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Extended building life cycle cost assessment with the inclusion of monetary evaluation of climate risk and opportunities

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ABSTRACT

The buildings and construction sector account for a significant part of the total energy use and related greenhouse gas emissions. However, climate change mitigation often becomes secondary or completely disregarded in building design assessment as the primary concern of building owners are economic tenability. Therefore, this study introduces an Extended Life Cycle Cost Assessment that include monetary evaluation of climate risk and opportunities in terms of Social Cost of Carbon (SCC). SCC could function as a tax to promote climate change mitigation within e.g. the construction industry. The purpose is to provide a more holistic assessment approach that is easy to relate to if economic tenability is of primary concern in decision making, which can be used to assess building design. Return on invested greenhouse gas emissions is used as an additional or standalone indicator for climate change mitigation. The introduced approach is exemplified by a case study where renovation and new construction are compared with keeping buildings in its original design. The case study show that with or without a flat greenhouse gas tax, renovation is the most climate and cost efficient alternative.

1. Introduction

Global warming of 1.5 °C above preindustrial temperatures will result in a severe loss of natural capital, i.e. a resilient ecosystem and access to clean air and water (Hoegh-Guldberg et al., 2018; Matthew et al., 2014; Stiglitz et al., 2017). Working out ways to tackle climate change is one of the key challenges facing society both today and in the decades ahead. The buildings and construction sector account for 40% of EU final energy use and for 39% of energy and process-related greenhouse gas emissions, out of which 11% results from manufacturing building materials and products (Abergel et al., 2019; EU, 2020). Thus, efficient resource use is critical to accommodate sustainable development that promote climate change mitigation. However, at present the primary concern of building owners in decision making is the economic tenability (Jakob, 2006).

The economic assessment method of Life Cycle Cost Assessment (LCCA) has been deployed to make a more economically compelling case for reducing resource use by adopting energy efficient strategies (Hajare & Elwakil, 2020; Marszal & Heiselberg, 2011). Generally, building LCCA include total investment cost, annual operational cost and cost of maintenance and disposal. However, upstream and downstream greenhouse gas (GHG) emissions are rarely included in building LCCA (De Boeck et al., 2015). Thus, building climate impact are not included in the economic building design assessment.

Including environmental parameters such as climate impact would provide a more holistic approach to building design assessment. This is generally done by complementing the LCCA with a life cycle GHG emissions assessment. Thus, the decision maker are faced with the task to weight financial cost to GHG emissions. Firstly, this can be perceived as complicated and unclear as two different entities are to be weighed against each other, in this case Euro and tCO_2-eqvivalents. Secondly, the decision will most probably fall on the most economically effective solution, since the main concern of commercial building owners in decision making is primarily the economic tenability (Jakob, 2006).

By valuing climate risk and opportunities of GHG emissions in monetary terms, GHG emissions can be included in the building cost assessment, providing a more holistic approach to building design assessment that may be less confusing for the building owner. This can

Abbreviations: LCA, Life cycle assessment; LCCA, Life cycle cost assessment; $LCCA_{GHGe}$, Life cycle carbon cost assessment; ELCCA, Extended life cycle cost assessment; SCC, Social cost of carbon; IAM, Integrated assessment model; GHG, Greenhouse gas; GWP, Global warming potential; ROI_{GHGe}, Return on invested greenhouse gas emissions; HFA, Heated floor area.

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be done by utilizing Social Cost of Carbon (SCC), which estimates the total net impact cost of an extra metric ton emission of CO_2-equivalents due to the associated climate change. SCC are estimated by utilizing Integrated Assessment Models (IAMs), which is a collection of tools developed by environmental and economic scientists to facilitate decision making. IAMs couple models of energy system technologies with economic and climate science models to evaluate different population, economic and technological pathways to achieve specific climate change mitigation goals (Hare et al., 2018). Negative and positive climate impacts are monetized, discounted and the net value is expressed as an equivalent loss of GDP today. Different models has valued the SCC from 0 EUR tCO_2-eqv^{-1} to 830 EUR tCO_2-eqv^{-1} (Pindyck, 2019). This wide variation depends on assumptions about future emissions, how climate will respond to increasing temperatures, the impacts this will cause, the value of future damages and choice of discount rate etc.

Monetary valuation of climate risk and opportunities are occasionally included in building design assessment. It is included in a study by Luo et al. to calculate the building life cycle carbon cost (Luo et al., 2021). In a study by Lu et al., the life cycle carbon cost are included in the LCCA of engineered wood, concrete and steel structural products (Lu et al., 2017). They utilize a carbon tax of 20 EUR tCO_2-eqv^{-1} (Strong Growth, 2011), which was introduced by the Australian government in 2012 and then repealed two years later. In addition to that study, the authors of this paper assessed building refurbishment from an economic perspective with the inclusion of future climate induced cost based on an SCC varying from 8 to 250 EUR tCO_2-eqv^{-1} (Nydahl et al., 2019). Also Guardigli et al. (2018) suggested, as a topic for future research, that operational SCC should be included in sustainable building LCCA. However, none of the reviewed papers introduces a systematic methodology for incorporating monetary evaluation of climate risk and opportunities into building LCCA that can be used to assess profitability of different building design for both renovation and new construction. Therefore, this study suggests the use of an Extended Life Cycle Cost Assessment (ELCCA) to provide a more holistic assessment approach that is easy to relate to if economic tenability is of primary concern in decision making by including monetary evaluation of climate risk and opportunities. This approach can be used to assess building design.

