructed between 1890 and 1959, lightweight wall constructions are not considered. However, this wall type is included for single-family houses from the same period and has a relatively high embodied impact. This explains why the annual emissions from external wall renovation are lower for apartment buildings than for single-family houses, even though the unrenovated external wall area is larger in the apartment building stock.

3.1.4 Potential contributions to 2030 and 2050 climate goals

Denmark aims to reduce greenhouse gas emissions by 70% by 2030 and to achieve climate neutrality by 2050. Embodied emissions are calculated by multiplying the impacts with annual renovation rate by the number of years until each target year. These values are then compared with cumulative operational carbon savings from energy retrofits to assess the net climate effect of renovation strategies.

Single family house: 1890-1959					
Embodied impact with annual renovation rate up to 2030 (ton CO2e/yr)					
Component	Common practice	Low carbon (wood fibre)	Low carbon (cellulose)	Low carbon (rec. EPS)	Hybrid (roof-only)
Roof	89 986	95 194	92 099	-	74 819
Ceiling	5 762	13 411	14 201	-	-
External wall	47 994	44 339	123 082	-	-
Ground floor	211 930	-	-	203 960	-
Floor (crawl space)	833	936	926	-	-
Single family house: 1960-1980					
Embodied impact with annual renovation rate up to 2030 (ton CO2e/yr)					
Component	Common practice	Low carbon (wood fibre)	Low carbon (cellulose)	Low carbon (rec. EPS)	Hybrid (roof-only)
Roof	89 705	86 752	86 205	-	73 579
Ceiling	3 670	8 542	9 340	-	-
External wall	28 615	26 674	79 012	-	-
Ground floor	251 105	-	-	242 780	-
Floor (crawl space)	4 743	5 131	5 170	-	-
Apartment building: 1890-1959					
Embodied impact with annual renovation rate up to 2030 (ton CO2e/yr)					
Component	Common practice	Low carbon (wood fibre)	Low carbon (cellulose)	Low carbon (rec. EPS)	Hybrid (roof-only)
Roof	41 639	44 049	42 617	-	34 621
Ceiling	2 431	5 658	5 991	-	-
External wall	26 479	35 097	118 376	-	-
Ground floor	125 321	-	-	120 608	-
Apartment building: 1960-1980					
Embodied impact with annual renovation rate up to 2030 (ton CO2e/yr)					
Component	Common practice	Low carbon (wood fibre)	Low carbon (cellulose)	Low carbon (rec. EPS)	Hybrid (roof-only)
Roof	15 937	15 412	15 315	-	13 072
Ceiling	911	2 119	2 317	-	-
External wall	10 013	9 547	22 003	-	-
Ground floor	66 950	-	-	64 103	-

Table 12: Embodied impacts with annual renovation rate by component up to 2030

Single family house: 1890-1959					
Embodied impact with annual renovation rate up to 2050 (ton CO2e/yr)					
Component	Common practice	Low carbon (wood fibre)	Low carbon (cellulose)	Low carbon (rec. EPS)	Hybrid (roof-only)
Roof	449 932	475 969	460 496	-	374 094
Ceiling	28 811	67 054	71 004	-	-
External wall	239 972	221 695	615 408	-	-
Ground floor	1 059 652	-	-	1 019 802	-
Floor (crawl space)	4 164	4 679	4 631	-	-
Single family house: 1960-1980					
Embodied impact with annual renovation rate up to 2050 (ton CO2e/yr)					
Component	Common practice	Low carbon (wood fibre)	Low carbon (cellulose)	Low carbon (rec. EPS)	Hybrid (roof-only)
Roof	448 527	433 762	431 025	-	367 897
Ceiling	18 352	42 711	46 699	-	-
External wall	143 077	133 371	395 062	-	-
Ground floor	1 255 527	-	-	1 213 902	-
Floor (crawl space)	23 713	25 653	25 852	-	-
Apartment building: 1890-1959					
Embodied impact with annual renovation rate up to 2050 (ton CO2e/yr)					
Component	Common practice	Low carbon (wood fibre)	Low carbon (cellulose)	Low carbon (rec. EPS)	Hybrid (roof-only)
Roof	208 195	220 243	213 083	-	173 103
Ceiling	12 155	28 288	29 955	-	-
External wall	132 397	175 485	591 880	-	-
Ground floor	626 605	-	-	603 041	-
Apartment building: 1960-1980					
Embodied impact with annual renovation rate up to 2050 (ton CO2e/yr)					
Component	Common practice	Low carbon (wood fibre)	Low carbon (cellulose)	Low carbon (rec. EPS)	Hybrid (roof-only)
Roof	79 685	77 061	76 575	-	65 360
Ceiling	4 553	10 596	11 585	-	-
External wall	50 064	47 734	110 014	-	-
Ground floor	334 748	-	-	320 517	-

Table 13: Embodied impacts with annual renovation rate by component up to 2050

3.1.5 Impact over reference lifecycle

The 2075 projection reflects the full 50-year reference study period and is not linked to a specific climate target. The calculation follows the same approach as for the 2030 and 2050 projections, with annual embodied emissions multiplied by the remaining years up to 2075. Unlike operational impacts, embodied emissions are assumed to be constant over time, as they are tied to material use at the point of renovation and are not affected by changes in energy-related emission factors.

Single family house: 1890-1959					
Embodied impact with annual renovation rate up to 2075 (ton CO2e/yr)					
Component	Common practice	Low carbon (wood fibre)	Low carbon (cellulose)	Low carbon (rec. EPS)	Hybrid (roof-only)
Roof	899 865	951 937	920 992	-	748 188
Ceiling	57 622	134 109	142 009	-	-
External wall	479 944	443 391	1 230 816	-	-
Ground floor	2 119 303	-	-	2 039 604	-
Floor (crawl space)	8 328	9 357	9 261	-	-
Single family house: 1960-1980					
Embodied impact with annual renovation rate up to 2075 (ton CO2e/yr)					
Component	Common practice	Low carbon (wood fibre)	Low carbon (cellulose)	Low carbon (rec. EPS)	Hybrid (roof-only)
Roof	897 055	867 525	862 050	-	735 794
Ceiling	36 703	85 423	93 398	-	-
External wall	286 153	266 743	790 123	-	-
Ground floor	2 511 053	-	-	2 427 804	-
Floor (crawl space)	47 426	51 306	51 704	-	-
Apartment building: 1890-1959					
Embodied impact with annual renovation rate up to 2075 (ton CO2e/yr)					
Component	Common practice	Low carbon (wood fibre)	Low carbon (cellulose)	Low carbon (rec. EPS)	Hybrid (roof-only)
Roof	416 391	440 486	426 167	-	346 206
Ceiling	24 309	56 577	59 910	-	-
External wall	264 794	350 970	1 183 759	-	-
Ground floor	1 253 210	-	-	1 206 081	-

	Apartment building: 1960-1980				
	Embodied impact with annual renovation rate up to 2075 (ton CO2e/yr)				
Component	Common practice	Low carbon (wood fibre)	Low carbon (cellulose)	Low carbon (rec. EPS)	Hybrid (roof-only)
Roof	159 369	154 123	153 150	-	130 720
Ceiling	9 105	21 192	23 170	-	-
External wall	100 128	95 469	220 028	-	-
Ground floor	669 497	-	-	641 033	-

Table 14: Embodied annual impacts over complete life cycle

3.1.6 Summary

The results show that a low-carbon choice of cladding in roof and external wall renovations offers potential to reduce embodied carbon emissions, while mineral wool remains the most effective insulation for limiting embodied impacts. The most suitable renovation strategy therefore varies by component. At the component level, ground floor renovations have the highest embodied emissions, followed by floors above ventilated crawl spaces. At the national scale, ground floors remain the most significant contributor, while the large unrenovated area of external walls makes them the second-largest source of embodied emissions.

3.2 Operational carbon savings

3.2.1 Component level

Single-family house

This section shows the operational energy savings from renovating the building envelopes of detached single-family houses built between 1890-1959 and 1960-1980. It compares Renovation Method #1 (common practice) with Method #2 (low-carbon solution). The following tables (15-18) summarize operational energy savings for all building envelope components across both construction periods and renovation methods.

SFH (-1890-1959)						
Renovation method # 1 (Common practice-insulation upgrade)						
Typology	Time frame	Building element	Limit W/m2/K		Upgrade to W/m2/K	Energy savings, kWh/m2/yr
Detached single family house	(-1890-1959)	Roof	2,58		0,12	222,29
		Ceiling	1,47		0,12	121,99
		Solid external wall	1,87		0,17	153,61
		Cavity external wall	1,46		0,17	116,56
		Lightweight external wall	1,89		0,18	154,52
		Ground floor	0,49		0,10	35,24
			0,47		0,10	33,43
		Ventilated Crawl floor	1,96		0,10	168,07
			1,13		0,10	93,07

Table 15: Annual operational energy savings by Renovation Method #1 (common practice)

SFH (-1890-1959)						
Renovation method # 2 (Low-carbon solution)						
Typology	Time frame	Building element	Limit W/m2/K		Upgrade to W/m2/K	Energy savings, kWh/m2/yr
Detached single family house	(-1890-1959)	Roof	2,58		0,12	222,29
		Ceiling	1,47		0,12	121,99
		Solid external wall	1,87		0,18	152,71
		Cavity external wall	1,46		0,18	115,66
		Lightweight external wall	1,89		0,16	156,32
		Ground floor	0,49		0,10	35,24
			0,47		0,10	33,43
		Ventilated Crawl floor	1,96		0,10	168,07
			1,13		0,10	93,07

Table 16: Annual operational energy savings by Renovation Method #2 (low-carbon solution)

SFH (1960-1980))						
Renovation method # 1 (Common practice-insulation upgrade)						
Typology	Time frame	Building element	BR standard	Limit W/m2/K	Upgrade to W/m2/K	Energy savings, kWh/m2/yr
Detached single family house	1960-1980	Roof	BR 61-72	0,45	0,12	29,82
			BR 77	0,2	0,12	7,23
		Ceiling	BR 61-72	0,45	0,12	29,82
			BR 77	0,2	0,12	7,23
		Solid external wall	BR 61-67	1,28	0,18	99,40
			BR 72	1	0,17	75
			BR 77	0,4	0,18	19,88
		Cavity external wall	BR 61-67	1,28	0,18	99,40
			BR 72	1	0,18	74,10
			BR 77	0,4	0,17	20,78
		Lightweight external wall	BR 61-72	0,6	0,18	37,95
			BR 77	0,3	0,17	11,75
		Ground floor	BR 61-72	0,45	0,10	31,63
			BR 77	0,3	0,10	18,07
		Ventilated Crawl floor	BR 61-67	0,58	0,10	43,37
			BR 72-77	0,6	0,10	45,18

Table 17: Annual operational energy savings by renovation method #1 (common practice)

SFH (1960-1980)						
Renovation method # 2 (Low-carbon solution)						
Typology	Time frame	Building element	BR standard	Limit W/m2/K	Upgrade to W/m2/K	Energy savings, kWh/m2/yr
Detached single family house	1960-1980	Roof	BR 61-72	0,45	0,12	29,82
			BR 77	0,2	0,12	7,23
		Ceiling	BR 61-72	0,45	0,12	29,82
			BR 77	0,2	0,12	7,23
		Solid external wall	BR 61-67	1,28	0,17	100,30
			BR 72	1	0,18	74,10
			BR 77	0,4	0,18	19,88
		Cavity external wall	BR 61-67	1,28	0,17	100,30
			BR 72	1	0,17	75,00
			BR 77	0,4	0,17	20,78
		Lightweight external wall	BR 61-72	0,6	0,18	37,95
			BR 77	0,3	0,18	10,84
		Ground floor	BR 61-72	0,45	0,10	31,63
			BR 77	0,3	0,10	18,07
		Ventilated Crawl floor	BR 61-67	0,58	0,10	43,37
			BR 72-77	0,6	0,10	45,18

Table 18: Annual operational energy savings by renovation method #2 (low carbon solution)

Across both construction periods, operational energy savings differ mainly by building components. The largest reductions in energy demand are observed for external walls and ventilated crawl floors, while ceilings and ground floors show smaller savings. Single-family houses built between 1890 and 1959 consistently achieve higher energy savings than those constructed between 1960 and 1980. For both periods, Renovation Method #1 and Renovation Method #2 deliver nearly identical operational energy savings across all components, indicating that operational performance is primarily determined by the achieved insulation level (final U-value). Detailed U-value calculations and construction build-ups for all scenarios are provided in Appendix C.

3.2.2 Building level

Figure 28 and Figure 29 compare the annual operational energy and CO₂ savings per square meter of heated floor for single-family houses constructed in the periods 1890-1959 and 1960-1980. For both construction periods, roof and external wall renovations deliver the largest operational energy and CO₂ savings, while ceilings, ground floors, and floors facing ventilated crawl spaces contribute to smaller savings. The older building stock (1890-1959) achieves higher overall savings per square meter of heated floor than buildings from 1960-1980, reflecting their poorer initial thermal performance. For each period, Renovation Method #1 and Renovation Method #2 result in identical operational savings and are therefore presented combined.

