Maintaining or replacing a building's windows: a comparative life cycle study

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Abstract

Purpose – Energy-efficiency measures have always been important when renovating aging building stock. For property owners, window intervention is a recurring issue. Replacement is common to reduce operational heating energy (OHE) use, something many previous building renovation studies have considered. Maintaining rather than replacing windows has received less attention, especially for multi-residential buildings in a subarctic climate where there is great potential for OHE savings. The objective was to assess the life cycle (LC) climate impact and costs of three window maintenance and replacement options for a 1980s multi-residential building in subarctic Sweden.

Design/methodology/approach – The options' embodied and operational impacts from material production, transportation and space heating were assessed using a life cycle assessment (LCA) focusing on global warming potential (LCA-GWP) and life cycle costing (LCC) with a 60-year reference study period. A sensitivity analysis was used to explore the impact of uncertain parameters on LCA-GWP and LCC outcomes.

Findings – Maintaining instead of replacing windows minimized LC climate impact and costs, except under a few specific conditions. The reduced OHE use from window replacement had a larger compensating effect on embodied global warming potential (E-GWP) than investment costs, i.e. replacement was primarily motivated from a LC climate perspective. The LCA-GWP results were more sensitive to changes in some uncertain parameters, while the LCC results were more robust.

Originality/value – The findings highlight the benefits of maintenance over replacement to reduce costs and decarbonize window interventions, challenging property owners' preference to replace windows and emphasizing the significance of including maintenance activities in future renovation research.

Keywords Building renovation, Energy efficiency, Life cycle carbon, Life cycle costs

Paper type Research paper

Nomenclature

AW	Aluminum-clad Windows	LCC	Life Cycle Costing
DH	District Heating	NPV	Net Present Value
E-GWP	Embodied Global Warming Potential	O-GWP	Operational Global Warming Potential
EPD	Environmental Product Declaration	OHE	Operational Heating Energy
GFA	Gross Floor Area	PW	Polyvinyl chloride (PVC) Windows
GHG	Greenhouse Gas	RSP	Reference Study Period
GWP	Global Warming Potential	SL	Service Life
LC	Life Cycle	WW	Wooden Windows
LCA	Life Cycle Assessment		

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1. Introduction

In response to Europe's energy-inefficient building stock, the European Union (EU) directive *on the energy performance of buildings* (Procedure, 2021/0426/COD, n.d.) urged an increase in energy renovations to reduce greenhouse gas (*GHG*) emissions throughout buildings' life cycles. Sweden's building stock accounts for about 34% of the country's total energy use and 21% of the total GHG emissions (Boverket, 2023), while the number of aged buildings in poor condition due to a lack of maintenance and renovation is increasing (Regeringen, 2020). Heating demands constitute a large share of existing buildings' total energy use, especially in Northern Sweden's subarctic climate with long winter seasons and relatively small solar heat gains. In such a climate, improving the building envelope's thermal properties is essential for reducing operational heating energy (OHE) use (Felius *et al.*, 2020) and approaching climate neutrality goals. However, energy-efficiency measures for buildings increase their embodied global warming potential (*E-GWP*) through the production of new materials (Litti *et al.*, 2018; Feng *et al.*, 2023). Therefore, efforts should be made to minimize the E-GWP to decarbonize the construction and real estate sectors further, especially in view of the pressure for increased energy renovation rates.

Poorly conditioned windows are a common issue for property owners, who can try to prolong their service lives (*SL*) by restoring and maintaining them or decide to replace them. The various options cause confusion and uncertainty over the best window intervention (BeBo, 2022), making it an interesting case for investigating maintenance versus replacement actions. Swedish property owners commonly prefer replacing windows, despite high investment costs and long payback periods, due to a perceived certainty of energy and cost savings compared to maintaining them (BeBo, 2022). However, according to the literature review by Souviron *et al.* (2019), the climate benefit of window replacements is uncertain, considering the potential trade-off effect between the reduced operational GWP (*O-GWP*) and the E-GWP of energy-efficient windows. Although the E-GWP of windows is generally smaller than that of components accounting for a larger proportion of a building's mass (e.g. walls and slabs), their contributing impact percentage is high considering their relatively low material weight (Feng *et al.*, 2023). Further uncertainty arises when considering window types with various SL and maintenance needs. For instance, aluminum-clad (*AW*) and polyvinyl chloride (PVC: *PW*) windows might need relatively little maintenance (Litti *et al.*, 2018; Asif, 2019), but more frequent replacement (Litti *et al.*, 2018). In addition, replacement and maintenance rates influence windows' life cycle (LC) impact (Eberhardt *et al.*, 2018; Grant, 2010). Shifting cost and climate impacts across the LC stages could alter the ranking of preferable intervention measures. In addition, the uniqueness and complexity of renovation projects cause uncertainties (Noori *et al.*, 2016) originating from (*inter alia*) sparse information and unforeseen conditions (Uotila *et al.*, 2020). In LC studies, transparency about uncertainties and sensitivities is essential to increase the generalizability of LCA results (Souviron *et al.*, 2019). Therefore, transparency and sensitivity analyses may be especially relevant for the generalizability of LC studies on renovation measures.

In their respective reviews of building LCA studies, Anand and Amor (2017) called for more case studies on renovation options in general, while Thibodeau *et al.* (2019) highlighted the lack of consideration of non-energy-related renovation measures. Also, previous building renovation research has reported inconsistent findings regarding the LC impacts of maintenance and replacement activities (Francart *et al.*, 2021). Previous window-related LC studies have compared various window types (e.g. Saadatian *et al.*, 2021; Asif, 2019; Menzies, 2013), but lack consideration of intervention options for multi-residential buildings. In addition, few have considered maintenance activities and potential changes in buildings' OHE. One exception is Switala-Elmhurst (2014), who compared window maintenance and replacement for a single-family house in a humid subtropical climate in the USA. No previous study considering window maintenance versus replacement in strongly heating-dominated climates has been found.

Our study aimed to provide more knowledge about LC impacts of maintenance and replacement by analyzing and comparing GWP and costs of three window intervention options for a 1980s multi-residential building in subarctic Sweden.