The introduced approach is exemplified by a comparative case study of a developed lot with fifteen buildings. The buildings were built in the late 1960 in Umeå, Sweden, and have the typical design of the million homes program that were built during that same time period (Hall & Vidén, 2005). However, in 2014 the buildings were regarded as increasingly inadequate. Therefore, the building owner chose to renovate six of the buildings and demolish nine of them to be replaced with new construction. An extended life cycle cost assessment is utilized to compare renovation and new construction with keeping the building in its original design.

2. Methodology

An extended building cost calculation is introduced to assess cost and climate impact of building renovation and new construction. The extended building cost calculation is based on LCCA, which is a commonly used method for investigating cost-optimal building solutions and design. The extension is done by valuing the climate risk and opportunities of GHG emissions in monetary terms and including it in the LCCA. Thus, this chapter presents the different parts of the method used in this study, i.e.

- framing the scope of the assessment,
- introducing the life cycle cost assessment,
- valuing GHG emissions in monetary terms,
- present the extended life cycle cost assessment.

2.1. Scope of comparative life cycle assessment

Building design can be evaluated by Life cycle assessment (LCA) which assess different parameters, such as economic, environmental and social parameters. This study includes economic and environmental LCA parameters. Furthermore, standardized LCA include modules A-D, where the A module include the production and construction stage, the B module include the use stage, the C module include the end-of-life stage and the D module include reuse, recycling and recovery (ISO, 2006b, 2006a).

Previous LCA studies on renovation and new construction have varying scope (Hasik et al., 2019; Rønning et al., 2009; Vilches et al., 2017). The recommended approach by Hasik et al. (2019) is based on the avoided burden approach, i.e. avoided impacts as a result of reuse, recycling and recovery are credited the studied product. Thus, Hasik et al. (2019) suggest that only newly added components should be included in the building impact assessment since they "burden" the assessment. However, demolished material that are not reused or recycled, i.e. end-of life stage (C-module) of the original building, should also be seen to "burden" the building impact assessment. This is confirmed by both Vilches et al. (2017) and Rønning et al. (2009) who suggest that the end-of-life stage (C-module) of the original building should be included in the building impact assessment. Renovation imply that the original building is partly demolished and to allow new construction the original building need to be fully demolished. Furthermore, to avoid "double counting", the end-of-life stage (*C*-module) of the renovated or new building should not be included in the impact assessment. It is difficult to estimate future waste disposal, reuse, recycling and recovery and therefore it is more suitable to account for this impact by including end-of-life stage (*C*-module) of the original building into the building impact assessment.

Moreover, studies on both economic costs and GHG emissions over the building life cycle show the significance of operational energy use (B6) as the main contributor of the use stage (module B) (Erlandsson et al., 2018; Sterner, 2002). Therefore, the LCA is simplified to only include operational energy use. Maintenance and repair are assumed negligible. Building operational energy use (B6) refers to the actual annual energy that is used in order to meet the different needs associated with defined uses of the building, i.e. heating, domestic hot water supply, ventilation, lighting and auxiliary energy used for pumps, control and automation.

Fig. 1 show the scope of the comparative life cycle assessment. Renovation means that the original building is partly demolished (C_{OB}). The degree of demolition varies depending on the performance of the original building as well as the desired performance of the renovated building. The desired performance of the renovated building affects the added embodied impact to the building (A_{new}) and these choices affect the building energy performance (B6). New construction that occur on a developed lot leads to full demolition of the original building (C). The desired performance of the constructed building affects the added embodied impact of the building (A) which affect the building energy performance (B6).

To allow comparison between different building designs, the LCA results are estimated for the floor area that are heated to 10 °C or above, called Heated Floor Area (HFA). Furthermore, a theoretical service life of the building is employed, which is set to 50 years in this study.

2.2. Life cycle cost assessment

In accordance with the introduced assessment scope, the LCCA for renovation or new construction include disposal cost from partial or full demolition of the original building, investment cost and operational energy cost, see Eq. (1).