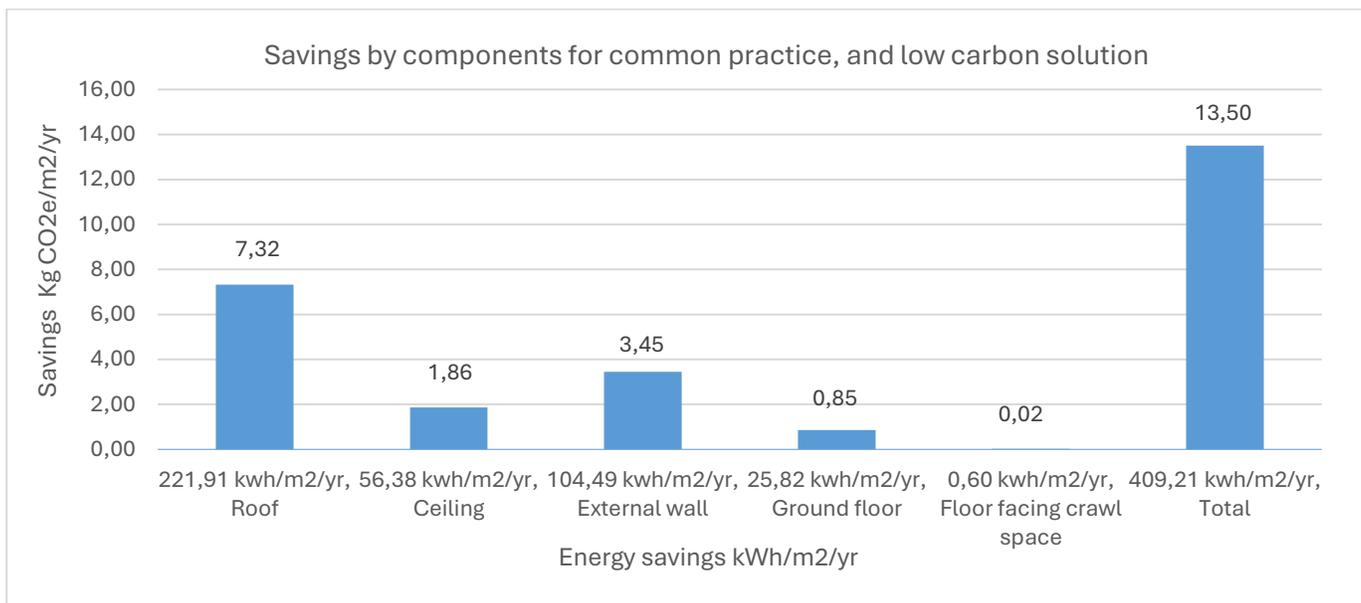


Figure 2828: Annual operational and CO₂ savings per m² heated floor, SFH (1890-1959)

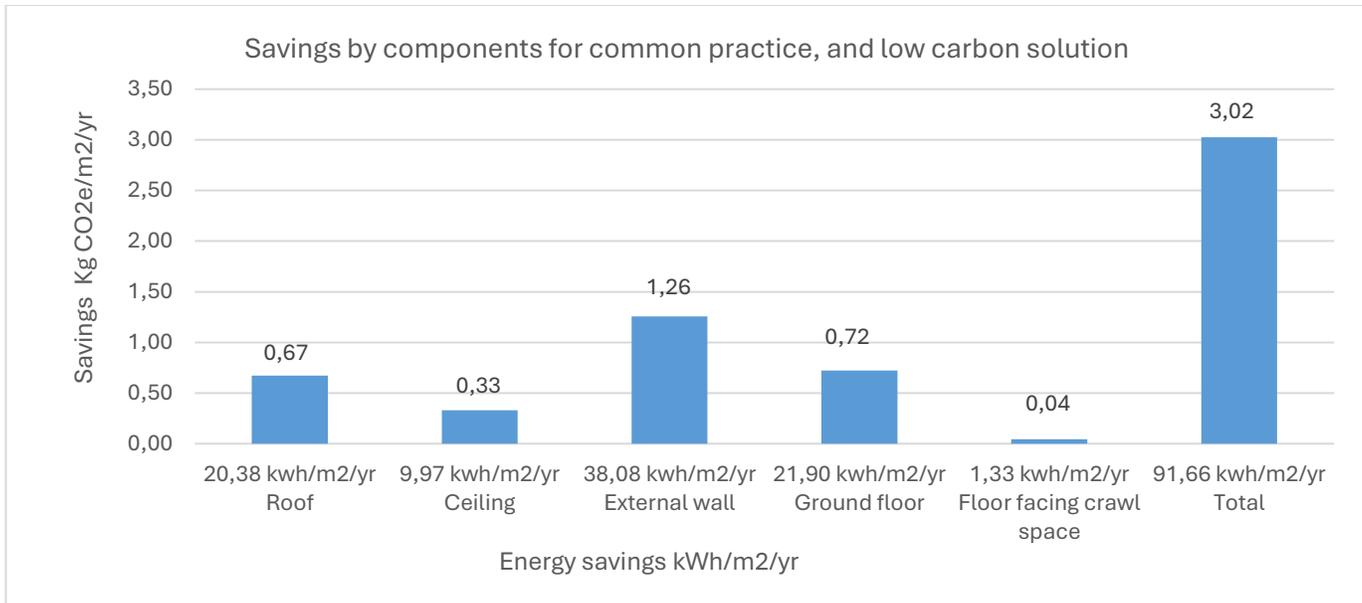


Figure 29: Annual operational and CO₂ savings per m2 heated floor, SFH (1960-1980)

3.2.3 Annual average operational savings (component level)

Figures 30 and 31 show the annual average operational energy and associated CO₂ savings per square meter of component area for single-family houses constructed between 1890-1959 and 1960-1980. Results are shown for Renovation Methods #1 and #2, which yield identical operational outcomes and are therefore presented jointly.

For both construction periods, external walls and roofs provide the highest operational energy and CO₂ savings per square meter of component. In the 1890-1959 building stock, total component-level savings reach 650,7 kWh/m²/yr and 21,47 kg CO₂e/m²/yr, whereas the corresponding values for the 1960-1980 stock are 161,9 kWh/m²/yr and 5,34 kg CO₂e/m²/yr. This reflects the higher baseline heat losses in older buildings.

Across both time periods, ground floors and ceilings contribute comparatively lower savings, while ventilated crawl floors show moderate contributions despite lower per-unit savings, due to their renovation extent. Component-level rankings are consistent across both construction periods, whereas older buildings show significantly higher absolute energy savings for all components.

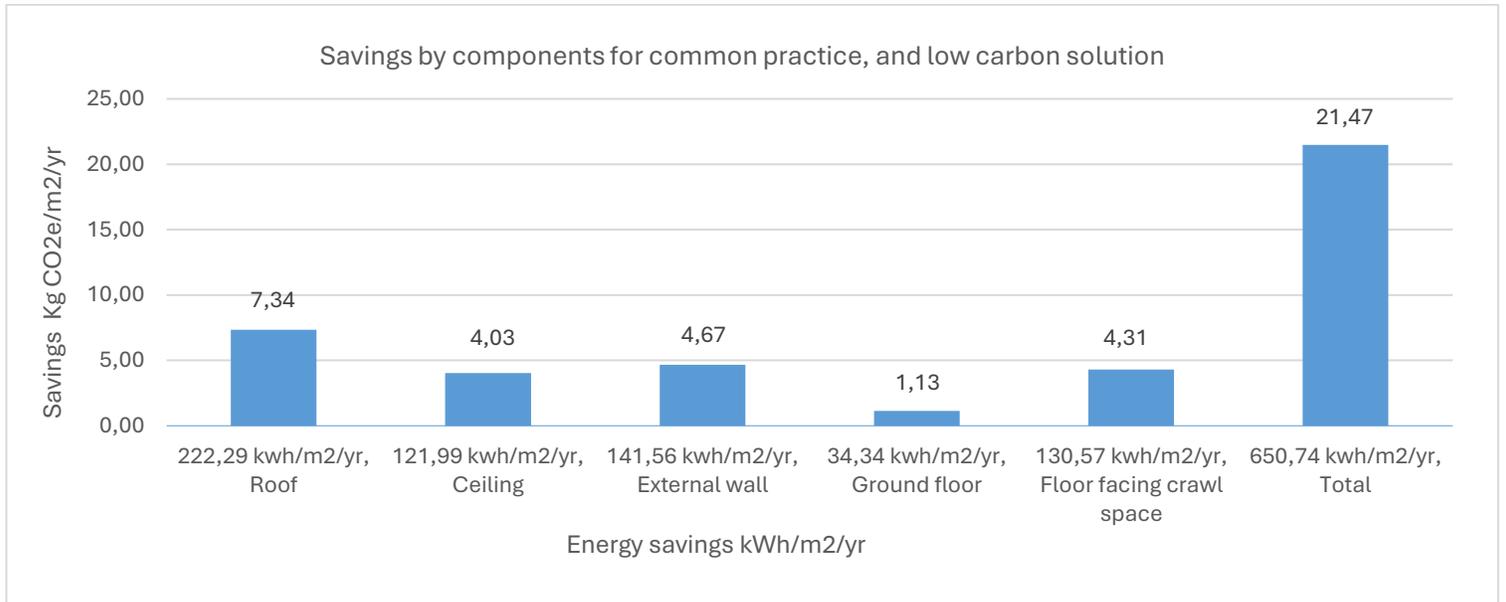


Figure 30: Annual operational energy and CO2e savings per m2 components, SFH (1890-1959)

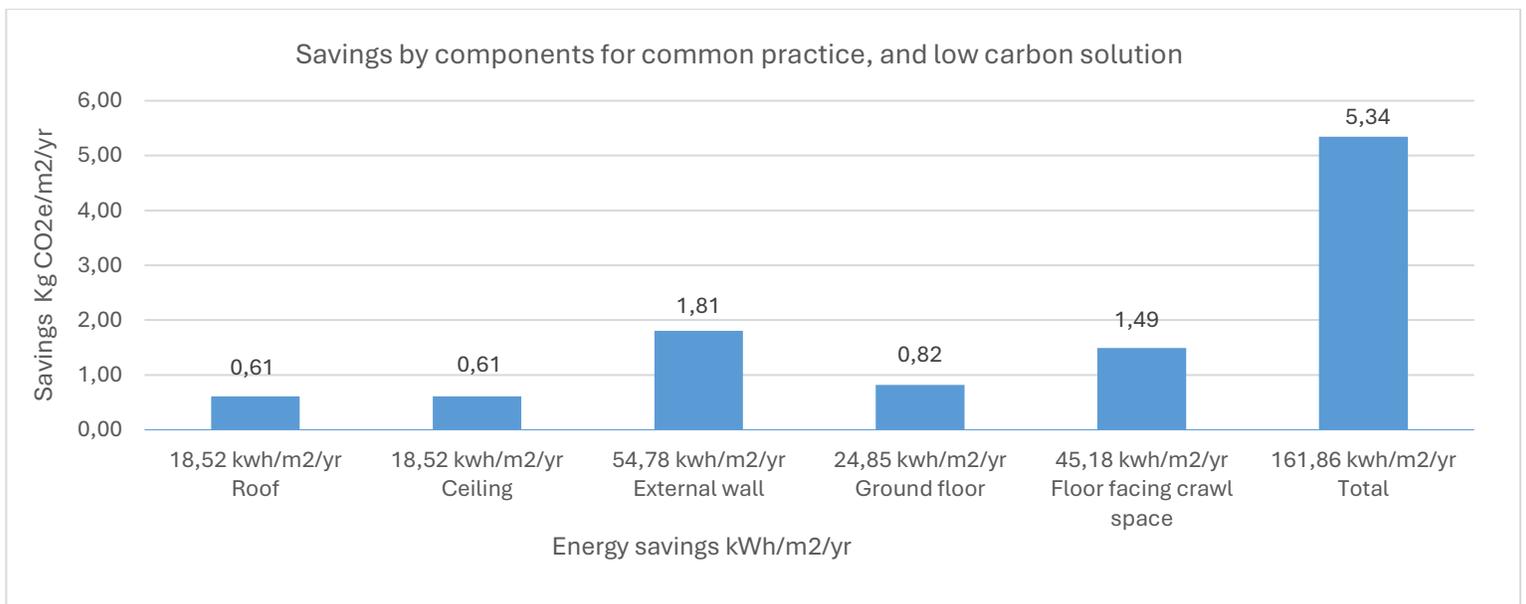


Figure 31: Annual operational energy and CO2e savings per m2 components, SFH (1960-1980)

3.2.4 Operational savings with annual renovation rate

Figures 32 and 33 present the annual operational energy and CO₂ savings by building components for single-family houses constructed in 1890-1959 and 1960-1980, respectively, assuming a renovation rate of 2%. Results are shown separately for renovated and unrenovated components.

For both construction periods, renovated components account for most total operational savings. In older buildings (1890-1959), roof and external wall renovations provide the largest contributions to annual energy and CO₂ reductions, followed by ceiling and ground-floor upgrades. Floor-facing crawl spaces contribute marginally. A similar pattern is observed for buildings constructed between 1960 and 1980, where roof and external wall renovations again provide the largest savings, followed by ceilings and ground floors, while floors facing crawl spaces contribute the least, although the overall savings are lower for all components. Unrenovated components still contribute to operational energy and CO₂ savings due to the gradual renovation rate of 2% per year, but their contribution is substantially lower than the savings achieved by components that have already been renovated.

Overall, buildings constructed earlier achieve higher reductions in operational energy use and CO₂e emissions than newer buildings, because their existing thermal performance is lower and therefore offers greater potential for improvement. Although the total amount of savings differs between the two construction periods, roofs and external walls consistently provide the largest reductions in operational energy use and CO₂ emissions, while other components contribute smaller shares in both cases.