2. Previous research on window maintenance and replacement

Despite inconsistent findings on the relative contribution of maintenance and replacement activities to the LC GWP, they can significantly affect assessment results, especially when using longer reference study periods (*RSP*) and pessimistic assumptions about SL (Malmqvist and Francart, 2023). For instance, extending and shortening the RSP can alter the LC results (Francart *et al.*, 2021; Goulouti *et al.*, 2020) since it impacts the number of maintenance and replacement activities. Furthermore, replacements generate investment costs and E-GWP from producing, transporting and installing new materials, meaning that material SL impacts the LCA and LCC, as Goulouti *et al.* (2020) noted. The outcomes can also be affected by national contexts, such as regulations and available databases (Malmqvist and Francart, 2023). For example, heating fuels can vary within and between countries, impacting emission factors and operating costs. Regarding the emission factors, Jerome *et al.* (2021), who analyzed two energy renovation strategies for a Swedish heritage multi-residential building, found them to impact the building's environmental performance significantly. The higher the emission factor, the greater the saving potential of O-GWP. Another parameter affecting the LC outcomes is the building envelope's initial thermal properties, which Milić *et al.* (2019) found when assessing the LCC of energy renovation measures on 12 different Swedish historical buildings. The impact of methodological choices highlights the importance of considering uncertain parameters that can affect the LC results' robustness: see 3. Research methodology.

Souviron *et al.* (2019) highlighted the need for greater insight into the extent to which the reduced OHE use can counterbalance the increased E-GWP from producing energy-efficient windows. While several studies suggest a balancing effect exists (Asif, 2019; Citherlet *et al.*, 2000; Saadatian *et al.*, 2021), this effect depends on the operational stage's energy production mix. Based on a study of window interventions for Swedish multi-residential buildings, BeBo (2022) argued that energy savings with low climate burden lose importance from a LC climate perspective and that investing in energy-efficient windows shows no evident LC economic benefit. When comparing two renovation strategies on a Danish heritage building, Serrano *et al.* (2022) saw the importance of the E-GWP when opting for the lowest LC environmental impact, where a window replacement significantly increased the embodied impacts compared to preservation. Among several energy-efficiency measures for single-family houses, Ekström *et al.* (2018) found window replacement to be the most economically unfavorable, despite meeting new-build or passive house standards. Similarly, the findings of La Fleur *et al.* (2019) indicated no cost-effectiveness from energy-efficiency investments for a 1960s multi-residential building. The uncertain LC benefit of reducing OHE use makes investigating to what extent savings in the operational stage counterbalance the product stage's costs and GWP worth studying.

Depending on the window type and its required maintenance or replacement rate, the LC GWP and costs will vary. Menzies (2013) compared AW, PW and wooden (*WW*) windows in different weather conditions, ranging from rural locations with little or no shelter to sheltered non-coastal locations at low altitudes. Asif *et al.* (2005) assessed the environmental impacts of different window frames, from production to disposal. Both studies found the lowest GWP for producing WW. Saadatian *et al.* (2021) obtained similar results from a comparative LCA of different window solutions for an office room when expanding the system boundary to include OHE savings. While PW appear less preferable for the GWP regardless of OHE savings (Menzies, 2013; Switala-Elmhurst, 2014; Asif *et al.*, 2005), PW have been found economically beneficial at a 30-year RSP and a 3% discount rate (Saadatian *et al.*, 2021). However, Asif *et al.* (2005) disagreed with the general perception that PWs are the cheaper option. For instance, when using a 60-year RSP, Menzies (2013) found that PW resulted in the highest LC costs due to their relatively short SL and, thus, higher replacement rate. Instead, Menzies (2013) found AW economically preferable for multi-story buildings with severe weather exposure and WW favorable for more mildly exposed buildings in urban environments. Since the optimal window type, economically and environmentally, depends on the scenario, this study considers AW, PW and WW as options for replacing the existing windows.

In line with previous research and this study's aim, the following research questions were addressed:

RQ1. How do window maintenance and replacement options compare regarding LC climate impact and costs?

RQ2. To what extent do savings in the operational stage counterbalance the product stage regarding LC climate impact and costs for the studied options?

RQ3. Which uncertain parameters critically impact the comparison between the maintenance and replacement options regarding LC climate impact and costs in the studied context?

3. Research methodology

In collaboration with a municipal housing company, a multi-residential building with worn triple-glazed WW (see Figure 1) was selected as the case study on window intervention scenarios regarding LC climate impact and costs. The building is typical of its 1985 construction and its location in northern Sweden. It retains its original windows, which the housing company plans to repair or replace in 2025.

The study adheres to Swedish regulations, definitions, standards, etc., relevant for studying the building within the Swedish context. However, to facilitate comparisons with previous research, the study followed commonly applied international standards for LCA and LCC. The LCA adheres to EN 15978:2011 (CEN, 2011) and is entirely focused on the GWP, aligning with the study's focus on climate impact. Other environmental impact categories are not considered in this study. From now on, the climate impact assessment will be called LCA-GWP to clarify this system boundary.

The LCC assessment follows ISO 15686–5:2017 (ISO, 2017) and the guidelines of the Swedish National Property Board (SFV, 2022). To estimate the change in OHE when replacing windows, building energy simulations were made using IDA ICE (version 4.8 SP2, Equa Simulation AB, Sweden) due to its past success in accurately predicting energy savings from renovation (see, e.g. La Fleur *et al.*, 2017).

The study considered the product and operational stages, including modules A1–A4 and B6. Window intervention occurs during the operational stage, relating the climate impact to the renovation stage (B5). However, according to EN 15978:2011, if there is no previous LCA for the building, impacts from renovations should be treated as a new life cycle (i.e. from module A). Therefore, in this study, modules A1–A4 address the climate impact of producing and transporting materials for maintenance or replacement activities. Module B6 was included to capture the reduced O-GWP from OHE savings. The remaining operational stage modules were assumed to be identical for all options. The LCC included the investment costs, comprising material and labor costs and operational cost savings from reduced OHE use.