$$LCCA = C_C + C_A + C_{B6} \tag{1}$$

C_C = End-of-life cost from partial or full demolition of the original

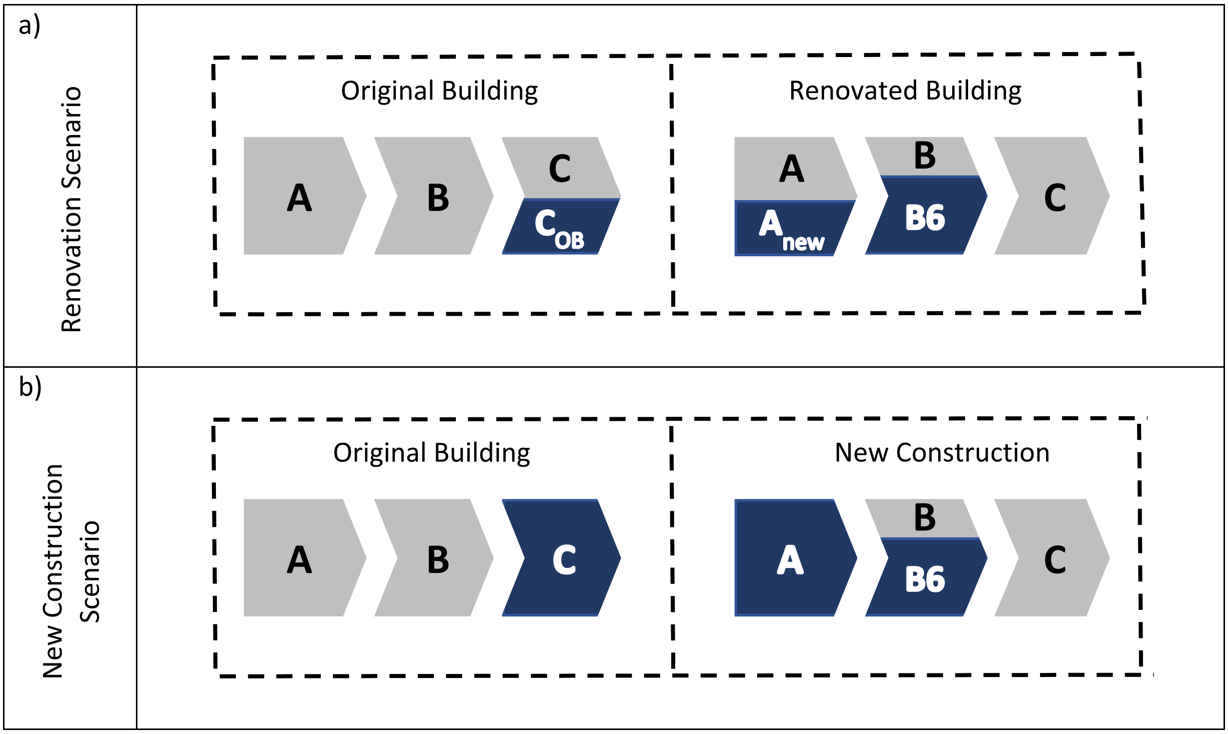

Fig. 1. Scope of comparative LCA of (a) renovation scenario, (b) new construction scenario. The A-module include production and construction stage, B-module include use stage and C-module include end-of-life stage. The asssessment of the renovation scenario include the original building that is partly demolished (C_{OB}), the added embodied impact of newly added components to the renovated building (ANew) and the energy use of the renovated building (B6). The asssessment of the new construction scenario include end of life stage (C) of the original building, production and construction stage (A) of the new construction and the energy use of the new construction (B6). The included modules are coloured in blue (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

building

C_A = Investment cost, i.e. construction costs, development costs and VAT

C_{B6} = Cost of building life cycle operational energy use

The disposal cost of the original building (C_C) are assumed to account for about 2% of the total construction life cycle cost based on a European average (Islam et al., 2015).

The investment cost (C_A) can either be estimated based on average cost, or be calculated based on project-specific cost data linked to a building project. The production cost for renovation differs depending on the level of renovation and therefore an average production cost for renovation could be difficult to estimate. However, previous projects with similar renovation level could be used to estimate average cost for renovation.

The building life cycle operational energy cost (C_{B6}) are calculated according to Eq. (2).

$$C_{B6} = \sum_{i=1}^{SL}\left(\left(OE_i \times EP \times (1+EPC)^{(i-1)}\right)_{Elec} + \left(OE_i \times EP \times (1+EPC)^{(i-1)}\right)_{Heat}\right) \tag{2}$$

OE_i = Annual operational use of property electricity or heating, year i

EP = Annual electricity or heating prize

EPC = Annual real price increase for electricity or heating

SL = Building service life

Annual operational energy use (OE_i) for a building can either be estimated in a design stage by building simulation software or in an evaluation stage by measured building specific data. The annual operational use of electricity refers to the property electricity and include electricity for ventilation, lighting and electricity used for pumps, control and automation. The property electricity can be reduced by installing fans and pumps that are more efficient or installing better control of lighting. The annual operational use of heating includes space heating and domestic hot water supply and are influenced by factors such building design, the climactic region were the building is located and the behavior of the residents. The annual electricity and heating prize (EP) are linked to the geographical location of the building. The prize for electricity and heating will change (EPC) with an annual real price increase, i.e. the price increase obtained if inflation is deducted from the nominal price increase.

2.3. Life cycle carbon cost

Greenhouse gas emissions associated with renovation and new construction are calculated with environmental life cycle assessment in accordance with the LCA scope of this study. The life cycle GHG emissions are expressed in monetary terms with the use of SCC, which values the total damage cost of an extra metric ton emission of CO_2 equivalents due to the associated climate change. Eq. (3) show how to calculate life cycle carbon cost for renovation or new construction.

$$LCCA_{GHGe} = (GHGe_C + GHGe_A + GHGe_{B6}) \times \text{SCC} \tag{3}$$

$GHGe_c$ = End-of-life GHG emissions from partial or full demolition of the original building

$GHGe_A$ = GHG emissions from production and construction

$GHGe_{B6}$ = GHG emissions from building life cycle operational energy use

SCC = Social Cost of Carbon

Data from the Swedish Environmental Research Institute (IVL) (Erlandsson & Pettersson, 2015) has been utilized to calculate GHG emissions from partial or full demolition of the original building ($GHGe_c$). To cohere with current LCA practice, energy use for mechanical processing of the most significant types of material is also included in the demolition data. The Global Warming Potential (GWP) for the energy use at end-of-life and reuse, recycling and recovery is calculated based on the assumption that the change in purchased electricity affect the margin. Thus, the emission factor for purchased electricity is assumed to 0.122 kg CO_2-eqv/MJ (Spath & Mann, 2000). Furthermore, an emission factor of 0.053 kg CO_2-eqv/MJ for vehicle diesel has been used (SEPA, 2020).

Climate impact from production and construction of newly added components ($GHGe_A$) are calculated using the calculation tool developed by The Swedish Environmental Research Institute (IVL) (BM tool) (Ebenå et al., 2019). The tool contains a complete database with climate data for construction resources used on the Swedish market. Climate impact is calculated for material production (A1–A3), transport (A4) and construction waste (A5.1).