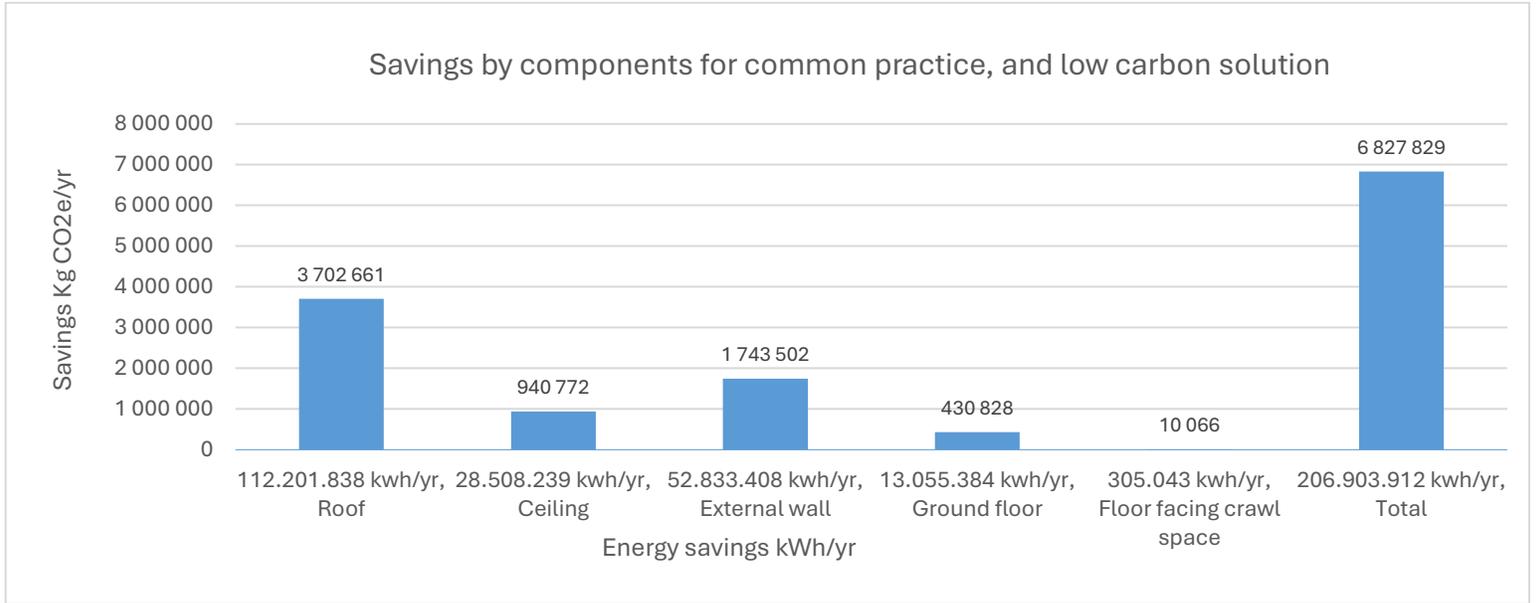


Figure 32: operational energy and CO2e savings by components, with annual renovation rate, SFH (1890-1959)

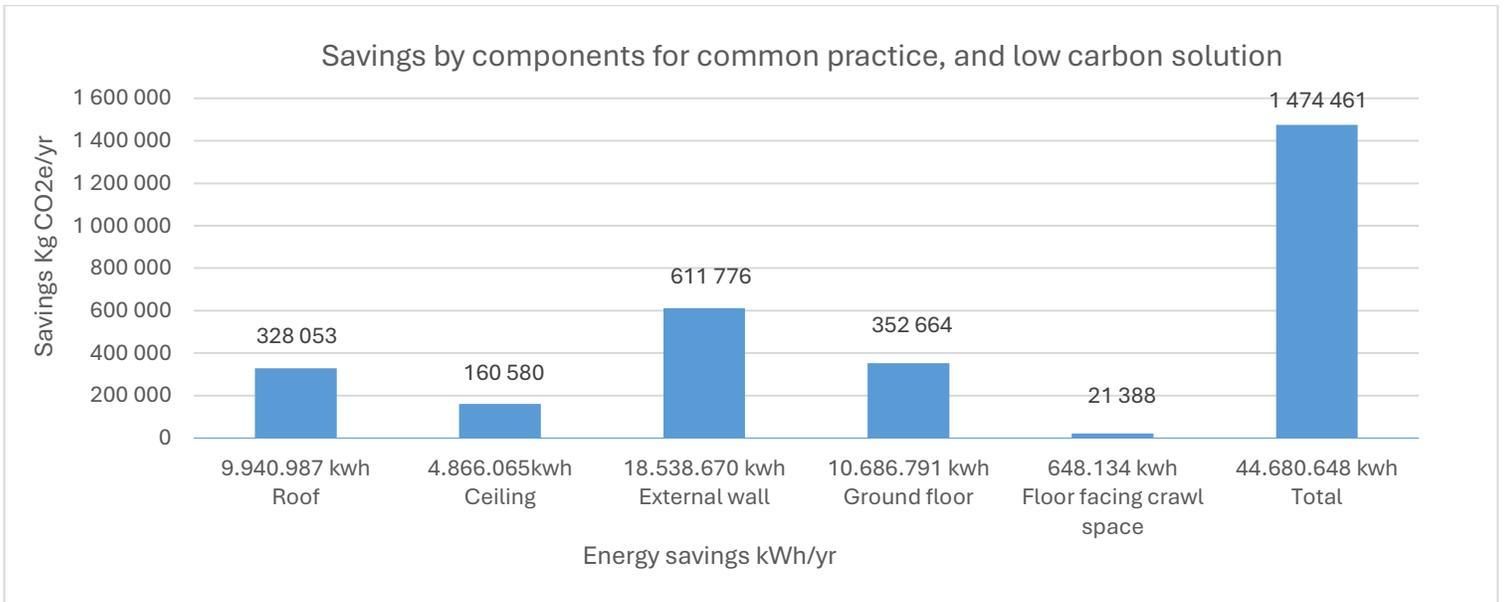


Figure 33: operational energy and CO2e savings by components, with annual renovation rate, SFH (1960-1980)

3.2.5 Potential contributions to 2030 and 2050 climate goals

Figures 34 and 35 present cumulative operational energy and CO₂ savings up to 2030 for single-family houses constructed in 1890-1959 and 1960-1980, respectively. For both construction periods, Renovation Method #1 and Renovation Method #2 produce identical results, as they achieve the same final thermal performance and are applied using the same renovation rate.

By 2030, envelope component renovations of single-family houses constructed between 1890 and 1959 resulted in a total operational CO₂ reduction of approximately 60.002 t CO₂e, with roof and external wall upgrades providing the largest contributions. For buildings constructed between 1960-1980, cumulative operational CO₂ reductions reach approximately 12.957 t CO₂e by 2030, following the same component contribution pattern but at a lower impact compared to single family house from the time frame (1890-1959)

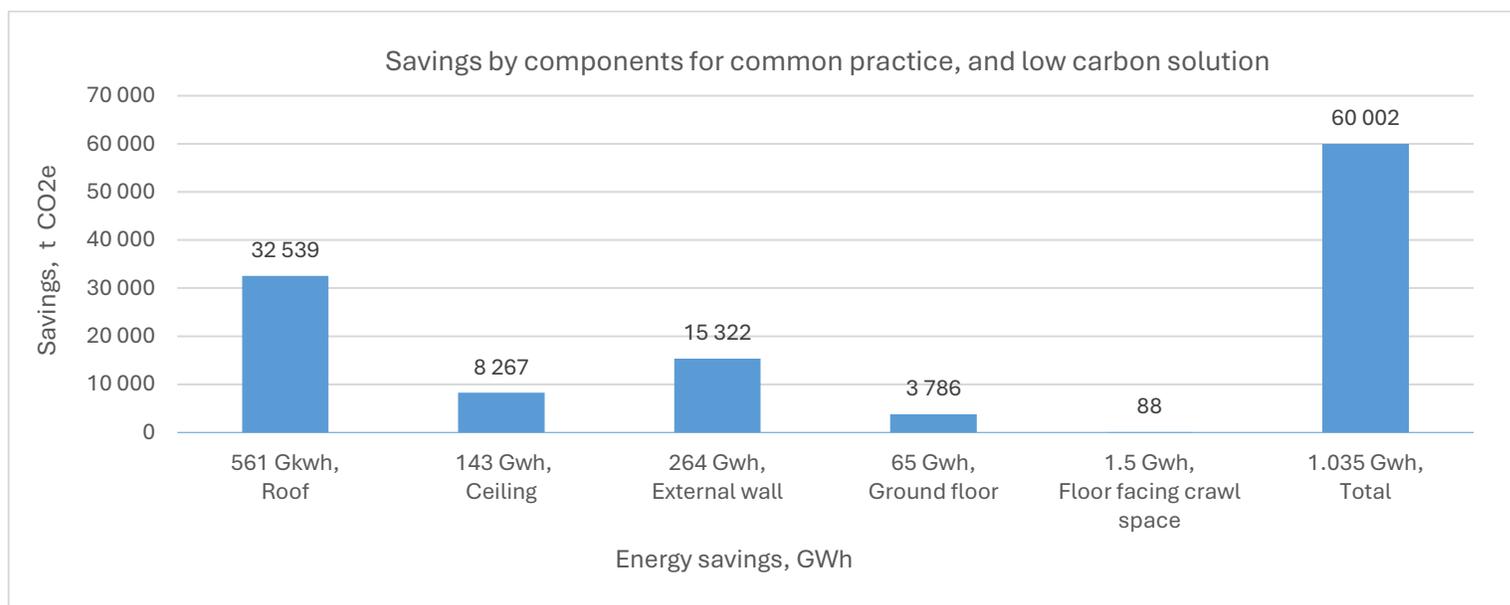


Figure:34 Operational energy and CO₂e savings contribution to the climate goal by 2030, SFH (1890-1959)

Overall, these results demonstrate that envelope component renovation of single-family houses can deliver measurable operational CO₂ reductions by 2030, directly supporting Denmark's climate target of a 70% reduction in greenhouse gas emissions. The

higher savings observed in older buildings underline their importance as a key focus for renovation strategies aimed at maximizing emission reductions within the 2030 timeframe.

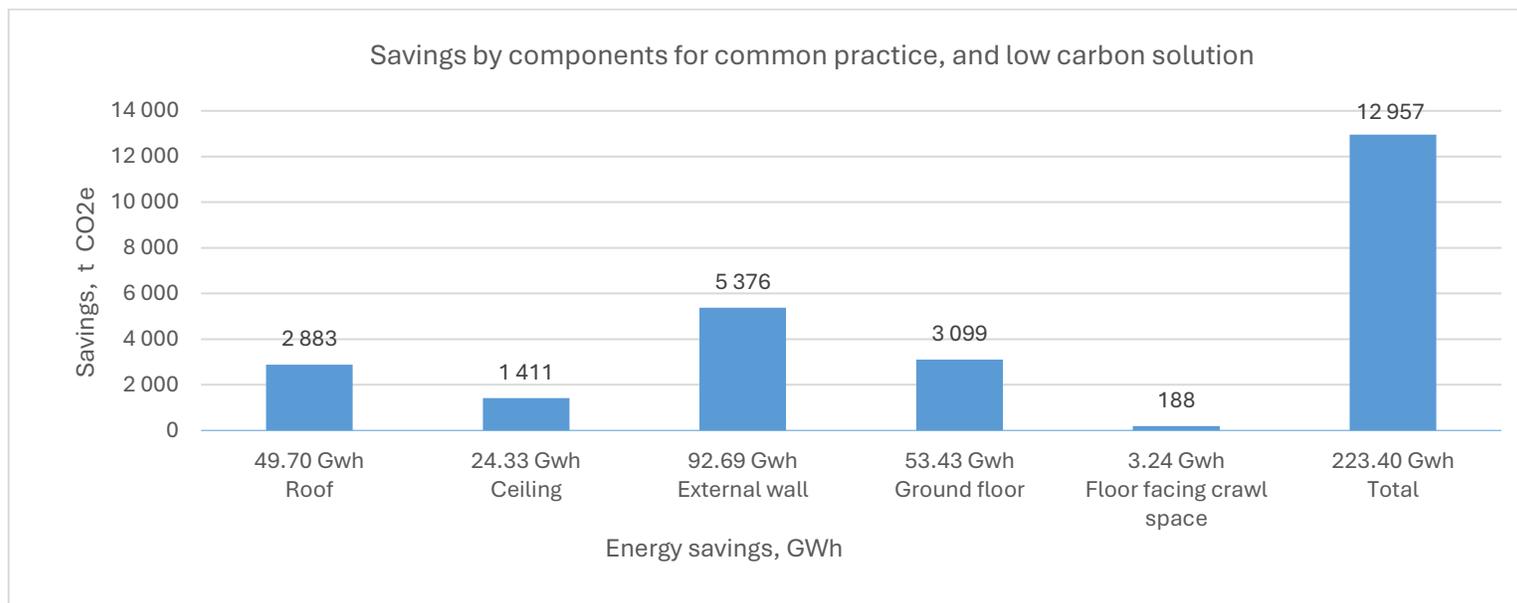


Figure:35 Operational energy and CO2e savings contribution to the climate goal by 2030, SFH (1960-1980)

Operational energy and CO2 savings are assessed up to 2050 to align with Denmark’s long-term goal of achieving climate neutrality by 2050. Figures 36 and 37 present cumulative operational savings for single-family houses constructed in 1890-1959 and 1960-1980, respectively. For both construction periods, Renovation Method #1 (common practice) and Renovation Method #2 (low-carbon solution) achieve identical results, as they reach the same final thermal performance and are implemented under the same renovation rate. For houses built between 1890-1959, renovated components provide significant cumulative savings by 2050, reaching approximately 5.173 GWh of energy savings and 186.214 t CO2e reductions. Roof and external wall renovations contribute the largest share, followed by ceilings and ground floors, while floor-facing crawl spaces have a negligible impact. Buildings constructed between 1960-1980 show the same component ranking and contribution pattern but achieve lower cumulative savings, totaling approximately 1.117 GWh of energy savings and 40.213 t CO2 reductions by 2050. Despite these lower absolute

values, roof and external wall upgrades remain beneficial sources of long-term operational savings. Overall, these results indicate that building envelope renovations, particularly roof and external wall upgrades, can make an effective and sustained contribution to Denmark’s 2050 climate-neutrality target, with older buildings offering the greatest mitigation potential due to their higher initial energy demand.