The study does not consider the on-site assembly (A5), end-of-life (EoL) (C) and reuse/recycle potential (D) modules. These are often negligible in a building's whole LC

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Figure 1.
The studied building and the window intervention options

(e.g. Frischknecht *et al.*, 2020; Souviron *et al.*, 2019) and unlikely to affect the comparison of window intervention options. In addition, knowledge regarding modules C and D for windows is limited (Souviron *et al.*, 2019). EoL and reuse/recycle activities also occur far into the future due to the windows' relatively long SL (see Section 4.1), requiring uncertain predictions to calculate their impact. Since the EoL is not covered, any biogenic carbon fixing for wooden products was neglected in the product stage. Similarly, the LCC does not cover deconstruction costs and residual values.

In Section 2, six uncertain parameters that can critically impact the LCA-GWP and LCC were identified, including the RSP and windows' SL, determining both the rate and number of window interventions; the local district heating (*DH*), varying locally (Energiföretagen, 2023) and over time (Fossilfritt Sverige, 2018); the unknown thermal transmittance (*U-value*) of the existing windows, affecting potential OHE savings from a window replacement and the discount rate, influencing the present value of future revenues (ISO, 2017). The impact of these parameters on the LCA-GWP and LCC outcomes was investigated using sensitivity analyses (see Section 4.5).

4. Case study

4.1 Maintenance and replacement options

Figure 1 shows the six-story building accommodating 128 student apartments and the three window intervention options.

Option 1: Periodic maintenance (the base scenario) implies recurring maintenance activities to restore and maintain the function and appearance of existing windows. This involves cleaning, sanding, priming, painting and partly re-puttying at a contractor's estimated 10-year maintenance interval throughout the RSP.

Option 2: Replacement + Periodic maintenance assumes the degeneration of existing windows, ending their SL and replacement with new WW that are periodically maintained throughout the remaining RSP, as in Option 1.

Option 3: Replacement comprises three sub-options involving new windows with different frame materials (*3.1 Wooden*, *3.2 Aluminum-clad*, or *3.3 PVC*) left without maintenance during the RSP. This aligns with common conceptions of AW and PW being "maintenance free" (Asif *et al.*, 2005), while WWs are left unmaintained, in contrast with Options 1 and 2. Additional window replacements were accounted for when the estimated window SL fell below the RSP. For the WW and AW, a 40- and 50-year SL, respectively, was assumed to align with their environmental product declaration (*EPD*) and standard industry practice (Asif, 2002 in Asif *et al.*, 2005). For PW, a 30-year SL was used in line with an average literature value reported by Menzies (2013).

The maintenance activities in Option 1 were assumed not to affect the heating energy use due to their limited heat reduction potential (Litti *et al.*, 2018) and lack of thermal measurements for maintained 1980s windows. In contrast, replacement with new, more energy-efficient windows in Options 2 and 3 lead to OHE savings, see Section 4.4.

The LC assessment assumes a simultaneous window intervention, excluding any differing degeneration rates due to weather conditions, user behavior, incorrect fitting or manufacturing defects. An RSP of 60 years was chosen to reflect the housing company's "100-year-perspective", meaning that the 40-year-old building is expected to last at least 60 more years after renovation.

4.2 LCA-GWP

The quantities of all materials required for window maintenance or replacement were obtained from contractors' tenders collected by the housing company to support their window intervention decision. The E-GWP from A1–A4 was estimated using the climate calculation tool BM (version 3.2, IVL Svenska Miljöinstitutet AB, Sweden) that follows the EN 15804 and EN 15978 standards. Input data included each material's estimated total weight (see Supplementary material), which was based on the tenders. The materials' climate data were collected from a combination of EPDs and the database integrated into BM, which contains generic data representative of the Swedish construction sector. The climate data are expressed in CO2-eq, which is a common unit to describe the different GHG emissions affecting the global warming potential. The total E-GWP for each window intervention option is the sum of each material's weight multiplied by related climate data. See Supplementary material for the climate data used in this study. EPDs were used as the primary climate data source to represent the studied case. The EPDs were chosen based on typical construction materials or products available on the Swedish market, apart from the PWs' EPD originating from Germany. Generic database climate data available in BM were used for materials used in small quantities and for which EPDs were missing. The transport data comprised travel distances between the material manufacturer and the studied building, assuming 100% diesel-fueled trucks, with average transportation distances of 748 km (maintenance) and 1,073 km (replacement) for the materials. See the total distances for the intervention options in the supplementary material. The reduced O-GWP (B6) was estimated using the OHE savings (see Section 4.4) and the emission factor of the local DH provider (Energiföretagen, 2023). The GWP was calculated in kg CO_2-eq per functional unit of m^2 gross floor area (GFA) [kg CO_2-eq/m^2 GFA] in accordance with the Swedish Act (SFS, 2021, p. 787) on climate declaration for new buildings.

4.3 LCC

Inflation changes the scenarios' future costs and revenues. Therefore, to enable comparisons, the monetary values were converted to net present values (*NPV*) using Eq. (1) and input data (see Supplementary material).

$$NPV = P(1+q)^n \frac{1}{(1+r)^n} \tag{1}$$

P: Investment cost of window intervention or DH price

q: Escalation rate of window intervention and DH prices

r: Discount rate

The material and labor costs were obtained from the tenders, while the annual average DH price follows the housing company's pricing model. Inflation (2%) and escalation rates (1.6% for maintenance and 1.5% for DH) were considered throughout the RSP. The calculated NPVs are the total LC costs in EURO per GFA [EUR/m^2 GFA] over the RSP.

4.4 Operational stage

An energy simulation model of the building was developed based on documents, drawings and discussions with the housing company (see input data in Supplementary material) and calibrated using actual measured data for the base case with original windows. The 5,298 m^2 building is heated through hydronic radiators connected to the local DH and ventilated through a mechanical supply and exhaust system with heat recovery. The average U-value of the building envelope is 0.43 W/m^2K. The validated model was used to estimate annual OHE savings from window replacements in Options 2 and 3. The U-value of the original windows from 1985 was estimated at 1.8 W/m^2K based on Fredlund's (1999) measurements of a similar 1980s window. The U-value of new windows was set to 1.3 W/m^2K based on a contractor's tender. The U-values were assumed to be constant during the RSP, neglecting any degeneration in their thermal properties.