GHG emissions from operational energy use ($GHGe_{B6}$) during the building service life is calculated according to Eq. (4). The operational energy use include property electricity (Elec) and heating (Heat).

$$GHGe_{B6}=\sum_{i=1}^{SL}\left(\left(OE_i\times EF\times(1+EFC)^{(i-1)}\right)_{Elec}+\left(OE_i\times EF\times(1+EFC)^{(i-1)}\right)_{Heat}\right) \tag{4}$$

OE_i = Annual operational use of property electricity or heating, year i

EF = Emission factor of electricity or heating

EFC = Emission factor change of electricity or heating

SL = Building service life

The emission factor (EF) of electricity and heating are linked to the geographical location of the building and changes with the fuel mix. During the building service life of 50 years, the emissions factor will change as energy sources and efficiency of the electricity and heating grid change. In this study an annual change rate is applied, called Emission Factor Change (EFC). To estimate the EFC, a scenario for the change over time of the Swedish energy system has been utilized. The scenario is developed by the Swedish Energy Agency and are based on a EU reference scenario, which is the main scenario used for emission calculations by the European Commission (SCB, 2020). Based on this scenario, the emission factor change for district heating is estimated to -0.59% and electricity is estimated to 0.30% over the coming 50 years in Sweden. The EU reference scenario assume that the emission factor for district heating will decrease annually since fossil fuels such as peat, petroleum products, natural gas and coal will be phased out over time. The emission factor for electricity, on the other hand, are assumed to increase annually since even though fossil fuels will be phased out to a certain extent, the nuclear power are also predicted to be phased out. Thus, it is assumed that the growing need for electricity over time cannot be met only by renewable energy sources (SCB, 2020).

SCC is calculated based on socioeconomic projections, climate change projections and climate change impact assessment together with economic costs associated with these impacts. In a study by Pindyck (2019), SCC estimations by roughly 600 economists and climate experts spread from 0 to 830 EUR tCO_2-eqv^{-1}, where on average the estimate of climate scientists imply a higher SCC than the estimates of economists. By analyzing the distribution among the estimates of the experts, the SCC estimates are narrowed down to 67–250 EUR tCO2-eqv^{-1}, with a best-fit distribution mean of 242 EUR tCO2-eq^{-1} (Pindyck, 2019). The SCC used in this study are therefore 242 EUR tCO_2-eqv^{-1} (SCC1) and 830 EUR tCO_2-eqv^{-1} (SCC2).

2.4. Extended life cycle cost assessment

ELCCA complements the "traditional" building cost calculation (LCCA) by adding the life cycle carbon cost ($LCCA_{GHGe}$), see Eq. (5). LCCA are calculated according to Eq. (1) and $LCCA_{GHGe}$ are calculated according Eq. (3).

$$ELCCA = LCCA + LCCA_{GHGe} \tag{5}$$

3. Case study

Fifteen buildings that were originally built in the late 1960 in Umeå, Sweden, has been studied. The city of Umeå in Sweden is located 455 km south of the Arctic Circle in Continental Subarctic Climate (Dfc) according to Köppen. In 2014, the buildings were regarded as increasingly inadequate, therefore six of them were renovated, and nine were demolished and replaced with new construction. The design of the original buildings correspond to the typical design of the million homes program that were built around Sweden between 1965 and 1974 (Hall & Vidén, 2005). The design of the renovated and newly constructed buildings are shown in Fig. 2.

The comparative assessment of renovation and new construction include structural and exterior construction, i.e. foundation, substructure, superstructure and exterior walls, roof, windows, glazing and doors. Excluded from the comparative assessment are interior and system construction, i.e. interior walls, ceilings, floors, doors, finishes and furniture and systems such as mechanical, electrical and plumbing. Interior and system construction are excluded from the assessment since the interior and systems are fully replaced with new components in both the renovated and new buildings. Therefore, it is assumed that the cost and climate impact from interior and system construction are more or less similar for the renovated and new buildings.

The structural renovation include replacement of the old roof structure to make space for an air-handling unit and the exterior renovation include change of windows and additional wall insulation with 28 mm insulation on the building gables and 45 mm insulation on the long sides. The investment cost for the structural and exterior renovation are estimated based on another renovation project in Umeå with similar level of renovation (Strong Growth, 2011). Thus, the investment cost are estimated to approx. 788 EUR HFA-1 (Strong Growth, 2011).

The investment cost for new construction are calculated based on the 2019 Swedish average production cost for new multi-dwelling buildings which amounted to 4522 EUR HFA^{-1} (SCF, 2017). Included in this cost is construction costs, development costs and VAT (Boverket, 2009). Structural and exterior construction accounts for about 74% of total construction cost (Werner, 2016), which equals 41% of total production cost. Moreover, new construction that takes place on a developed lot have reduced development costs since there are small or non-existent land costs which reduces the production cost. Land costs account for about 16% of the total production cost. Thus, investment cost are estimated to approx. 3 155 EUR HFA^{-1} for new construction on a developed lot.

Other estimated Swedish average input data for the comparative life cycle assessment of renovation and new construction are shown in Table 1.

The energy performance of the original buildings, renovated buildings and new buildings are shown in Table 2. Renovation of the original buildings reduced the yearly heating demand by 43% and the yearly electricity demand by 7%. Demolition and construction of a new buildings reduced the yearly heating demand by 67% and the yearly electricity demand by 54%.

The studied case buildings have been in use by tenants, therefore building specific energy use can be measured and evaluated. Heat and property electricity use for the original buildings were measured for the full year of 2013. At this time, heat and property electricity were measured at a centrally located substation that served all buildings on the lot. To calculate heat and property electricity use at building level, culvert losses were subtracted from the total measured use at the centrally located substation and thereafter divided by the total HFA of all buildings that were centrally supplied. The same approach was applied for the renovated buildings to measure and calculate heat and property electricity use. For the new buildings, on the other hand, measuring

Fig. 2. (a) building structure of the renovated case building with a HFA of 850 m^2 and (b) building structure of the newly constructed building with a HFA of 1289 m^2.