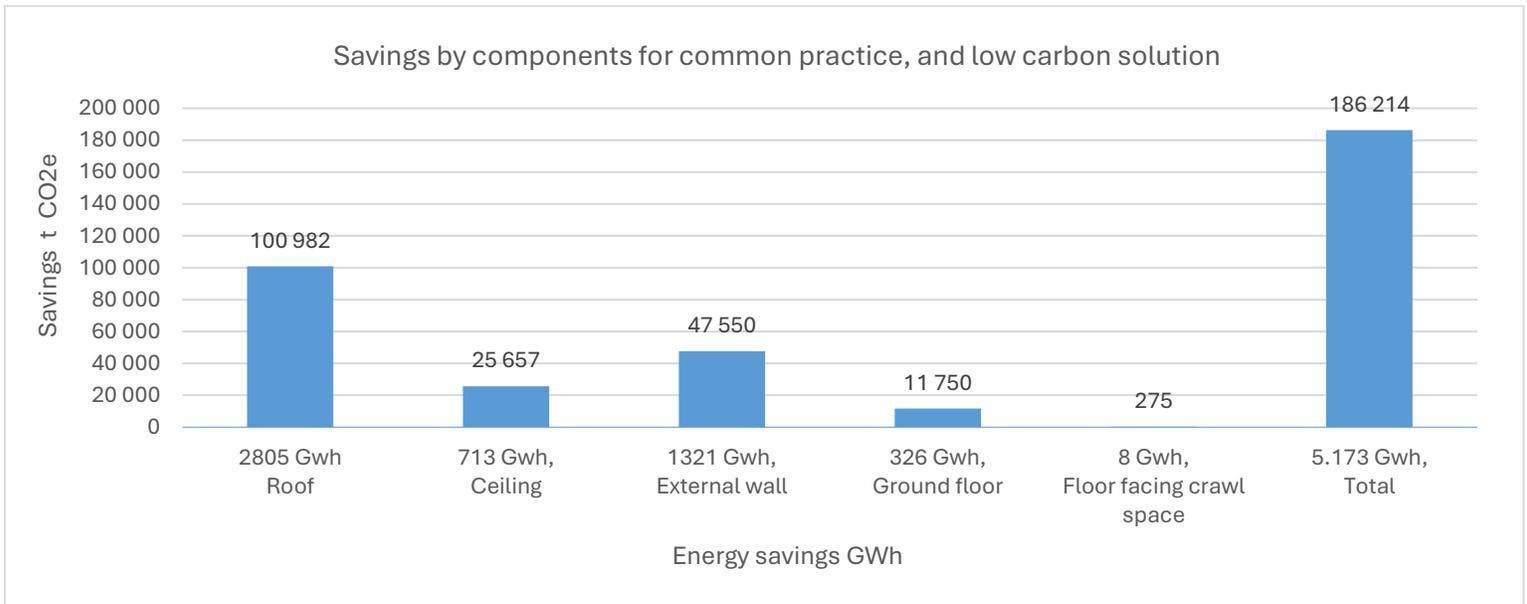


Figure:36 Operational energy and CO_{2e} savings contribution to the climate goal by 2050, SFH (1890-1959)

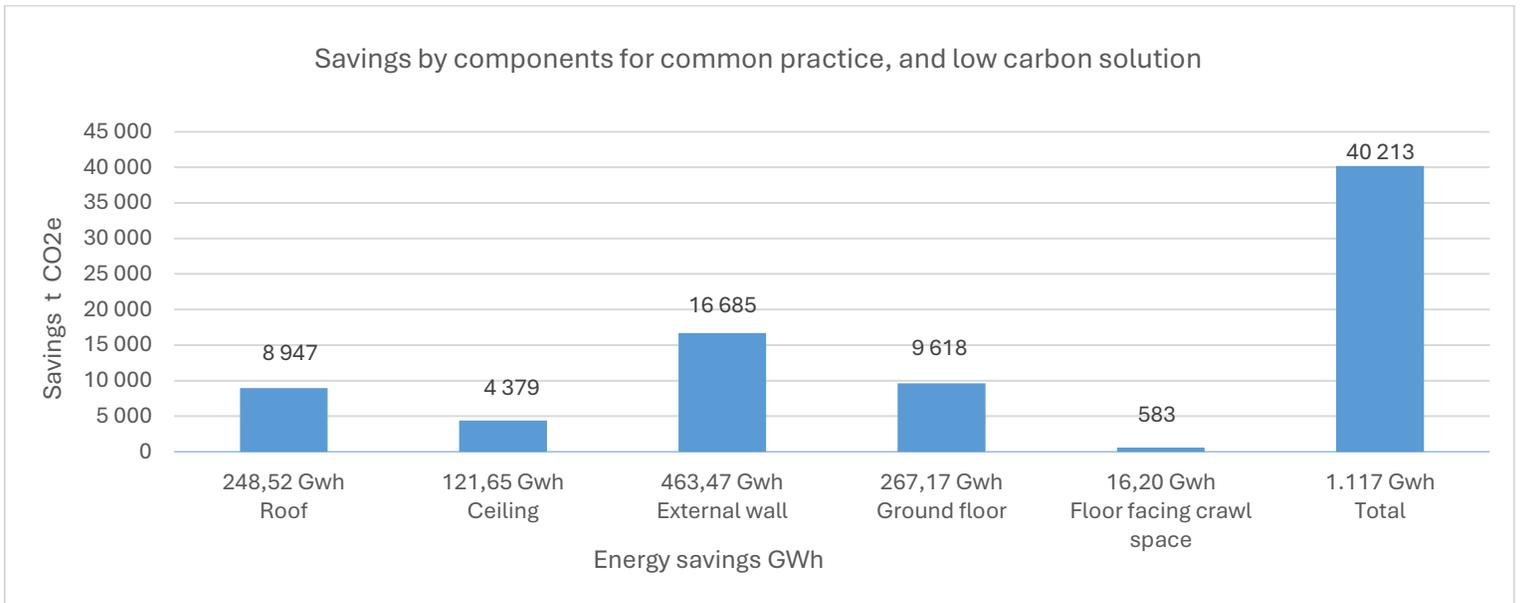


Figure:37 Operational energy and CO₂e savings contribution to the climate goal by 2050, SFH (1960-1980)

3.2.6 Operational savings over reference lifecycle

Over the full reference study period to 2075, significant cumulative operational energy and CO₂ savings are achieved through envelope renovations in single-family houses. Figures 38 and 39 represent that single-family houses constructed between 1890-1959 deliver the highest total savings, indicating a greater mitigation potential compared to the 1960-1980 stock. In both time frames, roof and external wall renovations account for the largest share of cumulative operational energy and CO₂ reductions, followed by ceiling and ground-floor upgrades, while floor-facing crawl spaces contribute marginally. Although both renovation strategies provide identical results within each time frame, the older building stock consistently provides higher effective savings across all components. These results indicate that pre-1960 single-family houses show the most strategic target for renovation when aiming to maximize long-term operational energy and emission reductions over the building life cycle.

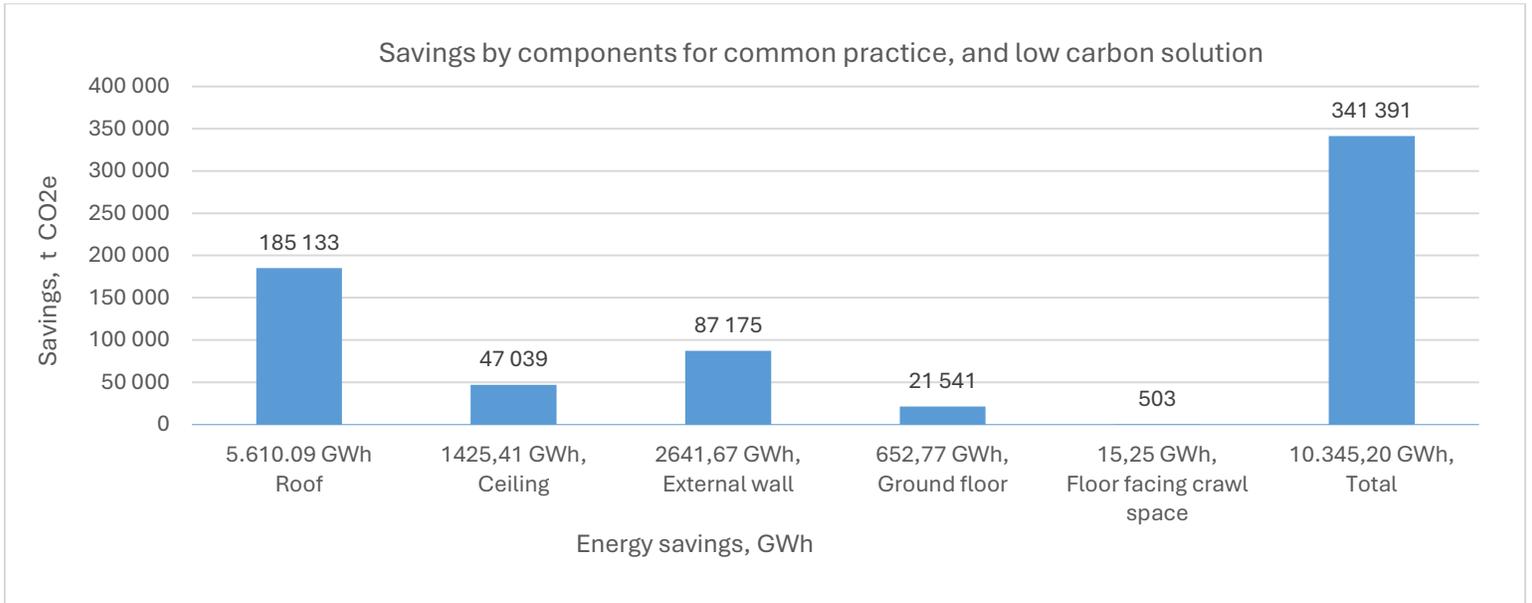


Figure:38 Operational energy and CO2e savings contribution over lifecycle by 2075, SFH (1890-1959)

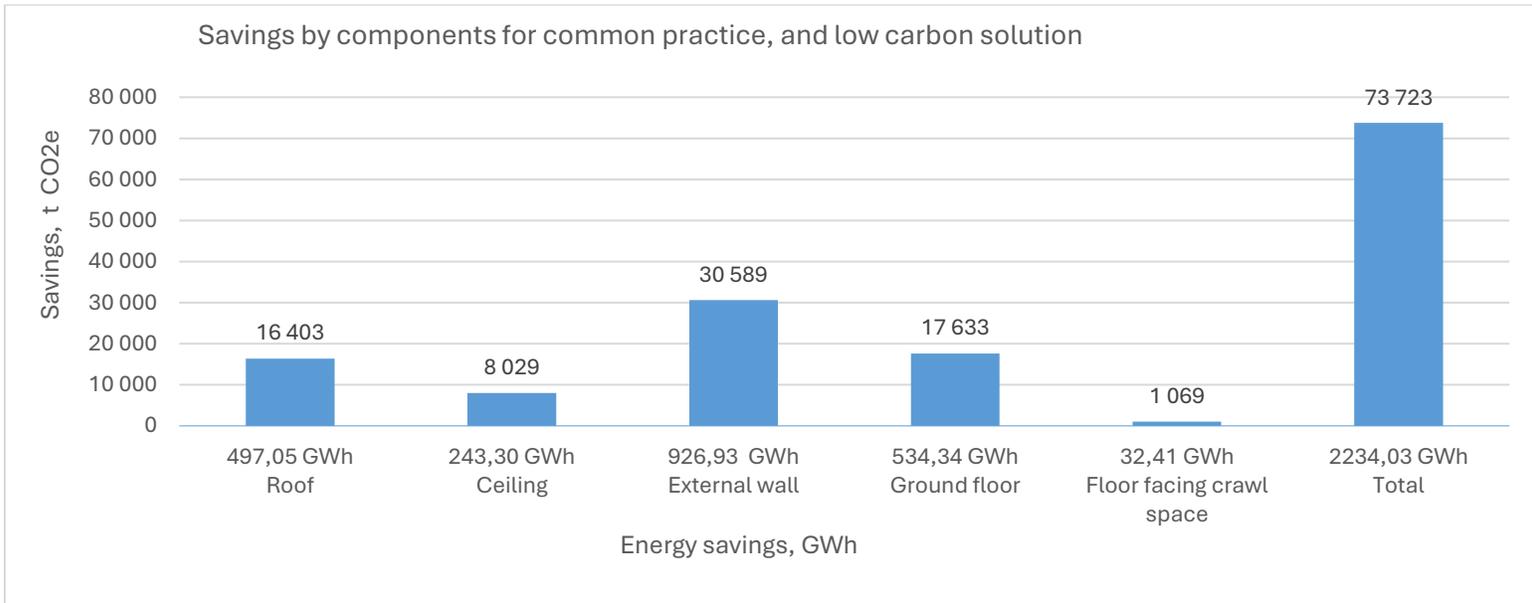


Figure:39 Operational energy and CO2e savings contribution over lifecycle by 2075, SFH (1960-1980)

3.2.7 Operational and CO2e savings summary

Figures 40 and 41 summarize results for single-family houses for 2030, 2050 and 2075 and show that continued renovation over time leads to a progressive reduction in operational energy use and relevant CO2e emissions. Early reductions contribute to near-term climate objectives, while ongoing renovation activity substantially increases cumulative emission savings toward mid-century and across the full life-cycle reference period. The results demonstrate that sustained renovation of the single-family housing stock supports national climate targets, with the largest long-term benefits achieved through consistent, sustained renovation efforts.

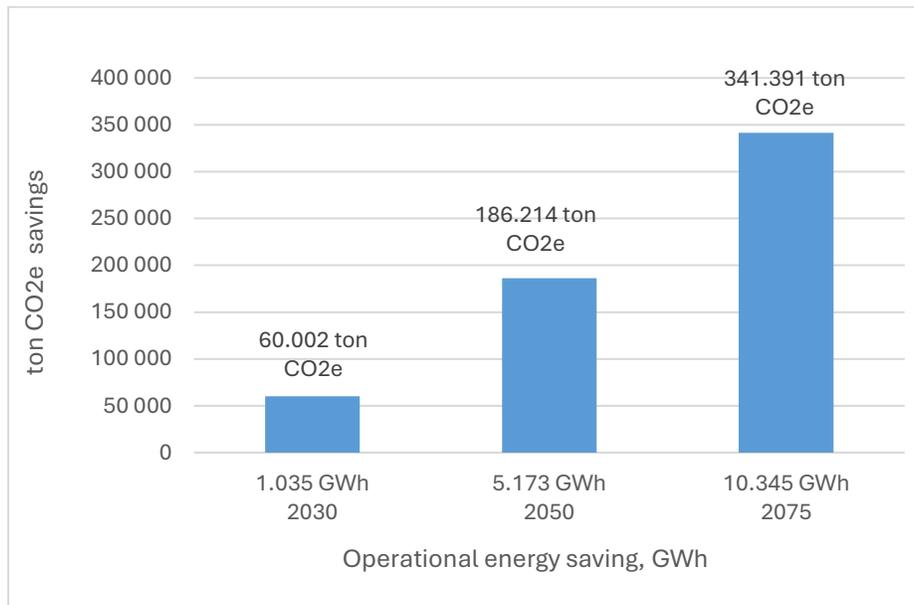


Figure:40 Projected operational savings and CO2e reduction, SFH (1890-1959)

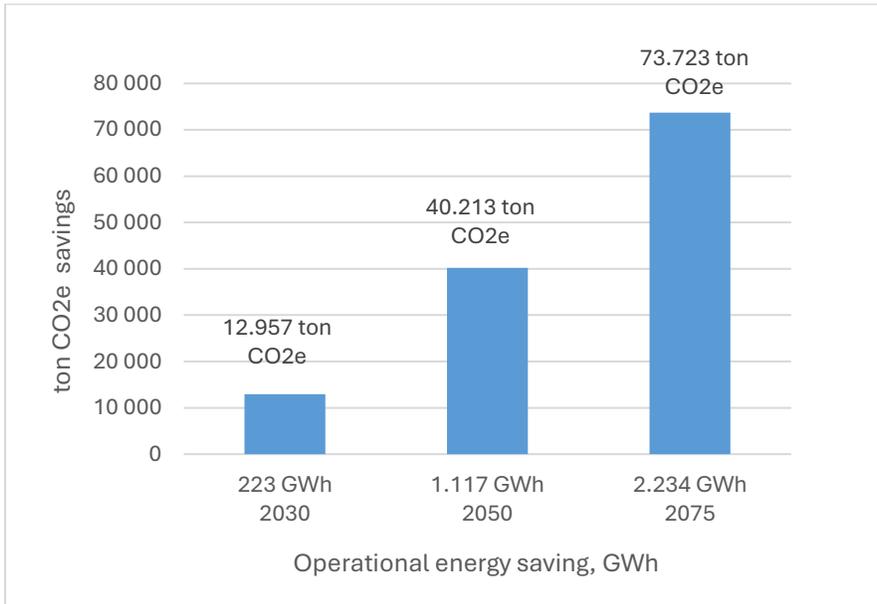


Figure:41 Projected operational savings and CO2e reduction, SFH (1960-1980)

Apartment building

Tables 20-23 summarize the annual operational energy savings for apartment buildings resulting from building envelope renovations under Renovation Method #1 (common practice) and Renovation Method #2 (low-carbon solution) for the two construction periods analyzed, 1890-1959 and 1960-1980.