4.5 Sensitivity analysis

The sensitivity analysis considered variations in six parameters (see Table 1):

(1) The *RSP* was extended from 60 to 100 years to explore the results' general direction if the building exceeds its estimated 100-year SL, but also to encourage a more long-term perspective (Francart *et al.*, 2021). Buildings are usually expected to last up to 100 years after renovation (Thibodeau *et al.*, 2019).

Table 1. Initial data input used for the “MID 60” scenario and the alternative inputs for the sensitivity analysis

Parameter	Initial input	Alternative		Unit
Reference study period, RSP	60	100		years
District heating cost	31	143		EUR/MWh
	MID	*HIGH*	*LOW*	
Emission factor	25	495	0	gCO_2-eq/kWh
U-value, windows	1.8	2.3	1.3	W/m^2K
Discount rate	4.4	10	0	%
Intervention rates				
Maintenance rate	10	4	15	years
Window replacement rate:				
- Wooden	40	30	50	years
- Aluminum-clad	50	40	60	years
- PVC	30	20	40	years

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(2) The *intervention rates* were varied from 4 to 15 years for maintenance and adjusted by ± 10 years for replacement to evaluate the effect of shortened or prolonged longevity, where the latter promotes a more long-term perspective (Francart *et al.*, 2021). The rates are based on variations in the windows’ estimated SL derived from standard Swedish construction and real estate practices.

(3) The *DH cost* varied by using Sweden’s most expensive DH at an annual average of 143.3 EUR/MWh as an upper limit (HIGH) to reflect a potential increase in the local DH prices. A LOW scenario was established using the base scenario since Luleå has had Sweden’s cheapest DH for many years (Nils Holgersson-rapporten, 2023).

(4) The *DH climate impact* varied from 0 (LOW) to 495.1 (HIGH) gCO_2-eq/kWh based on local DH systems’ emission factors in Sweden (Energiföretagen, 2023).

(5) The original *windows’ U-value* was adjusted by ± 0.5 W/m^2K to encompass scenarios where a replacement results in more or less energy savings.

(6) The *discount rate* varied from 0% (LOW) to 10% (HIGH), where 0% was chosen since it can encourage more long-term economic benefits (Gluch and Baumann, 2004) and 10% was set based on upper limits used in previous Swedish LCC studies of energy renovations (e.g. La Fleur *et al.*, 2019; Liu *et al.*, 2016).

5. Results and analysis

This section presents results and analysis for the base case (section 5.1) and the sensitivity analysis for evaluating the impact of altering the uncertain parameters (section 5.2).

5.1 Base scenarios

The LC GWP and costs of the three window intervention options are shown in Figure 2, where the black line illustrates the net total impact when totaling the product and operational stages. The results show that Option 1, maintaining existing windows, has the lowest LC

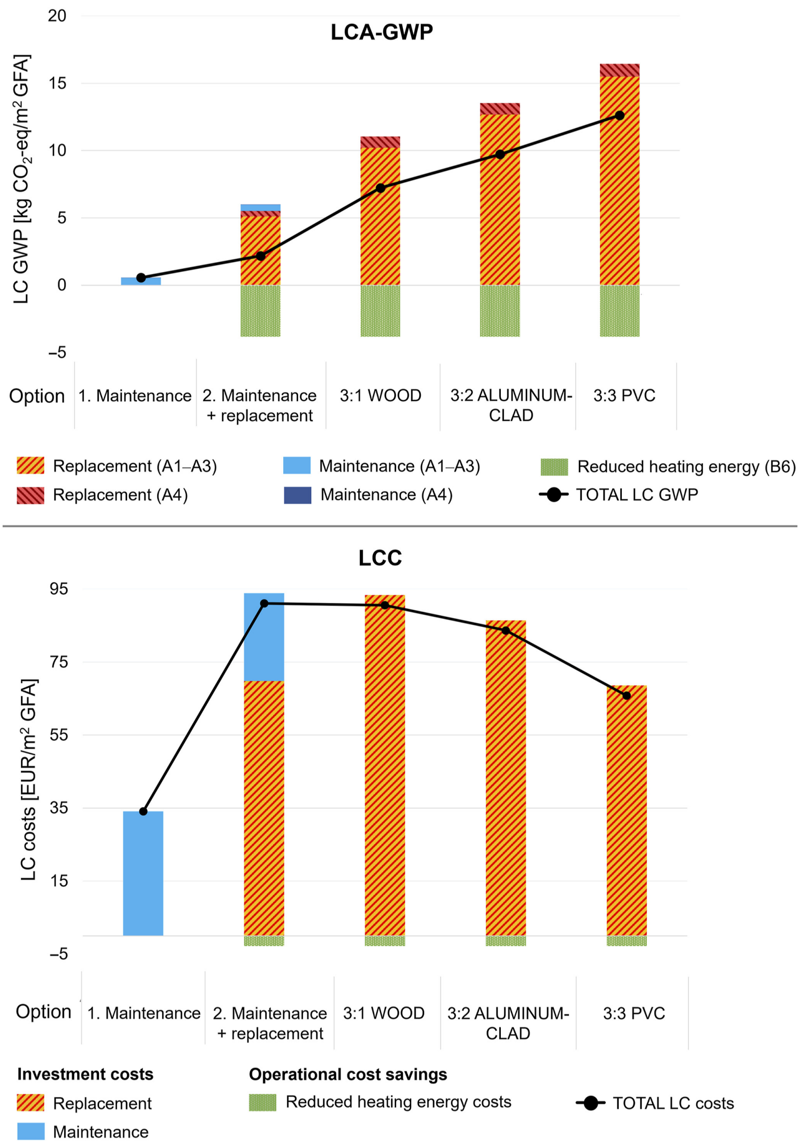

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Figure 2.
LCA-GWP and LCC results for each option with initial inputs from Table 1

GWP and costs among the studied options. Comparing the replacement scenarios suggests that PW (3.3) is the cheapest option but has the highest climate impact. The E-GWP is divided between the product stage (A1–A3) and transportation (A4) for the window intervention activities. The transportation's relative impact in module A is small and does not affect the comparison between the options. To simplify, module A's impact is shown as the total of A1–A4 in Figures 3–5.