Table 1
Input data and assumptions made for the life cycle cost assessment (LCCA) and life cycle carbon cost ($LCCA_{GHGe}$).

LCCA	C_c	Assumed 2% of the total construction life cycle cost.
	C_A	Assumed 3 155 EUR HFA^{-1} for new construction on a developed lot.Assumed 788 EUR HFA^{-1} for renovation.
	C_{B6}	Average Swedish heating price assumed to 0.086 EUR/kWh (Eurostat, 2020).Average Swedish electricity price assumed to 0.183 EUR/kWh (Rydegran, 2020).The annual real price increase are assumed to a steady rate of 3% for both heating and electricity.
$LCCA_{GHGe}$	$GHGe_C$	Calculated based on data from the Swedish Environmental Research Institute (IVL) (Erlandsson & Pettersson, 2015).
	$GHGe_A$	Calculated using average data from the BM tool developed by The Swedish Environmental Research Institute (IVL) (Ebenå et al., 2019).
	$GHGe_{B6}$	Heating are supplied by district heating with an average Swedish emission factor of 0.06 kg CO_2-eqv/kWh (Martinsson et al., 2012). Electricity are assumed to be supplied by the Nordic electricity grid with an emission factor of 0.13 kg CO_2-eqv/kWh (VVS-tekniska, 1974). The emissions factor change is estimated to −0.59% for district heating and 0.3% for electricity based on the EU reference scenario effect on the Swedish energy system (SCB, 2020).
	SCC	Assumed to 242 EUR tCO_2-eqv^{-1} (SCC1) and 830 EUR tCO_2-eqv^{-1} (SCC2).

equipment were installed at building level, which enabled building specific heat and property electricity use measurements. Heat and property electricity for the renovated and new buildings were measured during 2019. All measurements were made with a resolution of one month and the annual operational heating was degree-day corrected.

4. Result and discussion

In this section, ELCCA is utilized in a comparative assessment of renovation and new construction. The assessed options are to keep the existing building in its original design, renovate the building or demolish the building and replace it with new construction. Table 3 show the result of the comparative assessment of renovation and new construction with the use of the ELCCA. Table 3 also report LCCA and $LCCA_{GHGe}$ separately to show the influence of these parameters on the ELCCA.

Table 2
Energy performance of the original buildings, renovated buildings and newly constructed buildings.

	Annual Operational heating (OE_{heat}) [kWh $year^{-1}$ HFA^{-1}]	Annual Operational Electricity (OE_{El}) [kWh $year^{-1}$ HFA^{-1}]
Original buildings	137	18
Renovated buildings	78	16
New construction	45	8

The result in Table 3 shows that the renovation scenario has the lowest ELCCA. The result in Table 3 also show that new construction has a slightly lower ELCCA than keeping the existing building in its original design. This difference is not very big and may be the result of assumptions and estimations made. However, keeping the existing building in its original design could potentially be more costly than indicated in Table 3, if maintenance and repair would be included in the assessment. The need for maintenance and repair would probably be higher for the original building than for new construction. Still, if the original building satisfies the health and need of the tenants without larger interventions it may be an as viable option as new construction.

The result in Table 3 show that $LCCA_{GHGe}$(SCC2) accounts for 10.0%, 9.1% and 7.1% of the ELCCA for the original, renovated and newly constructed building, respectively. Thus, the ELCCA result in Table 3 are strongly influenced by the LCCA. In order to obtain an equal impact from $LCCA_{GHGe}$ and LCCA when combining them in ELCCA, the SCC would have to increase to approx. 7600 EUR tCO_2-eqv^{-1} in for the original building, 8400 EUR tCO_2-eqv^{-1} for the renovated building and 10,800 EUR tCO_2-eqv^{-1} for the new construction. However, in this case, not even a very high SCC will affect the priority order between the three studied options.

In a time where climate change mitigation is one of the key challenges facing society both today and in the decades ahead it is important to evaluate the three different building design alternatives based on their ability to reduce climate impact in a near future, i.e. 50 years in this study. To compare the climate efficiency of renovation and new con-

Table 3
Life cycle cost assessment (LCCA), life cycle carbon cost ($LCCA_{GHGe}$) and extended life cycle cost assessment (ELCCA) for the case building in its original design (HFA 850 m^2), the renovated building (HFA 850 m^2) and the newly constructed building (HFA 1289 m^2). The social cost of carbon applied are 242 EUR tCO_2-eqv^{-1} (SCC1) and 830 EUR tCO_2-eqv^{-1} (SCC2).

		Original Building [EUR HFA^{-1}]		Renovation [EUR HFA^{-1}]		New Construction [EUR HFA^{-1}]	
		SCC1	SCC2	SCC1	SCC2	SCC1	SCC2
LCCA	Disposal cost	–	–	67	67	100	100
	Investment cost	–	–	788	788	3155	3155
	Cost of operational energy use	4434	4434	2065	2065	1139	1139
	Total	**4434**	**4434**	**2920**	**2920**	**4394**	**4394**
$LCCA_{GHGe}$	End-of-life	–	–	0.7	2.4	1.6	5.5
	Production and Construction	–	–	13	43	58	197
	Operational Energy use	143	491	72	247	39	134
	Total	**143**	**491**	**85**	**292**	**98**	**337**
ELCCA	**Total**	**4577**	**4924**	**3005**	**3212**	**4492**	**4731**

Table 4
Input data and assumptions made for the life cycle cost assessment (LCCA) and life cycle carbon cost ($LCCA_{GHGe}$) when the case building is relocated to Poland.