For each construction period, both renovation methods result in identical operational energy savings across all building elements. This is because the same insulation levels (final U-values) are achieved in both approaches, leading to the same reduction in operational energy demand. Differences between the two methods, therefore, do not affect operational performance but are instead reflected in embodied carbon impacts, which are assessed separately.

Apartment buildings constructed between 1890-1959 show higher absolute energy savings for all components compared to those built between 1960-1980, reflecting their poorer initial thermal performance. In both time frames, roof and external wall upgrades provide the largest energy savings, followed by ceilings and ground floors.

Overall, the results confirm that operational energy savings depend primarily on building age and achieved thermal performance, while the choice between common practice and low-carbon renovation strategies does not influence operational energy outcomes for the same construction period.

Apartment building (-1890-1959)					
Renovation method # 1 (Common practice-insulation upgrade)					
Typology	Time frame	Building element	Limit W/m ² /K	Upgrade to W/m ² /K	Energy savings, kWh/m ² /yr
Detached single family house	(-1890-1959)	Roof	2,58	0,12	222,29
		Ceiling	1,47	0,12	121,99
		Solid external wall	0,69	0,17	46,99
		Solid external wall	1,00	0,17	75,00
		Cavity external wall	1,44	0,18	113,85
		Ground floor	0,49	0,10	35,24
			0,47	0,10	33,43

Table 20: Annual operational energy savings by Renovation Method #1 (common practice)

Apartement building (-1890-1959)					
Renovation method # 2 (Low-carbon solution)					
Typology	Time frame	Building element	Limit W/m2/K	Upgrade to W/m2/K	Energy savings, kWh/m2/yr
Detached single family house (-1890-1959)		Roof	2,58	0,12	222,29
		Ceiling	1,47	0,12	121,99
		Solid external wall	0,69	0,17	46,99
		Solid external wall	1,00	0,17	74,10
		Cavity external wall	1,44	0,18	114,76
		Ground floor	0,49	0,10	35,24
			0,47	0,10	33,43

Table 21: Annual operational energy savings by renovation method #2 (low carbon solution)

Apartement building (1960-1980)						
Renovation method # 1 (Common practice-insulation upgrade)						
Typology	Time frame	Building element	BR standard	Limit W/m2/K	Upgrade to W/m2/K	Energy savings, kWh/m2/yr
Detached single family house	1960-1980	Roof	BR 61-72	0,45	0,12	29,82
			BR 77	0,2	0,12	7,23
		Ceiling	BR 61-72	0,45	0,12	29,82
			BR 77	0,2	0,12	7,23
		Lightweight external wall	BR 61-72	0,6	0,18	37,95
		Cavity external wall	BR 77	0,4	0,17	20,78
		Solid external wall	BR 77	0,4	0,18	19,88
		Ground floor	BR 61-72	0,45	0,10	31,63
			BR 77	0,3	0,10	18,07

Table 22: Annual operational energy savings by Renovation Method #1 (common practice)

Apartement building (1960-1980)						
Renovation method # 2 (Low-carbon solution)						
Typology	Time frame	Building element	BR standard	Limit W/m2/K	Upgrade to W/m2/K	Energy savings, kWh/m2/yr
Detached single family house	1960-1980	Roof	BR 61-72	0,45	0,12	29,82
			BR 77	0,2	0,12	7,23
		Ceiling	BR 61-72	0,45	0,12	29,82
			BR 77	0,2	0,12	7,23
		Lightweight external wall	BR 61-72	0,6	0,18	37,95
		Cavity external wall	BR 77	0,4	0,17	20,78
		Solid external wall	BR 77	0,4	0,18	19,88
		Ground floor	BR 61-72	0,45	0,10	31,63
			BR 77	0,3	0,10	18,07

Table 23: Annual operational energy savings by renovation method #2 (low carbon solution)

Operational energy and CO₂e savings (Building level)

For apartment buildings, the annual operational energy and CO₂e savings per square meter of heated floor differ clearly between the two construction periods, although operational savings are identical for the similar time frame for both renovation methods (Figures 42 and 43). Buildings constructed between 1890-1959 achieve significantly higher operational savings across all envelope components, with a total reduction of 4,46 CO₂e/m²/yr, compared to 0,79 kg CO₂e/m²/yr for buildings from 1960-1980, reflecting the poorer initial thermal performance of the older stock.

Within each construction period, Renovation Method #1 (common practice) and Renovation Method #2 (low-carbon solution) result in identical operational energy and CO₂e savings, as both approaches reach the same final U-values and thermal performance. Differences between renovation methods, therefore, do not affect operational impacts at the building level but become relevant only when embodied carbon impacts are assessed. Across both time frames, roof and external wall renovations provide the largest operational energy and CO₂e reductions, while ground floors and ceilings contribute more modestly, confirming that apartment buildings constructed before 1960 offer the greatest operational mitigation potential through envelope renovation.

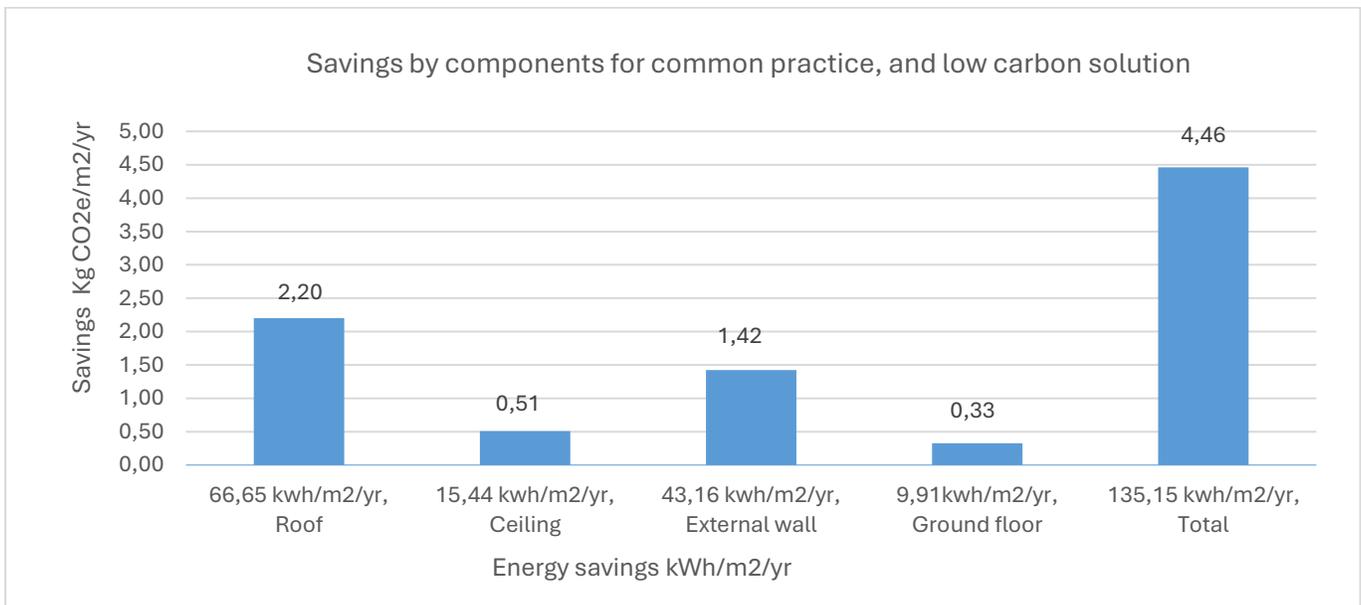


Figure 42: Annual operational and CO₂ savings per m² heated floor, AB (1890-1959)

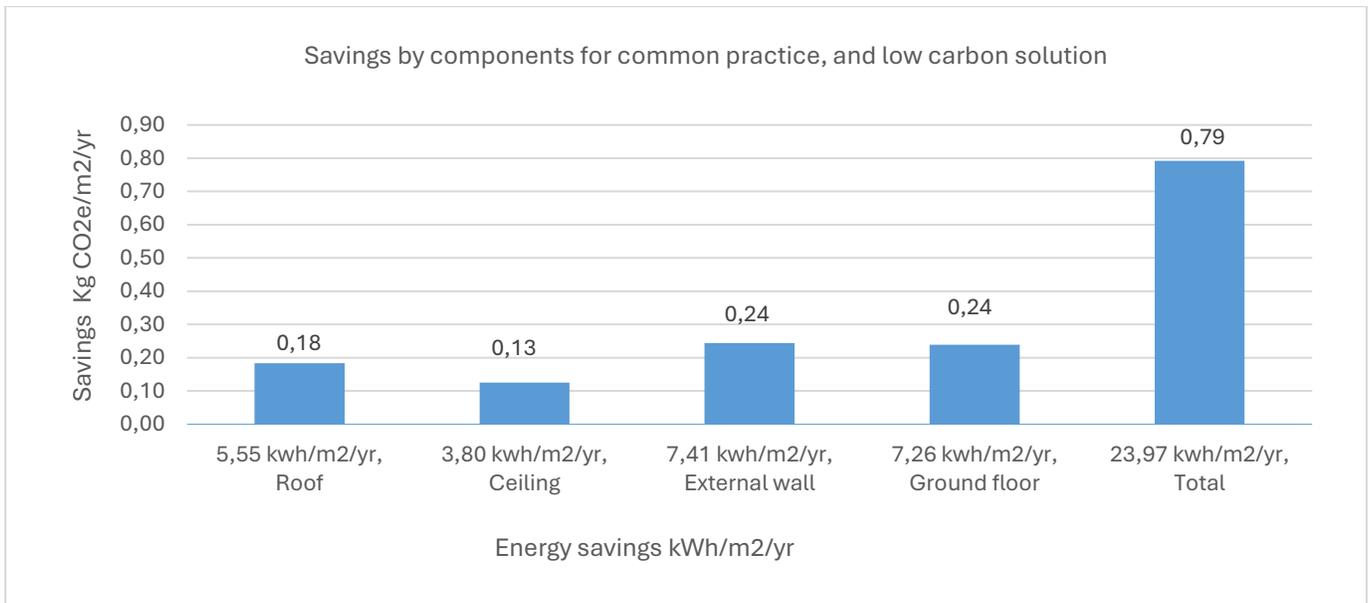


Figure 43: Annual operational and CO₂ savings per m² heated floor, AB (1890-1959)

Annual average operational savings (Component level)

When looking at individual building parts, both renovation methods lead to similar energy and CO₂e savings because each construction period reaches the same level of thermal performance. Figures 44 and 45 show that, in apartment buildings constructed between 1890 and 1959, roof renovation delivers the highest energy savings. Ceilings and external walls come next, while ground floors offer the least savings. Buildings from 1960 to 1980 show the same order of savings by component, but the savings are lower for all components compared to older buildings because these newer buildings started with better thermal performance. Overall, the findings show that upgrading roofs and walls is most effective in both periods, while improving ground floors brings only limited benefits.