The energy simulations showed a reduced OHE of 3.3 kWh/m^2 GFA per year when replacing the windows with new ones. Comparing the LCA-GWP and LCC results, this reduction (green columns below 0 in Figure 2) impacts the LC GWP more than the costs. Over a 60-year RSP, the saved heating energy from a window replacement translates into a reduced GWP of 4.8 kg CO_2-eq/m^2 GFA, which can be compared to the new windows' E-GWP of 7.3–43.8 kg CO_2-eq/m^2 GFA. On the other hand, the saved operational costs from reduced OHE do not result in net-zero LC costs; the investment costs can be recouped by, at best, 4% for the cheapest scenario (3.3 PW).

5.2 Sensitivity analysis

5.2.1 Reference study period and intervention rate. In Figure 3, the results' sensitivity to adjusting the RSP and intervention rate is shown by the black line between the columns. The replacement Options (3.1–3.3) are more sensitive in the LCA-GWP than the maintenance Options (1 and 2) due to the higher E-GWP when replacing. Overall, LC GWP is best for Options 1 and 2, regardless of RSP and intervention rate. Only when extending the RSP does Option 2 overtake the maintenance options, and this is true for any intervention rate. Considering costs, window maintenance has less robust results, especially at a high intervention rate, since relatively high maintenance costs occur at closer intervals compared to replacement. Despite this, maintaining windows remains the most economically preferable intervention, whatever the scenario.

When using initial data input (see each option's first column in Figure 3), the reduced OHE impacts the LCA-GWP more than the LCC, regardless of RSP and intervention rate. Depending on the intervention rate, Option 2 reaches net-zero GWP after 75–94 years and net-negative GWP when the building operates longer. This is the only option involving replacement where saved O-GWP counterbalances the increased E-GWP. Similar to Figure 2, the results are never close to net-zero LC costs; on average, the investment costs can be recouped at 3.3%.

5.2.2 Discount rate. As shown in Figure 3, a 100-year RSP and a high intervention rate cause an increased sensitivity to a changed discount rate, especially when combined. An increased discount rate reduces the total LC costs but does not impact the outcome of the comparison between the options. A replacement can only outperform maintenance with a 0% discount rate and a high maintenance rate.

5.2.3 DH cost and emission factor. Adjusting the DH emission factor reveals that window replacement is more beneficial the higher the emission factor, especially if the building operates for a longer period of time (see Figure 4). For a high emission factor, a replacement is always better to minimize the LC GWP, regardless of the RSP or intervention rate. For PW with a high replacement rate over 100 years, an emission factor of 125 gCO_2-eq/kWh would be enough to reach net-zero GWP. In contrast, operational cost savings are slight and cannot compensate for the high investment costs, even with Sweden's most expensive DH. To pay back the cheapest scenario, PW with a low replacement rate, the DH price must be at least 702 EUR/MWh over 60 years of operation. Maintaining windows remains economically preferable, except at a high intervention rate when AW and PW are slightly cheaper.

5.2.4 Original windows' U*-value.* As shown in Figure 5, a high initial U-value results in higher operational savings, which better counterbalances the E-GWP from installing new windows. For instance, Option 2 will reach net-zero GWP after only 45 years with the initial (MID) intervention rates. A window replacement is preferable in almost every scenario except for PW, which never has a lower GWP than Option 1. A high U-value also slightly increases a window replacement's economic benefit, but only in one scenario (HIGH, 100) is Option 1 marginally outperformed. However, operational cost savings are still far from recouping high investment costs.

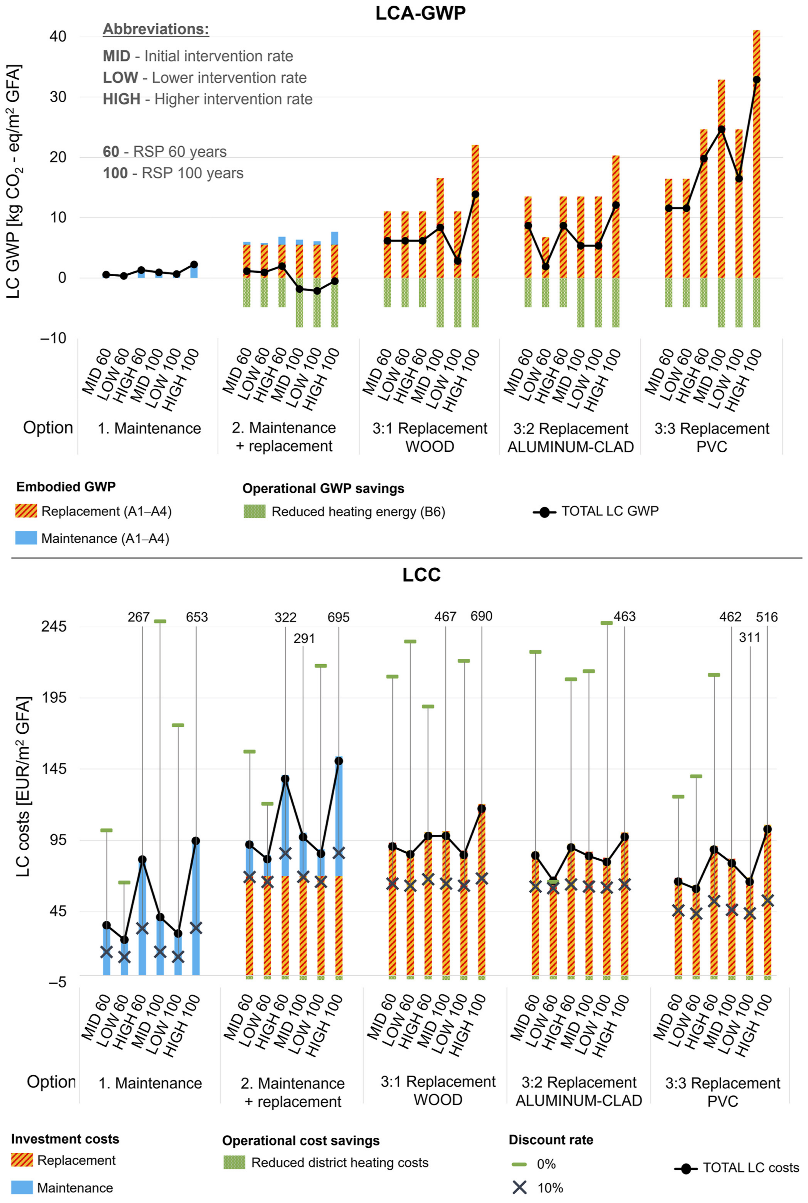

Figure 3.
LCA-GWP and LCC results for each scenario with initial and alternative input for the RSP and intervention rate