LCCA	C_c	Assumed 2% of the total construction life cycle cost.
	C_A	Assumed 598 EUR HFA^{-1} for new construction on a developed lot (Euroheat, 2019).Assumed 134 EUR HFA^{-1} for renovation.
	C_{B6}	Average Polish district heating price assumed to 0.043 EUR/kWh (Eurostat, 2020).Average Polish electricity price assumed to 0.146 EUR/kWh (Rydegran, 2020).The annual real price increase are assumed to a steady rate of 3% for both district heating and electricity.
$LCCA_{GHGe}$	$GHGe_C$	Unchanged
	$GHGe_A$	Unchanged
	$GHGe_{B6}$	Heating are supplied by district heating with an estimated emission factor of 0.33 kg CO_2-eqv/kWh based on an fuel mix of 82% coal, 5% natural gas and 13% bio fuel (Schakenda & Askham, 2010). Electricity are assumed to be supplied by the European electricity grid with an emission factor of 0.63 kg CO_2-eqv/kWh (Wierzbowski et al., 2017). The emissions factor change is estimated to −2.21% for both district heating and electricity based on the EU reference scenario effect on the Polish energy system (Stern, 2007).
	SCC	Assumed to 242 EUR tCO_2-eqv^{-1} (SCC1) and 830 EUR tCO_2-eqv^{-1} (SCC2).

struction, the concept of return on investment (ROI) could be used. The ROI show the relation between the operational GHG emission-savings from the original building design and embodied emissions. Within the boundaries of the set scope in this study (Fig. 1), the ROI_{GHGe} are calculated according to Eq. (6), where SL equals 50 years.

$$ROI_{GHGe} = \frac{\sum_{i=1}^{SL}\left(GHGe_{B6\ original\ building} - GHGe_{B6\ renovated/new\ construction\ building}\right)_i}{\left(GHGe_C + GHGe_A\right)_{renovated/new\ construction\ building}} \quad (6)$$

The renovation scenario has a ROI_{GHGe} of 5.37 and the new construction scenario a ROI_{GHGe} of 1.76. This means that the climate change mitigation is 5.37 times greater than the embodied emissions for the renovation scenario and 1.76 times greater from the new construction scenario. Thus, the ROI indicator shows that the renovation scenario has the highest climate efficiency. The results in Table 3 together with the ROI indicator show that the renovation scenario is the most economic and climate efficient alternative.

The ELCCA and ROI result are dependent on local and national conditions that influence investment cost and cost of operational energy, embodied GHG emissions, present and future GHG emission from heat and electricity supply and the estimated SCC. Hence, a more carbon intense energy market together with significantly lower construction and energy costs would probably lead to an increased influence of $LCCA_{GHGe}$ on the ELCCA result. Therefore, as a thought experiment to test this hypothesis, the case buildings are theoretically relocated to a country with one of Europe's most carbon intense energy markets and that also have significantly lower construction and energy costs than in Sweden.

The case buildings are theoretically relocated to Poland. Poland is situated in Humid Continental Climate (Dfb) according to Köppen, which is a different climactic region than Umeå. Thus, the building heating demand are different in Poland. The degree-day method (Statista, 2018) is used to estimate the change in operational heating demand when the case buildings are relocated to Warsaw, Poland. The property electricity use, on the other hand, are assumed unchanged when the case buildings is relocated. Furthermore, the building design are kept unchanged and therefore the embodied emissions ($GHGe_C$ and $GHGe_A$) are assumed to be the same as in Sweden.

Average construction cost for multi-dwelling buildings in Poland are 81% lower than in Sweden. Furthermore, the average Polish district heating price is 40% lower and the average electricity price 20% lower than the Swedish average. At the same time, the district heating emission factor increases by 448% and the electricity emission factor by 386%. Input data and assumptions for the LCCA and $LCCA_{GHGe}$ when the case buildings is relocated to Poland is described in Table 4 and the results in Table 5.

Table 5 show that the renovation scenario is still the most cost and climate efficient option. However, while the new construction scenario in Poland has a clearly lower ELCCA than keeping the existing building in its original design, the ELCCA for new construction is comparable to renovation. The ROI_{GHGe} indicator, on the other hand, show that the climate change mitigation is 8.73 times greater than the embodied

Table 5
Buildings relocated to Poland – Life cycle cost assessment (LCCA), life cycle carbon cost ($LCCA_{GHGe}$), extended life cycle cost assessment (ELCCA) and climate impact return on investment (ROI_{GHGe}) for the case building in its original design (HFA 850 m^2), the renovated building (HFA 850 m^2) and the newly constructed building (HFA 1289 m^2). The social cost of carbon applied in the calculation is 242 EUR CO_2-eqv^{-1} (SCC1) and 830 EUR tCO_2-eqv^{-1} (SCC2).

	Original Building [EUR HFA^{-1}]		Renovation [EUR HFA^{-1}]		New Construction [EUR HFA^{-1}]	
	SCC1	SCC2	SCC1	SCC2	SCC1	SCC2
LCCA	1873	1873	1074	1074	1124	1124
$LCCA_{GHGe}$	213	732	111	381	113	388
ELCCA	2087	2605	1185	1455	1237	1512
ROI_{GHGe}	–		8.73		2.69	

emissions for the renovation scenario and 2.69 times greater from the new construction scenario. Thus, the renovation scenario is the most resource efficient alternative based on a holistic assessment approach. Furthermore, the result in Table 5 confirms the hypothesis that the $LCCA_{GHGe}$ would have an increased influence on the ELCCA on a more carbon intense energy market together with significantly lower investment and energy costs. The $LCCA_{GHGe}$ accounts for 28.1%, 26.2% and 25.7% of the ELCCA for the original, renovated and new building, respectively. Thus, even in this scenario the ELCCA result in Table 5 are mainly influenced by the LCCA.