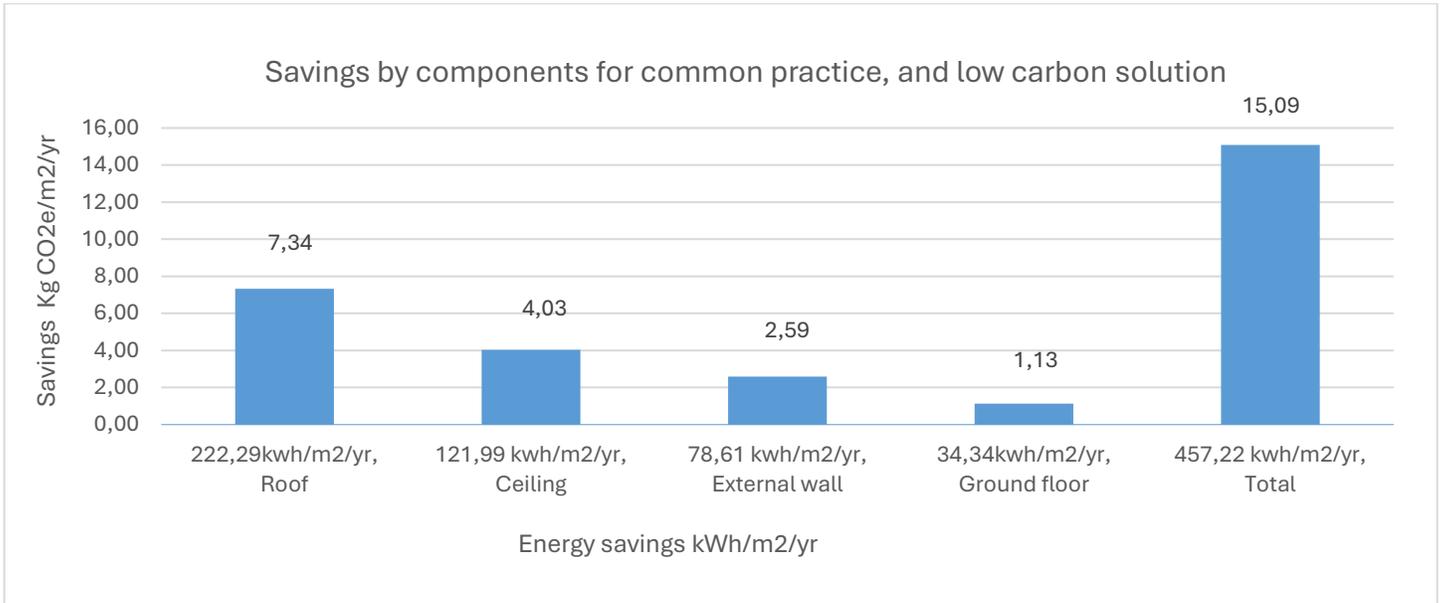


Figure 44: Annual operational energy and CO2e savings per m2 components, AB (1890-1959)

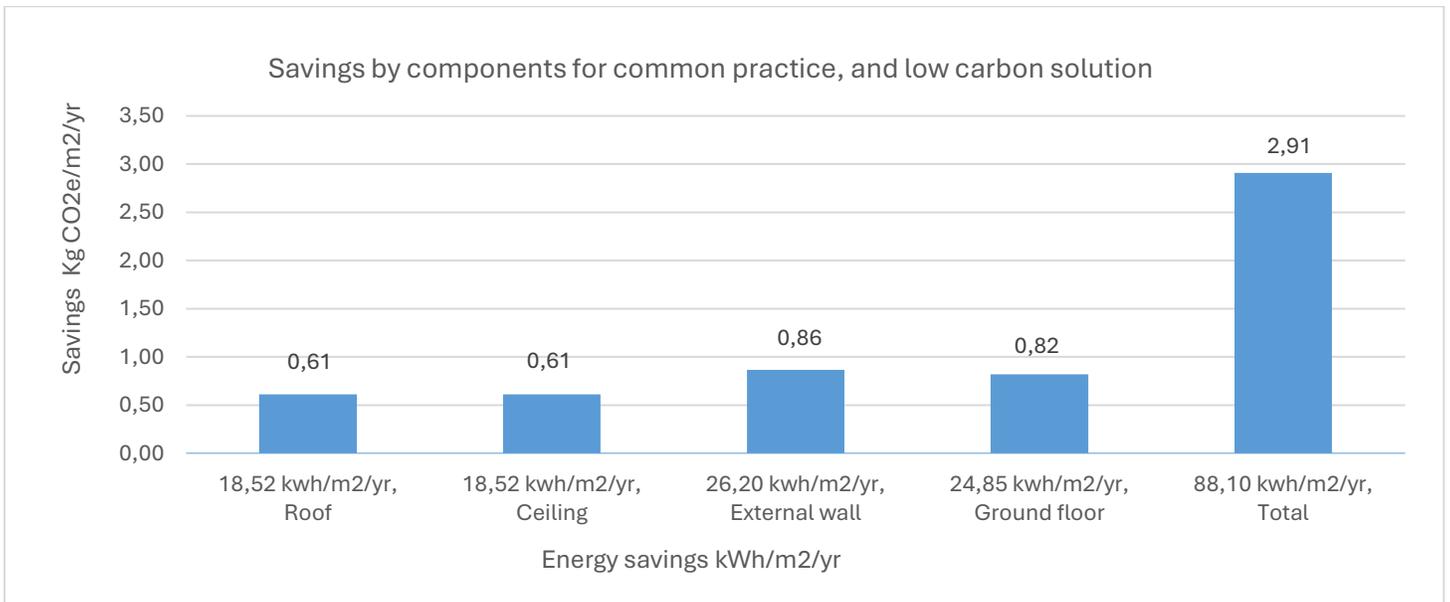


Figure 45: Annual operational energy and CO2e savings per m2 components, AB (1960-1980)

Operational savings with annual renovation rate (Component level)

Figure 46, for 1890-1959 apartment housing stock, renovating the roof leads to the biggest yearly savings, with external walls and ceilings also making a difference. Ground floors help the least. This shows that older buildings lose a lot of heat, so focusing on roofs and walls is the best approach for step-by-step renovations.

Figure 47, for housing stock, between 1960 and 1980, yearly savings are much lower for all components of the building. External walls and ground floors save almost the same amount, while roofs and ceilings save a bit less. These results show that gradual renovations make a bigger difference in older buildings, where upgrades lead to much greater energy and CO₂ reductions.

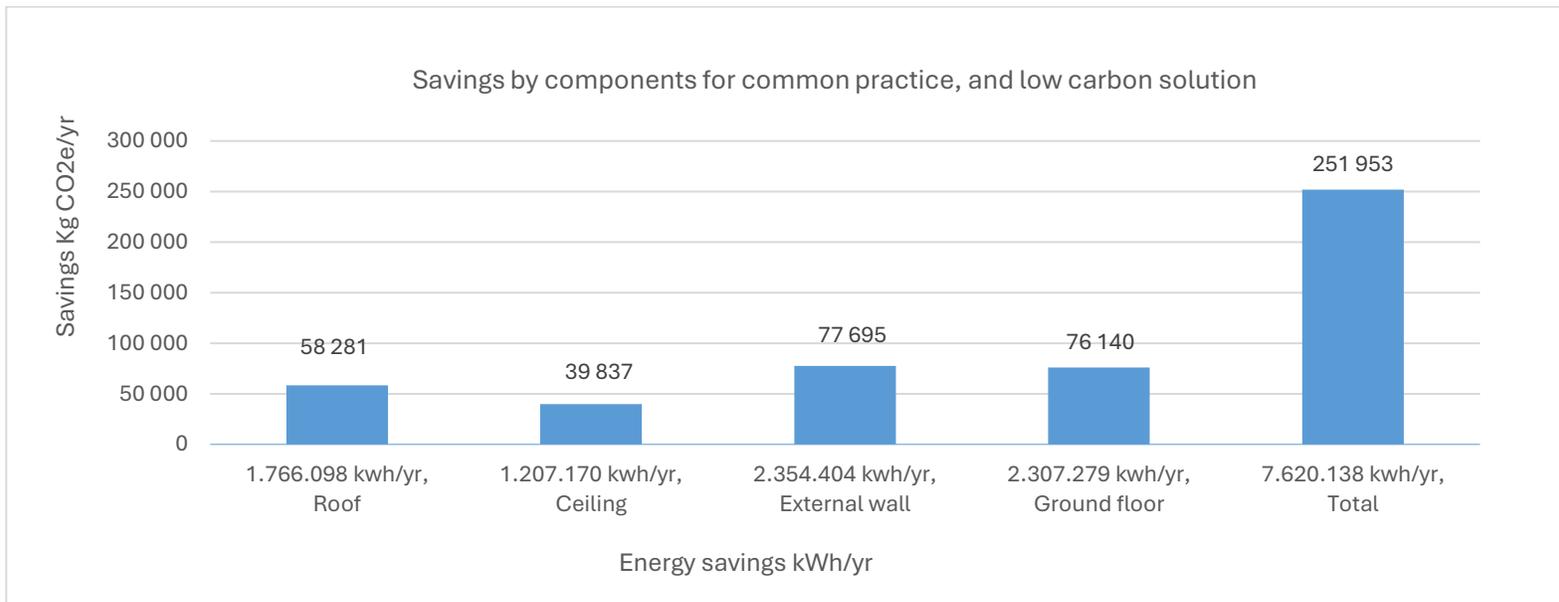


Figure 46: operational energy and CO₂e savings by components, with annual renovation rate, AB (1890-1959)

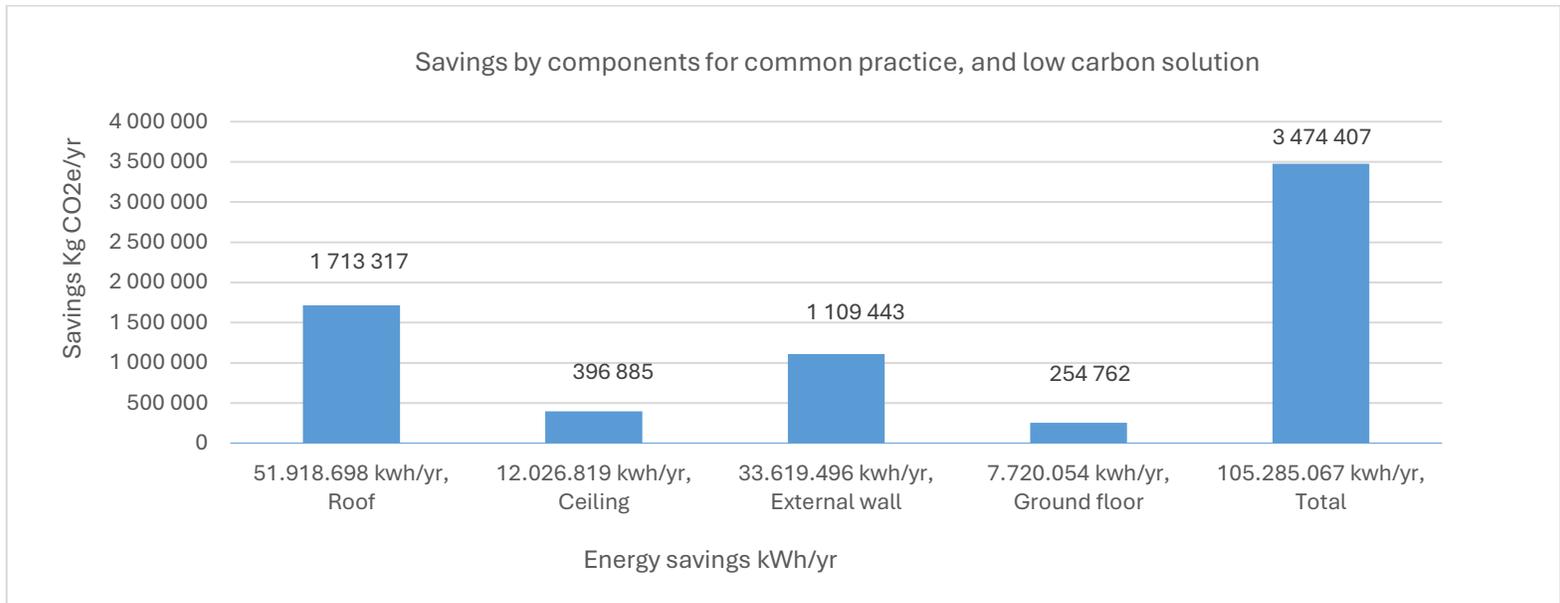


Figure 47: operational energy and CO2e savings by components, with annual renovation rate, AB (1960-1980)

Potential contributions to 2030 and 2050 climate goals

Figures 48 and 49 show the cumulative operational energy and CO2e savings from apartment building envelope renovations up to 2030 under Renovation Methods #1 and #2. For each construction period, both renovation methods deliver identical operational savings, as they reach the same final thermal performance; differences between methods are therefore relevant only for embodied impacts discussed in the embodied chapter. By 2030, apartment buildings constructed between 1890-1959 deliver substantially higher operational CO2e reductions than those built between 1960-1980, indicating a stronger near-term contribution to Denmark’s 2030 climate target. Roof and external wall renovations account for the largest share of operational energy and CO2e savings in both time frames, while ceilings and ground floors provide smaller but still measurable contributions. Savings from unrenovated components remain limited, reflecting the gradual renovation rate and

reinforcing the importance of prioritizing early renovation of high-impact components in older apartment buildings to maximize emission reductions by 2030.

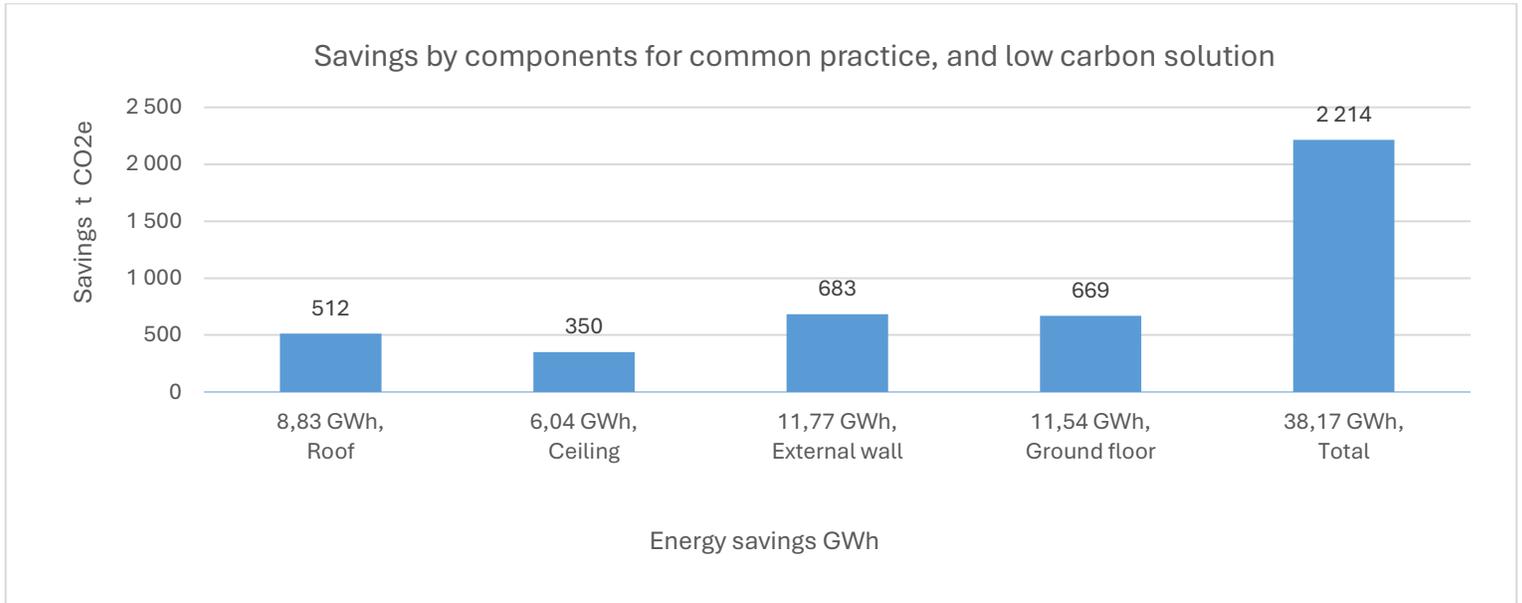


Figure 48: Operational energy and CO2e savings contribution to the climate goal by 2030, AB (1890-1959)