Note(s): LCC results include the scenarios sensitivity of a changed discount rate (whiskers). Horizontal lines: lower discount rate. Crosses: higher discount rate

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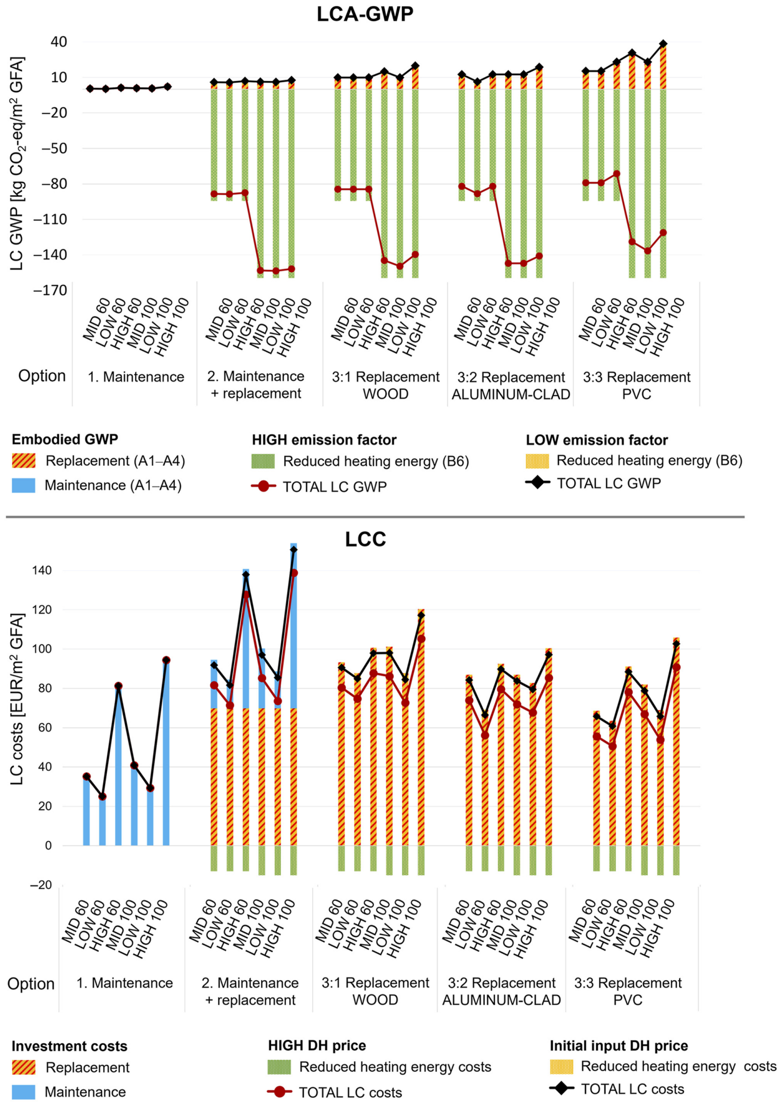

Figure 4.
LCA-GWP results in case of a LOW (black line) and HIGH (red line) emission factor for the district heating

Note(s): The absence of yellow columns in the LCA-GWP results from the LOW DH emission factor of 0 g CO_2-eq/kWh, meaning that the operational stage's GWP remains unaffected regardless of any reductions of space heating from a window replacement. The LCC results show the case of Sweden's cheapest (initial data input, black line) and most expensive DH cost (HIGH, red line)

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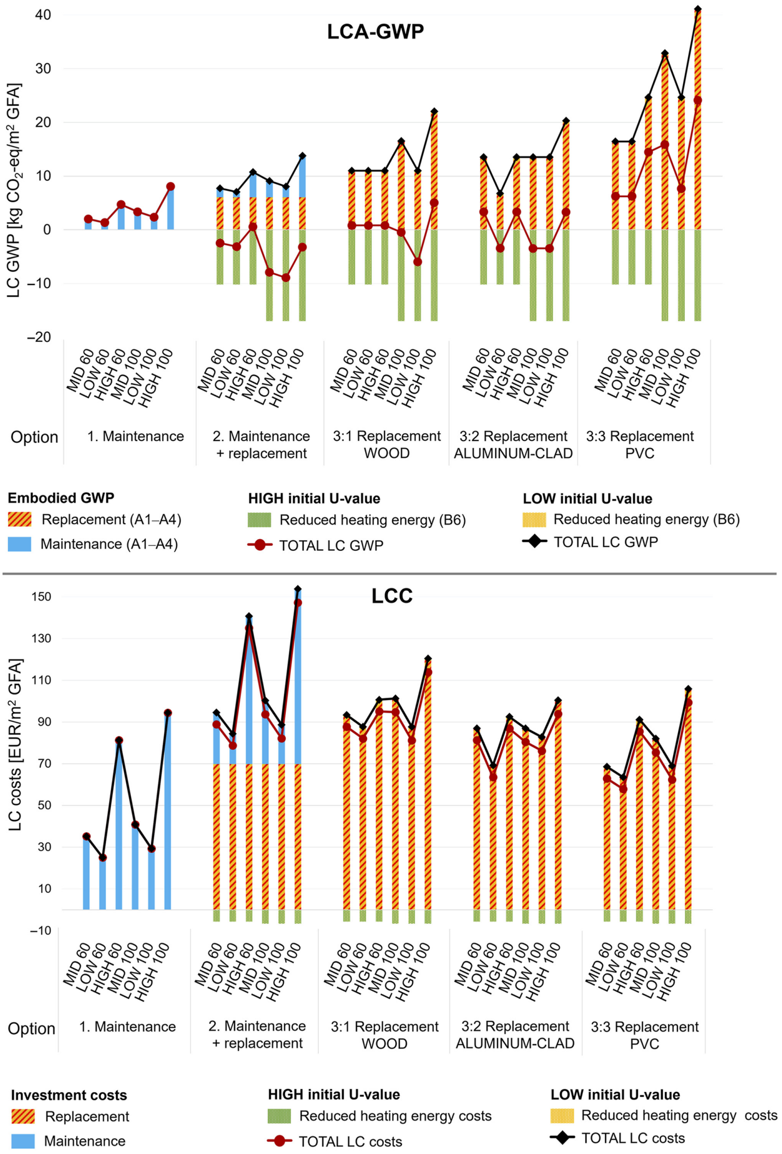