The estimated emission factor change (EFC) influence the result in Table 5. An annual emission reduction of 2.21% in Poland is a quite ambitious reduction target, even though it is considered realistic according to the EU reference scenario (SCB, 2020; Stern, 2007). Nevertheless, if there would be no change in the Polish heat and electricity emissions, i.e. an EFC of 0%, the $LCCA_{GHGe}$(SCC2) would account for 53.9%, 49.4% and 40.3% of the ELCCA for the original, renovated and new building, respectively. Thus, the $LCCA_{GHGe}$ would have a greater influence on the ELCCA for the studied case buildings. However, this would not affect the relative ranking of the studied building design alternatives. The renovation scenario would still have the lowest ELCCA, followed by new construction and lastly keeping the existing building in its original design. Furthermore, the renovation scenario would have a ROI_{GHGe} of 26.12 and the new construction scenario a ROI_{GHGe} of 8.06.

Simplifications and assumptions has been made in this thought experiment. For instance, the building design is assumed similar in Sweden and Poland and GHG emissions for end-of-life ($GHGe_C$) and production and construction ($GHGe_C$) are not adjusted for the Polish market. However, the thought experiment indicate how a more carbon intense energy market together with significantly lower construction and energy costs influence the ELCCA and ROI_{GHGe} result. It also indicates the impact on the relative raking between the studied building design alternatives.

4.1. Social cost of carbon

Economists has described climate change as a market failure (ISO, 2019; Nordhaus & Boyer, 2000). To correct this, policy intervention are called for to increase the price of activities that emit greenhouse gases and thereby provide a clear signal to guide economic decision making. Such policy intervention could be a flat tax on GHG emissions, i.e. a fixed amount per ton GHG emission that corresponds to the social cost of carbon. With a GHG-tax instead of SCC, ELCCA becomes a policy instrument to achieve climate change mitigation targets. Without a GHG-tax, SCC is only a fictitious cost that can be applied in good will to guide economic decision making. Thus, ELCCA can only be seen as a climate change mitigation indicator.

In this study, the SCC estimations applied are 242 EUR tCO2-eqv^{-1} (SCC1) and 830 EUR tCO2-eqv^{-1} (SCC2), where SCC2 is considered a high SCC estimate (Pindyck, 2019). However, if the global warming increases well above 2 °C, the socioeconomic and environmental damages and associated costs will be extensive, probably much higher than SCC2. Thus, an increase in SCC would increase the influence of $LCCA_{GHGe}$ on ELCCA. However, an increase in SCC would not affect the relative ranking of the studied building design alternatives in either Sweden or Poland. This means that in the context of the studied case study, a flat GHG-tax will not affect the economic decision making. A flat GHG tax could potentially be more influential when assessing investments with a high $LCCA_{GHGe}$. This could occur in the assessment of e. g. individual energy efficiency measures or within other areas than the construction industry. Furthermore, to allow for an even more comprehensive sustainability assessment, tax could also be applied to other environmental impact parameters in addition to GHG emissions with the use of the ISO 14,008:2019, standard (ISO, 2019).

5. Conclusion

The introduced ELCCA approach provide a more holistic approach to life cycle assessment that is easy to understand if economic tenability is of primary concern, as climate impact is monetized with the use of SCC. Monetary evaluation of climate risk and opportunities could be used as a policy instrument functioning as a tax on GHG emissions to promote climate change mitigation within e.g. the construction industry. As an additional or standalone indicator to promote climate change mitigation, ROI_{GHGe} can be used.

The case study show that the methodology is applicable to the assessment of renovation and new construction. Furthermore, the case study show that the inclusion of a flat GHG tax does not affect the relative ranking of the studied buildings in either Sweden or Poland. Therefore, an inclusion of a flat GHG tax will not affect the economic decision making for the studied case buildings. The renovation scenario is the most climate and cost efficient alternative in both countries and the ROI_{GHGe} indicator reinforces this. Thus, renovation of the existing building stock should be seen as a viable option to be considered.

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Declaration of Competing Interest

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

References

Abergel, T. et al.,(2019). 2019 Global Status Report for Buildings and Construction - Towards a zero-emissions, efficient and resilient buildings and construction sector. p. 39.

Boverket, Produktionskostnader för nyproduktion av flerbostadshus - En jämförelse mellan tre projekt i Stockholm, Linköping och Norrköping (Production costs for new multi-dwelling buildings - a comparison between three projects in Stockholm, Linköping and Norrköping). (2009). p. 60.

De Boeck, L., et al. (2015). Improving the energy performance of residential buildings: A literature review. *Renewable & Sustainable Energy Reviews, 52*, 960–975.

Ebenå, G., Holmgren, K., & Lindmark, S. (2019).Scenarier över Sveriges energisystem 2018 (Scenarios of the Swedish energy system 2018).

Erlandsson, M. et al.,(2018). Minskad klimatpåverkan från nybyggda flerbostadshus - LCA av fem byggnader.

Erlandsson, M., & Pettersson, D. (2015).Klimatpåverkan för byggnader med olika energiprestanda.

EU. Challenges faced by the construction industry. [cited (2020). Aug-28]; Available from: Https://ec.europa.eu/growth/sectors/construction_en.

Euroheat. District energy in Poland. (2019). [cited 2021 02-03]; Available from: Https://www.euroheat.org/knowledge-hub/district-energy-poland/.

Eurostat. Electricity price statistics. (2020). [cited 2021 01-19]; Available from: Https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics.

Guardigli, L., et al. (2018). Energy retrofit alternatives and cost-optimal analysis for large public housing stocks. *Energy & Buildings, 166*, 48–59.

Hajare, A., & Elwakil, E. (2020). Integration of life cycle cost analysis and energy simulation for building energy-efficient strategies assessment. *Sustainable cities and society, 61*, Article 102293.