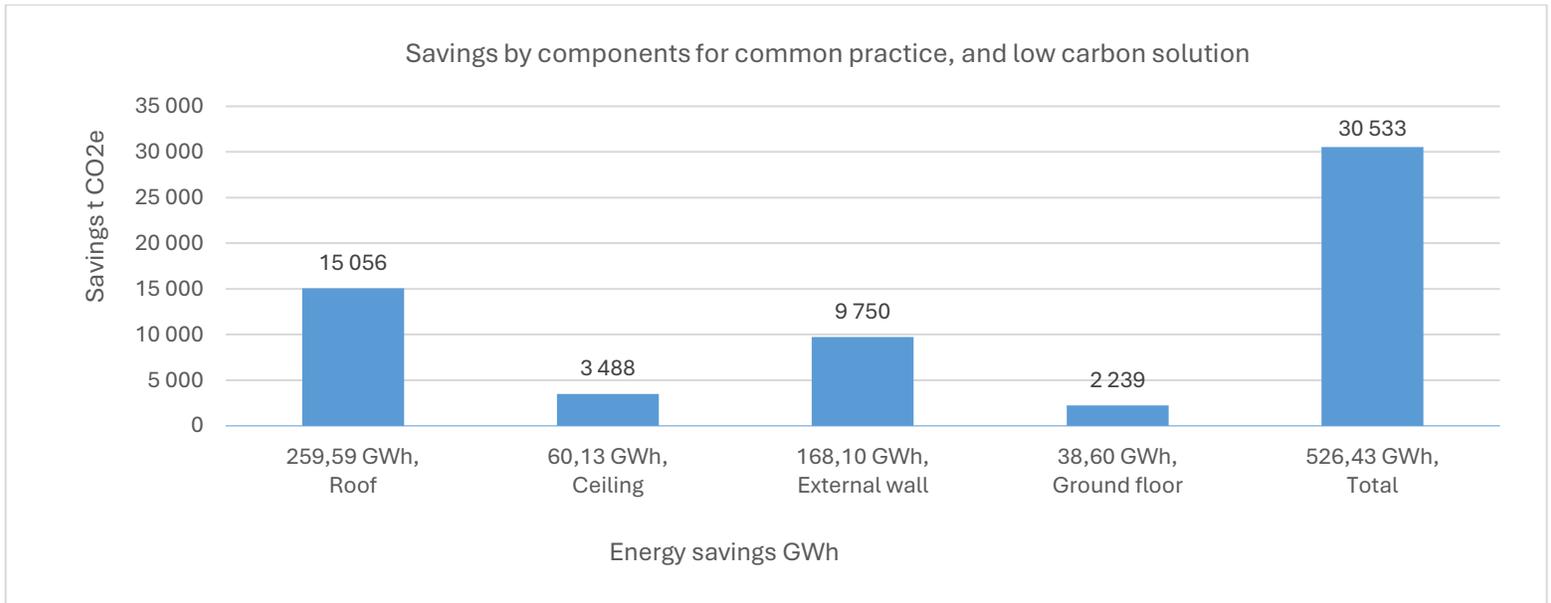


Figure 49: Operational energy and CO2e savings contribution to the climate goal by 2030, AB (1960-1980)

Figures 50 and 51 reflect that by 2050, renovating building envelopes leads to significant reductions in energy use and CO₂ emissions for apartment buildings from both construction periods. Renovation Methods #1 and #2 represent the same operational results

within each period. Older buildings from 1890 to 1959 contribute the most, saving almost 2.632 GWh of energy and around 94.757 t CO₂e. Buildings from 1960 to 1980 saved less, but still achieved about 191 GWh in energy savings and roughly 6.871 t CO₂e.

In both periods, renovating roofs and external walls provides the biggest operational savings, with ceilings and ground floors also helping. This suggests that focusing on older apartment buildings and prioritizing roofs and external walls is the best way to cut emissions and help Denmark reach its 2050 climate-neutral goal.

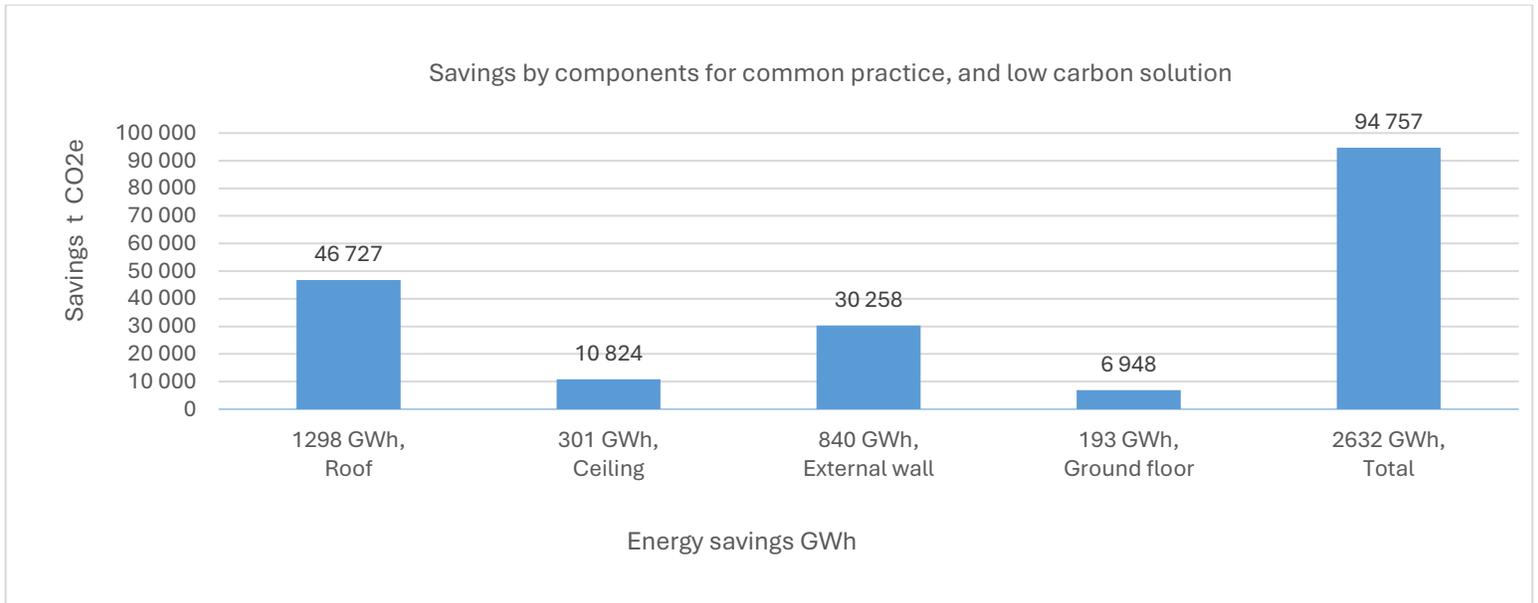


Figure:50 Operational energy and CO₂e savings contribution to the climate goal by 2050, AB (1890-1959)

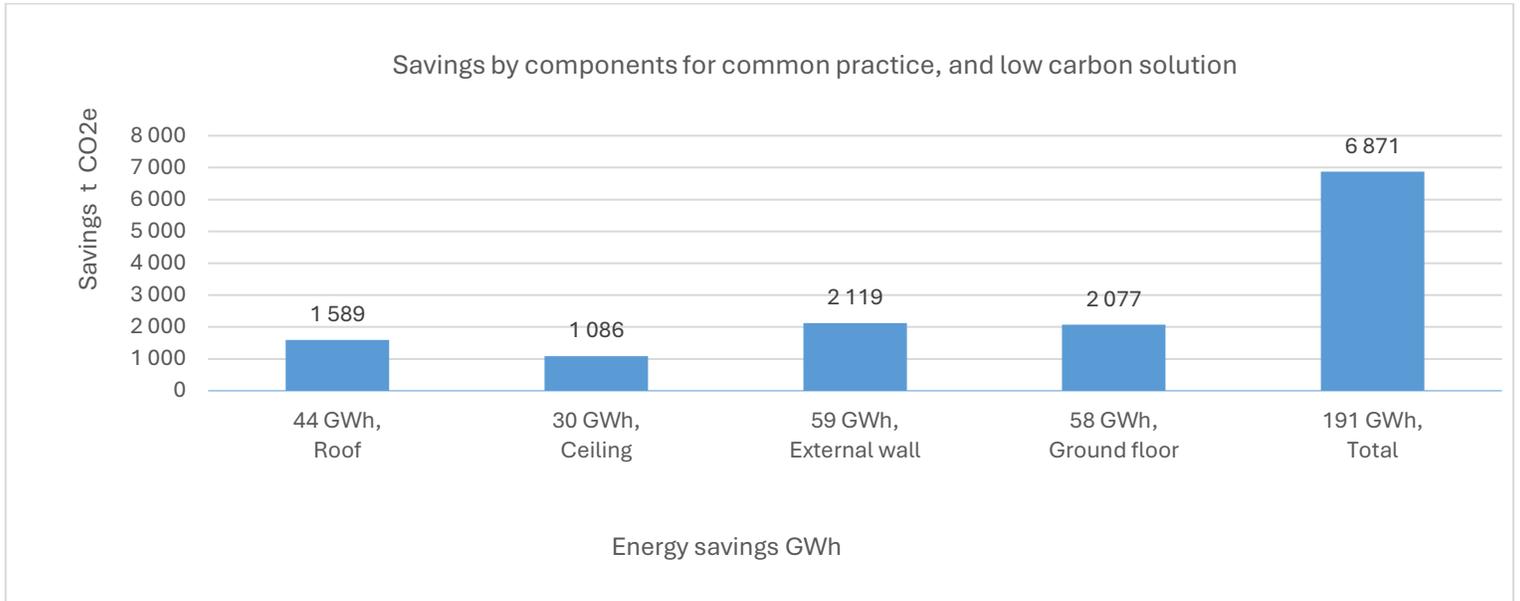


Figure:51 Operational energy and CO2e savings contribution to the climate goal by 2050, AB (1960-1980)

Operational savings over lifecycle (component level)

Figures 52 and 53 show the projected total operational energy and CO2e savings up to 2075 for apartment buildings built in 1890-1959 and 1960-1980, based on a 50-year study period according to LCA framework. By 2075, renovating apartments from 1890-1959 has the biggest long-term effect, saving about 5.264 GWh of energy and reducing CO2e by 173.720 t at national level. Most of these savings come from upgrading roofs and external walls. Apartment buildings from 1960-1980 show a lower but still substantial long-term mitigation potential, reaching around 382 GWh of energy savings and 12.598 t CO2e reductions by 2075, again driven primarily by improvements to roofs and external walls. Across both construction periods, renovated components lead to cumulative savings, while unrenovated components contribute only marginally due to delayed intervention under the applied renovation rate.

Overall, the results show that renovating older apartment buildings offers the highest long-term energy and emissions reduction potential, making this housing stock the most strategic target for sustained national decarbonization beyond 2050.

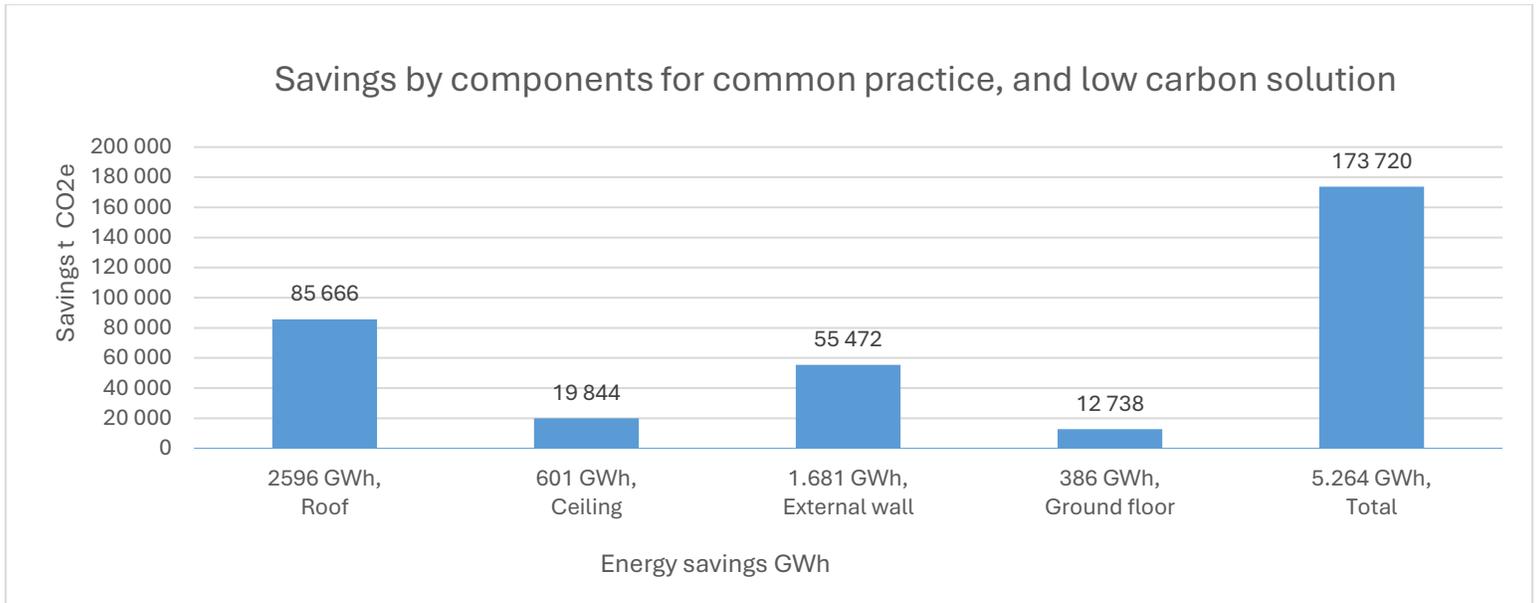


Figure:52 Operational energy and CO2e savings contribution over lifecycle by 2075, AB (1890-1959)