Note(s): a LOW initial U-value leads to identical thermal transmittance before and after a window replacement, giving zero reductions of O-GWP and operational costs. Hence, the figure does not display yellow columns

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Figure 5.
LCA-GWP and LCC results in case of a HIGH (red line) and LOW (black line) initial thermal transmittance of the original windows

6. Discussion

6.1 Comparison between window maintenance and replacement interventions

As shown in Figure 2, when using initial data input from Table 1, the results favor maintaining windows to minimize the LC GWP. The alternative with the second lowest LC GWP is replacement with WW that are periodically maintained (see Figure 2). Similar to previous studies (Asif *et al.*, 2005; Saadatian *et al.*, 2021; Menzies, 2013), the results suggest that new WW are the most climate-friendly option for replacement. The high climate impact found for PW aligns with previous research (Menzies, 2013; Asif *et al.*, 2005; Switala-Elmhurst, 2014). However, the PW may have been disadvantaged in the comparison because Germany's production fuel mix has a higher emission factor than Sweden's (Carbon Footprint Ltd, 2023). Another noteworthy aspect is that the product stage's GWP was assumed to be static throughout the RSP. However, the transition from fossil fuels will likely reduce the E-GWP since material production is expected to become more eco-efficient, as Serrano *et al.* (2022) pointed out, causing burden shifting across LC stages in favor of window replacement.

Figures 2 and 3 show that the lowest LC costs are related to the base scenario in the maintenance option, regardless of the scenario's sensitivity to changes in intervention rate (see Figure 3). Administrative costs, which were not included, could increase the estimated maintenance costs slightly more than replacement costs due to more frequent interventions. Investment in new WW that are periodically maintained is the most costly option, even compared to more frequently replaced PW. This contradicts the findings of Menzies (2013), who, however, used shorter SL for the WW, requiring more frequent replacements and higher investment costs.

Overall, the results in Figures 2–5 highlight the potential of maintaining windows while replacing the triple-glazed windows, which appears unappealing from a LC climate impact and cost perspective. This agrees with Switala-Elmhurst (2014), who found maintenance the most viable option.

6.2 Trade-offs between the operational and product stages

Despite the subarctic climate, a window replacement saves relatively little OHE since the building's original average U-value is relatively low (0.43 W/m^2K, which is close to the Swedish requirement for new multi-residential buildings, BFS, 2011:6, n.d.). Depending on window type, embodied GWP is more or less balanced by reductions in operational GWP (see Figure 2). While previous research (Asif, 2019; Saadatian *et al.*, 2021) showed that net-zero GWP can be reached, this only occurred after 75 years or more of operation for the studied building (see Figure 3). However, a replacement is increasingly beneficial the poorer the original windows' U-value is (see subsection 5.2.4). This agrees with the LCC findings by Milić *et al.* (2019), highlighting that investing in comprehensive energy renovations is less economical for buildings with relatively good initial thermal properties. It should be noted that, with fossil fuels almost phased out of the heating sector and an average DH emission factor of 32 gCO_2-eq/kWh (Energiföretagen, 2023), Sweden has one of the lowest average GHG intensities from heating in the EU (Bertelsen and Vad Mathiesen, 2020). With the ongoing transition to a more climate-friendly DH, the significance of the climate benefit of energy-efficiency measures will decrease even further (BeBo, 2022).

6.3 Parameters critically impacting the LC climate impact and costs

Project-specific complexities and uncertainties are inherent renovation projects (Noori *et al.*, 2016; Uotila *et al.*, 2020), which means that no renovation is the same. Our study was therefore extended with sensitivity analyses to improve its generalizability, robustness and relevance beyond the studied building's context.

The LCA-GWP results indicate that all varied parameters could change the ranking of the window intervention options, thereby reducing the reliability of the assessment, as seen in

Goulouti *et al.* (2020), where different building elements showed different sensitivity depending on the methodological choices. However, the intervention rate only altered the ranking between the AW and WW, not the comparison between maintaining or replacing windows (Figure 3). In contrast, the DH emission factor was one of the most critical parameters, with high values favoring window replacement irrespective of window type (even in the case of PW), RSP or intervention rate (Figure 4). The sensitivity of the DH emission factor aligns with Jerome *et al.* (2021), who found the carbon payback time to increase by 26 years when lowering the DH's climate data from 140 to 59 gCO_2-eq/kWh. With more climate-intensive heating, such as can be found in EU countries with average GHG intensities of 100–270 gCO_2-eq/kWh (Bertelsen and Vad Mathiesen, 2020), window replacement is increasingly justified. This holds especially true for buildings with low thermal performance but also for a thermally better-performing building like the one studied here (see Figure 4). The original windows' U-value was the second most crucial parameter for the LCA-GWP results (Figure 5).

Agreeing with Ekström *et al.* (2018), window replacement did not result in any significant economic benefit, not even when assuming a high DH energy price, poor initial window U-value, long RSP, or low replacement rates. Replacing existing windows became slightly cheaper than maintaining them only when combining a high DH price, a high U-value, or a low discount rate with a high intervention rate. However, in line with La Fleur *et al.'s* (2019) findings, the investment costs were higher than the saved operational costs in all sensitivity analyses (see Figures 3–5). A DH price five times higher than Sweden's most expensive DH would be needed to compensate for the cheapest window replacement option.