Hall, T., & Vidén, S. (2005). The million homes programme: A review of the great Swedish planning project. *Planning Perspectives, 20*(3), 301–328.

Hare, B., Brecha, R., & Schaeffer, M. (2018).Integrated assessment models: What are they and how do they arrive at their conclusions? 11.

Hasik, V., et al. (2019). Comparative whole-building life cycle assessment of renovation and new construction. *Building and Environment, 161*, Article 106218.

Hoegh-Guldberg, O. et al.,(2018). Impacts of 1.5°C global warming on natural and human systems. In: Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the

threat of climate change, sustainable development, and efforts to eradicate poverty. p. 264–265.
Islam, H., Jollands, M., & Setunge, S. (2015). Life cycle assessment and life cycle cost implication of residential buildings—A review. *Renewable & Sustainable Energy Reviews, 42*, 129–140.
ISO. (2006a). *Environmental management - Life cycle assessment - Requirements and guidelines (ISO 14044:2006)* (p. 112). International Organization for Standardization.
ISO. (2006b). *Environmental management - Life cycle assessment - Principles and framework (ISO 14040:2006)* (p. 60). International Organisation for Standardization.
ISO. (2019). *Monetary valuation of environmental impacts and related environmental aspects (ISO 14008:2019)* (p. 48). Swedish Institute for Standards.
ISO. (2019). Monetary valuation of environmental impacts and related environmental aspects (ISO 14008:2019). (p. 48). Swedish Institute for Standards.
Jakob, M. (2006). Marginal costs and co-benefits of energy efficiency investments: The case of the Swiss residential sector. *Energy policy, 34*(2), 172–187.
Lu, H. R., El Hanandeh, A., & Gilbert, B. P. (2017). A comparative life cycle study of alternative materials for Australian multi-storey apartment building frame constructions: Environmental and economic perspective. *Journal of Cleaner Production, 166*, 458–473.
Luo, W., et al. (2021). Life cycle carbon cost of buildings under carbon trading and carbon tax system in China. *Sustainable Cities and Society, 66*, Article 102509.
Marszal, A. J., & Heiselberg, P. (2011). Life cycle cost analysis of a multi-storey residential net zero energy building in Denmark. *Energy (Oxford), 36*(9), 5600–5609.
Martinsson, F., et al. (2012). *Emissionsfaktor för nordisk elmix* (p. 35). Stockholm: IVL Swedish Environmental Research Institute.
Matthew, A., et al. (2014). Natural capital accounting and climate change. *Nature Climate Change, 4*(7), 520.
Nordhaus, W.D., .& Boyer, J. (2000).Warming the world: Economic models of global warming.
Nydahl, H., et al. (2019). Including future climate induced cost when assessing building refurbishment performance. *Energy and buildings, 203*, Article 109428.
Pindyck, R. S. (2019). The social cost of carbon revisited. *Journal of Environmental Economics and Management, 94*, 140–160.
Rønning, A., Vold, M., & Nereng, G. (2009). *Refurbishment or replacement of buildings–What is best for the climate?* Joint actions on climate change.
Rydegran, E. (2020).Fjärrvärmens minskade koldioxidutsläpp (Reduced carbon dioxide emissions from district heating in Sweden). [cited 2021 02-26]; Available from: Https://www.energiforetagen.se/statistik/fjarrvarmestatistik/fjarrvarmens-koldioxidutslapp/.
SCB. Construction: Prices for newly produced dwellings 2019. (2020). [cited 2021 01-18]; Available from: Https://www.scb.se/en/finding-statistics/statistics-by-subject-area/housing-construction-and-building/construction-costs/prices-for-newly-produced-dwellings/pong/statistical-news/construction-prices-for-newly-produced-dwellings-2019/.
SCF, Bostadsbyggande – begrepp och kostnadsfördelning (Building construction - concepts and cost allocation). (2017).: Sweden.
Schakenda, V., & Askham, C. (2010).Nyland, CO2-emissions associated with different electricity mixes.: Norway. p. 20.
SEPA. (2020). *Calculate emissions of air pollutants (Beräkna dina utsläpp av luftföroreningar). 2020, swedish environmental protection agency29. IVL, byggsektorns miljöberäkningsverktyg (Climate impact calculation tool)*. The Swedish Environmental Research Institute (IVL).
Spath, P., & Mann, M. (2000).Life cycle assessment of a natural gas combined-cycle power generation system. p. 56.
Statista. Average cost per square meter of internal area in selected European cities/regions for constructing a building in 2018, by region. (2018). [cited 2021 01-19].
Stern, N. (2007). *The economics of climate change: The stern review*. Cambridge: Cambridge: Cambridge University Press.
Sterner, E. (2002). *Green procurement of buildings: Estimation of environmental impact and life-cycle cost*. Luleå Tekniska Universitet.
Stiglitz, J.E. et al.,(2017). Report of the high-level commission on carbon prices.
Strong Growth, Low pollution modelling a carbon price. (2011). [cited 2020 Feb 07]; Available from: Https://treasury.gov.au/programs-initiatives-consumers-community/modelling-a-carbon-price.
Vilches, A., Garcia-Martinez, A., & Sanchez-Montañes, B. (2017). Life cycle assessment (LCA) of building refurbishment: A literature review. *Energy and Buildings, 135*, 286–301.
VVS-tekniska, VVS handboken (HVAC manual). (1974). Stockholm, Sweden: Förlags AB VVS.
Werner, S. (2016).European district heating price series.
Wierzbowski, M., Filipiak, I., & Lyzwa, W. (2017). Polish energy policy 2050–An instrument to develop a diversified and sustainable electricity generation mix in coal-based energy system. *Renewable and Sustainable Energy Reviews, 74*, 51–70.