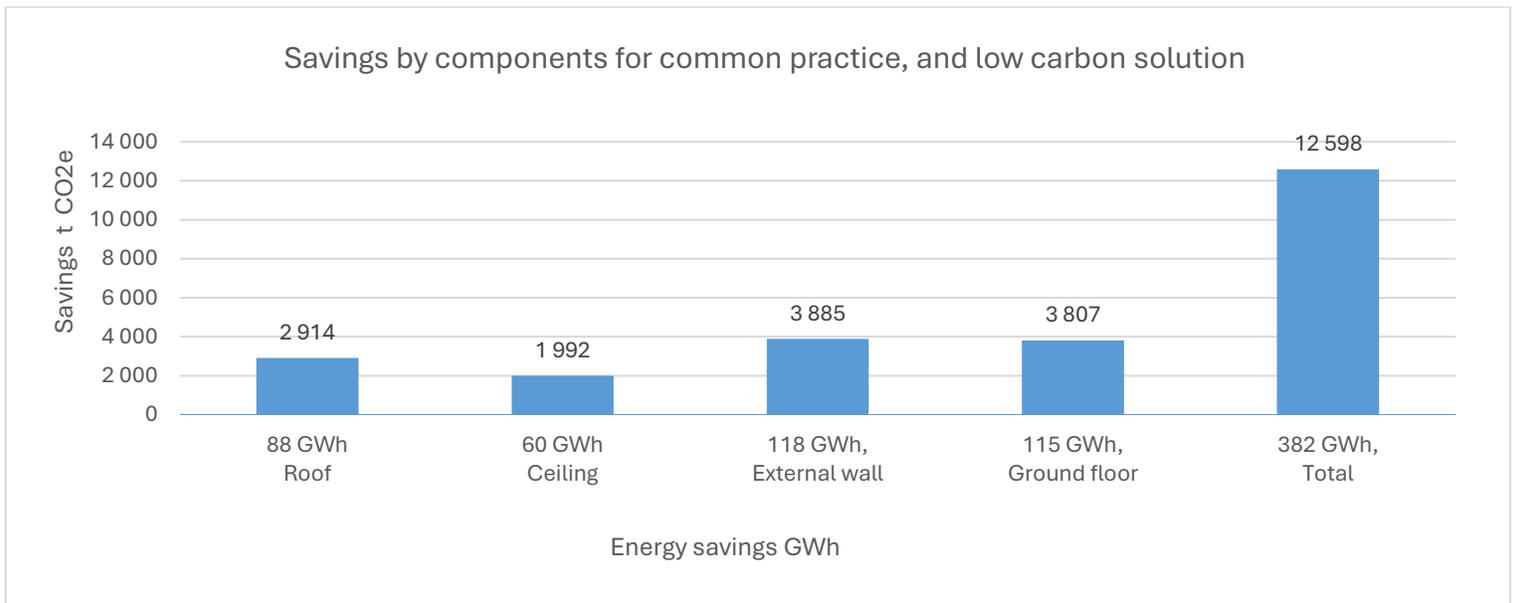


Figure:53 Operational energy and CO2e savings contribution over lifecycle by 2075, AB (1960-1980)

Operational and CO2e savings summary

Figures 54 and 55 summarize results for 2030, 2050 and 2075 and show that as renovations continue over time, both operational energy use and CO2e emissions decrease. Early savings support short-term climate goals, while sustained renovation activity continuously increases emission reductions toward mid-century and over the full life-cycle reference period. These findings indicate that the steady renovation of apartment buildings contributes significantly to supporting national climate goals, with the highest impact resulting from sustained, long-term initiatives.

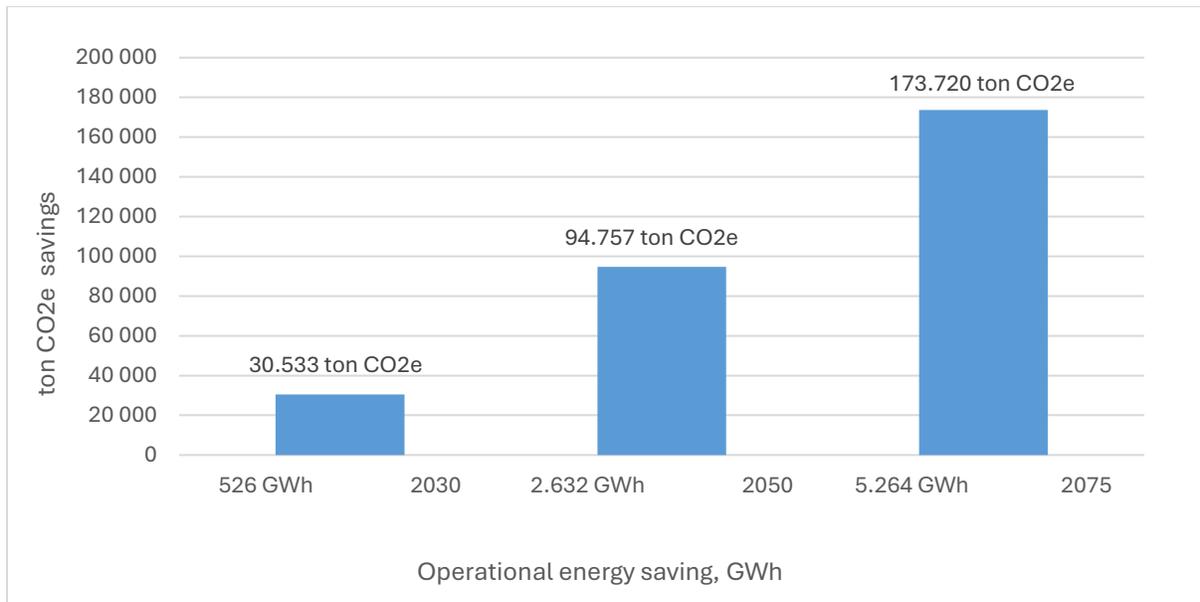


Figure:54 Projected operational savings and CO2e reduction, AB (1890-1959)

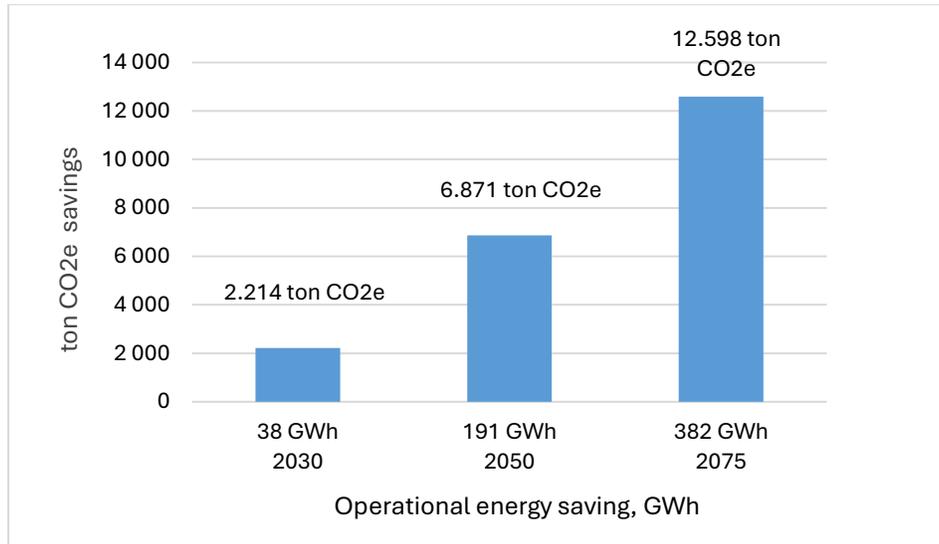


Figure:55 Projected operational savings and CO2e reduction, AB (1960-1980)

3.3 Carbon payback time

Carbon payback time is calculated to compare the carbon performance of common-practice renovation and low-carbon renovation methods across different components over their typical service life for single-family houses and apartment buildings from 1890 to 1959, and 1960 to 1980. This metric helps identify renovation solutions and building envelope components that achieve carbon payback within their service life, as well as those that do not and therefore remain net carbon contributors.

3.3.1 Component Payback - Single-family house

Payback time-Component level					
Renovation method # 1 (Common practice-insulation upgrade)				Renovation method # 2 (Low-carbon solution)	
Typology	Time frame	Building component	Payback year	Building component	Payback year
Detached single family house	1890-1959	Roof	5	Roof	4
		Ceiling	1,2	Ceiling	2,9
		External wall	5,5	External wall	5,1
		Ground floor	98	Ground floor	95
		Ventilated Crawl floor	17	Ventilated Crawl floor	18
Detached single family house	1960-1980	Roof	55	Roof	45
		Ceiling	4,6	Ceiling	10,6
		External wall	9,4	External wall	8,7
		Ground floor	142	Ground floor	138
		Ventilated Crawl floor	44	Ventilated Crawl floor	48

Table 24: Carbon payback time for renovated component

Table 24 presents the component-level carbon payback times for single-family houses across the two construction periods and renovation methods. Ceiling, roof and external wall renovations show the shortest carbon payback times in both construction periods, typically below 10 years, indicating strong short-term climate effectiveness. Ground floor insulation consistently exhibits the longest payback times (approximately 95-142 years), making it the least effective measure within common policy and assessment horizons. Buildings constructed between 1890 and 1959 achieve faster payback than those built between 1960 and 1980 due to higher initial energy losses and greater operational savings potential. In contrast, newer buildings show longer payback periods as insulation upgrades yield smaller marginal energy reductions. The particularly high payback times for ground floor measures are driven by significant embodied emissions associated with thick insulation layers, additional material use and the demolition of existing concrete structures. Differences between Renovation Method #1 and Renovation Method #2 remain limited, with

the low-carbon solution showing slightly shorter payback times in some components due to reduced embodied impacts.

3.3.2 Component Payback - Apartment building

Payback time-Component level					
Renovation method # 1 (Common practice-insulation upgrade)				Renovation method # 2 (Low-carbon solution)	
Typology	Time frame	Building component	Payback year	Building component	Payback year
Apartment building	1890-1959	Roof	5	Roof	4
		Ceiling	1,2	Ceiling	3
		External wall	7,1	External wall	6,3
		Ground floor	98	Ground floor	95
Apartment building	1960-1980	Roof	55	Roof	45
		Ceiling	4,6	Ceiling	11
		External wall	25,8	External wall	24,6
		Ground floor	176	Ground floor	168

Table 25: Carbon payback time for renovated components, Apartment building

Table 25 shows the summary for component-level carbon payback times for apartment buildings across the two construction periods and renovation methods. Roof and external wall renovations show the shortest payback times in both time frames, indicating the most climate-effective measures in the short to medium term. Ceiling upgrades also achieve relatively fast payback, while ground floor measures exhibit very long payback periods, making them the least effective intervention within typical assessment horizons. Apartment buildings constructed between 1890 and 1959 achieve faster payback than those built between 1960 and 1980, reflecting higher baseline energy losses and greater operational savings potential. The long payback times for ground-floor renovations are driven by high embodied emissions, resulting from extensive insulation requirements, additional material use, and demolition of existing concrete floor structures. Differences between Renovation Method #1 and #2 are limited, with the low-carbon solution showing slightly shorter payback times due to reduced embodied impacts.

4. Discussion

Retrofitting building envelopes always lowers operational energy use, no matter the building type or age. However, when looking at the whole life cycle, embodied carbon emissions can differ a lot depending on the component and renovation method. This shows that calculating operational energy only is not enough to judge climate impact, especially as energy sources become less carbon-intensive.

Operational savings mostly depend on the achieved U-values and how the building performed before renovation. Embodied impacts are influenced by how much material is used, what is assumed about replacements and the building's structure. This means that two renovations with the same operational results can have very different life-cycle greenhouse gas emissions.

The comparison between common practice and low-carbon renovation methods shows that biobased insulation materials do not always guarantee lower embodied carbon outcomes. When assessing the embodied impact using the generic dataset provided by BR18, mineral wool frequently performs better in terms of embodied emissions when the same thermal performance is needed or when cladding choices are fixed. This proves the sensitivity of LCA outcomes due to the use of different material datasets and modelling assumptions.

When looking at individual components, roofs and external walls offer the best balance between operational savings and embodied impacts. In contrast, ground floor slab renovations have high embodied emissions and take a long time to pay back their carbon cost. In the case of the studied building types, differences between single-family houses and apartment buildings are primarily related to construction assumptions and the inclusion of specific wall types rather than typology itself.

5. Conclusion

This study assessed how embodied carbon reduction strategies can be integrated with building envelope energy retrofitting to improve the sustainability performance of existing residential buildings. The analysis combined component-level life cycle assessment with national-level upscaling for Danish single-family houses and apartment buildings constructed in the periods 1890–1959 and 1960–1980. A thorough life-cycle assessment must be performed in order to find a balance between carbon emissions and savings. Strategies prioritising energy performance alone do not necessarily lead to lower total life-cycle emissions, especially in times of declining carbon intensity in the energy supply.

The study found that the most effective embodied carbon reduction strategy varies by building component. For roofs and external walls, renovation that allows optimisation of both cladding and insulation has the greatest potential for reducing embodied emissions. The hybrid roof renovation scenario, with a low-impact cladding and mineral wool combination, outperformed both conventional and biobased practice. For components where insulation is the main addition, such as ground floors and floors above ventilated crawl spaces, common renovation practice using mineral wool results in the lowest embodied carbon impact.

Material choice and renovation design influence both operational and embodied impacts. Although biobased materials achieve comparable thermal performance, they do not necessarily reduce embodied emissions under the generic datasets applied, due to differences in required material quantities or high contributions in the end-of-life stages. Cladding choice plays a significant role in components where finish materials are to be replaced.

Across the selected time periods, older buildings have greater operational savings due to the greater change in thermal transmittance post-renovation, while requiring more insulation to meet the energy performance requirements. The period of construction affects the life-cycle emissions more than the building typology.

National-scale calculation proved that sensible renovation strategies can contribute to Denmark's climate targets, but the net effect depends on renovation rate, material

selection and prioritisation of components to renovate. It is important to keep in mind that the evaluation was performed under a fixed renovation rate and predefined modelling assumptions, thus it is difficult to tell how accurate these projections are.

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