Overall, the uncertain parameters impacted the ranking of window intervention options more in the LCA-GWP than in the LCC. Comparing Figures 2–5 suggests that, besides the fewer scenarios favoring window replacement over maintenance in the LCC, the percentage change between maintenance and replacement is slight (often below 10%). In contrast, the changes when replacement overtakes maintenance in the LCA-GWP are more significant. The smaller effect on the LCC could, as pointed out by Goulouti *et al.* (2020), be partially caused by the discounting of future costs, which is not done when estimating the LCA-GWP. It should be noted that there are challenges and uncertainties in using long RSPs due to uncertainties in future developments, i.e. technology, climate, fuel sources, etc. However, this study aimed to investigate parameters that can critically affect the LC results. Since the RSP is highlighted as a potentially critical parameter in LC studies (e.g. Malmqvist and Francart, 2023; Francart *et al.*, 2021; Goulouti *et al.*, 2020), it was included here to examine the results' general direction when altered.

7. Conclusion

Window maintenance and replacement scenarios for a multi-residential building in a subarctic climate were analyzed and compared in terms of LC climate impact and costs. The answers to the research questions are, in essence:

(1) Regarding the comparison between window maintenance and replacement, it was found that opting for maintenance is, overall, preferable to minimize both LC climate impact and costs. Climate-conscious choices do not necessarily come with the highest costs. Replacing windows instead of maintaining them was beneficial only under specific circumstances, such as having high intervention rates together with climate-intensive and expensive heating.

(2) When it comes to the trade-offs between the operational and product stages, the effect was greater in the LCA-GWP than in the LCC, where the investment costs were far from being recouped by saved operational costs. Also, despite the subarctic climate,

heating energy savings from new windows balanced the increased embodied GWP and investment costs to various but mostly low degrees.

(3) Concerning the studied uncertain parameters (RSP, DH price, DH emission factor, U-value, intervention rate and discount rate), their impact varied depending on window intervention, thereby strengthening the notion of the uniqueness of renovation projects, meaning the preferred intervention will differ as well. However, the LCA-GWP was more sensitive to parameter changes compared to the LCC, indicating a higher level of uncertainty when choosing the most climate-conscious option. Among the parameters, the DH's emission factor and the original windows' U-value were the most critical, with high values favoring replacement over maintenance.

7.1 Implications

This study challenges prevailing perceptions of window interventions among property owners by highlighting the LC benefits of window maintenance over replacement. The findings offer insights for more sustainable building practices when deciding on renovation measures. Maintenance shows potential regarding LC climate impact and costs and might prove beneficial in other building renovation projects besides window interventions. Apart from exploring window replacements' energy-efficiency potentials, our study extends the knowledge of non-energy-related renovations by investigating window maintenance, providing a reference point for window intervention options in a strongly heating-dominated climate.

7.2 Limitations and suggestions for further studies

In line with previous research, the outcomes of the LC assessments are context-dependent, suggesting a possibility to expand this study's sensitivity analysis of six uncertain parameters to explore other potentially critical ones, such as different escalation rates and climate zones. It could also be valuable to investigate how to manage the complexity of using long RSPs in LC assessments. Since this study focuses on investigating potential trade-off effects between the product and operational stages, future research could broaden the scope to include other LC stages. For instance, due to a lack of studies, the EoL constitutes an uncertain proportion of renovations' total LC impact.

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(The Appendix follows overleaf)

Supplementary material

Materials/Transportation	Quantity	Climate data	Climate data source
Life cycle assessment (LCA)			
Maintenance (scenarios 1 and 2)			
Wood preservative	20 kg	1.52 $kgCO_2$-eq/kg	EPD
Primer	72 kg	1.90 $kgCO_2$-eq/kg	EPD
Alkyd paint (oil-based)	144 kg	1.90 $kgCO_2$-eq/kg	EPD
Sealant	9 kg	7.08 $kgCO_2$-eq/kg	EPD
Total transportation (A4)	2,993 km	0.001 MJ/kg*km	BM, generic
Replacement			
Wooden windows (*scenarios 2 and 3:1*)	15,193 kg	1.4 $kgCO_2$-eq/kg	EPD
Aluminum-clad windows (*scenario 3:2*)	16,077 kg	1.74 $kgCO_2$-eq/kg	EPD
PVC windows (*scenario 3:3*)	15,988 kg	2.4 $kgCO_2$-eq/kg	EPD
Window casing	1,160 kg	0.46 $kgCO_2$-eq/kg	EPD
Insulation	65 kg	0.33 $kgCO_2$-eq/kg	EPD
Exterior window sill	790 kg	2.59 $kgCO_2$-eq/kg	BM, generic
Sealant	469 kg	7.08 $kgCO_2$-eq/kg	BM, generic
Total transportation (A4)	5,365 km	0.001 MJ/kg*km	BM, generic

Parameter	Input	Data source
Life cycle costs (LCC)		
Real discount rate	4.4%	Housing company
Maintenance escalation rate	1.6%	SFV (2022)
District heating escalation rate	1.5%	SFV (2022)
District heating	31 EUR*/MWh	Housing company
Maintenance	56,446 EUR*	Tender from contractor
Replacement wooden windows	378,272 EUR*	Tender from contractor
Replacement aluminum-clad windows	375,037 EUR*	Tender from contractor
Replacement PVC windows	265,919 EUR*	Tender from contractor

Parameter	Quantity	Data source/Reference
Building energy simulation		
Indoor temperature	21 °C	Housing company
Ventilation airflow (constant)	0.665 l/s, m^2	Housing company
Heat exchanger efficiency	67%	Estimated value
Internal heat gains from occupants, equipment, lighting and domestic hot water	42.7 kWh/m^2, year	Sveby (2012) and Housing company
Window opening (energy loss)	4.0 kWh/m^2, year	Sveby (2012)
Original G-value (windows)	68%	Sveby (2012)
New G-value (windows)	60%	Tender from contractor
Total integrated shading (windows)	50%	Sveby (2012)
Climate for Luleå, Sweden 2021	–	The Swedish Meteorological and Hydrological Institute

Note(s): *Converted from Swedish Krona to EUR with the exchange rate 0.094 Swedish Krona/EUR
Specific data for the studied building are marked “Housing company”
Source(s): Table created by authors

Table A1.
Parameters and input data for the LCA and LCC calculations and the building energy simulation

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