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# Explorative life-cycle assessment of renovating existing urban housing-stocks

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ABSTRACT

Urban building-stocks are responsible for a significant share of resource and energy use. To quantify the potential for reducing energy and environmental impact, building-stock modelling (BSM) is commonly used. Recently, the focus of BSM has expanded to include environmental impacts and life-cycle assessment (LCA). However, impact categories are often limited to climate change and representative buildings are often used. In addition, the future state of the stock is often calculated as a step-change to highlight the technical potential of an ideal future state. The aim of this paper is to assess the environmental impact of the future development of an urban housing-stock under business-as-usual scenarios using a building-specific GIS based model applied to the multi-family building stock of the City of Gothenburg. This paper uses an explorative LCA to account for environmental impacts based on dynamic uptake of common renovation measures and resulting energy savings until 2050. Two main scenarios are used where the renovation logic is based on either end-of-life of components or cost-effectiveness and further divided using limiting factors regarding investment capacity and annual share of the stock to be renovated. Results show possible energy savings of up to 23% and a corresponding 31% reduction in greenhouse-gas emissions. Greenhouse-gas emissions avoided due to reduced energy demand are offset by up to 65% by accounting for material use due to construction related renovation measures. For scenarios that favour construction related interventions, PV panels are responsible for the major part of the environmental impact across the 15 mid-point indicators used.

## 1. Introduction

Buildings worldwide account for considerable energy use and related climate impact. Furthermore, it is estimated that for developed countries, most of the buildings in use in 2050 have already been built [1]. In Europe, the existing building stock is responsible for 40% of total energy use and 36% of $CO_2$ emissions [2]. On a local level, municipalities and cities have set ambitious targets for reducing energy use and greenhouse-gas (GHG) emissions. Thus, environmental impact assessment of building-stocks is needed on a local scale. To investigate the current state and potential development of building-stocks, building-stock modelling (BSM) is commonly used. The energy use of the building-stock is often the subject of study, either focusing on the current state of the stock [3,4] or to evaluate potential developments [5,6]. Modelling approaches have evolved from using representative buildings with scaling factors to account for the building stock on a national or pan-national level [7,8] to increased use of building-specific modelling techniques utilizing geographic information system (GIS) to model the building stock of regions, cities and neighbourhoods [9]. Similarly, modelling practices have evolved from focusing on energy use during the operational phase to also encompass embodied energy [10] and $CO_2$ emissions [11]. It is commonly stated that BSM are developed to support policy-makers [12]. To achieve this, three methods are used to assess the current state and future evolution of the building-stock. The first one are baseline models which focus on modelling the current state of the stock, often to highlight hot-spots for intervention [13]. The second method are step-wise models that assess the (theoretical) technical potential for energy savings and related environmental impacts by applying a step-wise change to the stock [14]. Lastly, there are dynamic approaches using scenarios to model the future development of the stock [10]. These range from static assumptions using a fixed renovation rate [12,15] to decision models based on economic [16] or socio-economic [17] feasibility. However, the use of limiting factors is not applied at a stock scale where investment capacity and other bottlenecks may delay the transformation.

Recently, the use of Life-cycle assessment (LCA) have become more

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prevalent in BSM [18]. It has been used to assess the environmental performance of façade renovations in an urban setting [19], to assess the environmental impact of renovation measures on the European residential stock [20] and to investigate the end-of-life (EOL) impact of building stocks [21]. While the use of environmental LCA has increased, the use of impact categories is often limited to global warming potential (GWP) [14,15,22–24]. The use of additional impact categories is more diverse but typically consist of indicators such as embodied energy (EE) [19,25], abiotic depletion potential (ADP) [21,26], acidification and eutrophication potential (AP, EP) [21,26–28], ozone depletion potential (ODP) [21,26–29] and photochemical ozone creation potential (POCP) [21,26–28]. There have been a few cases were other more specialised impact categories have been used such as particulate matter formation (PM10) [30] and embodied water [31]. Furthermore, which life-cycle stages are included differ but generally conform to those described in Ref. [32]. Typically, environmental impacts from the operational phase are included [10,14,22,27,30,33] as well as environmental impacts from production of materials and components [19,27,33]. In addition, some studies go further and include environmental impacts relating to the construction process [15,27,33]. There are also studies that have included maintenance [34] as well as EOL [21] stages.

The aim of this paper is to explore the environmental impact of future development of an urban housing stock under business-as-usual scenarios using a building-specific GIS based model applied to the multi-family building (MFB) stock of the City of Gothenburg. Two main scenarios where the renovation logic is based on EOL of components or cost-effectiveness. These two scenarios are further divided using limiting factors regarding investment capacity and annual share of the stock to be renovated. Energy use for the building stock is calculated using a previously developed dynamic method and an explorative LCA [35] is used to assess the environmental impact of construction materials. The City of Gothenburg has twelve categories of environmental targets which cover aspects such as climate change, acidification, eutrophication, nitrogen oxides ($NO_x$), particulate matter (PM10), human toxicity, eco-toxicity and photochemical oxidant formation [36,37]. The timeline for these targets differs and they are continuously revised and updated. Hence, the timeline used for this paper is until 2050 to coincide with long-term climate-goals. The environmental impact categories used in the LCA are chosen to broadly correlate to environmental targets set for the City of Gothenburg to indicate if and where trade-offs can be found. While environmental targets cover a larger scope than the MFB stock, it provides an opportunity to showcase to what extent the building-stock can contribute to such targets and what is required of other sectors. In addition, it provides an opportunity to showcase trade-offs where local environmental impacts are shifted to global impacts.

## 2. Methodology

The energy demand is calculated using previously developed methodologies for describing [12,38] and calculating [11] the energy performance of building-stocks using a building specific bottom-up engineering-based approach. A building-specific stock description of 5901 MFBs in the City of Gothenburg have been developed using the property register supplied by The Swedish Mapping, Cadastral and Land Registration Authority, energy performance certificates (EPC) supplied by The National Board of Housing, Building and Planning, and GIS shape files from the City planning office. Building surface areas are derived from the building geometry for each individual building. The current state of each building in the stock is based on the year of construction in combination with the economic extent of previous renovation activities. The energy performance of each building is modelled using the ECCABS model [11]. The model is dynamic, uses hourly specification of input data and the accuracy of the model has previously been validated using inter-model comparisons and empirical validations [11]. In addition, scenario modelling has been developed for the uptake and quantification of energy saving measures (ESMs) and evaluated using LCA which is described below.

### 2.1. Scenario modelling

Two types of dynamic scenarios are considered with different driving forces (technical or economical), as well as two levels of restrictions with respect to the investment and workmanship capacities [39]. Scenario 1 considers that the different building components will be updated at the end of their lifetime, regardless of the cost-effectiveness of the ESM. The technical lifetime of the building components is determined based on the value-year and the lifetime of building components is based on EN 15459 [40]. The value year is weighted based on the year of construction, year of renovation and economic extent of previous renovation activities or extensions and relates to the expected remaining lifetime of each building [41]. However, renovation that costs less than 20% of new construction is not accounted for. Scenario 2 considers that ESMs are implemented if they are cost-effective, with the renovation taking place at the end of the lifetime of the building component. Cost-effectiveness is evaluated using equivalent annual cost based on the method described in Ref. [42]. This scenario assumes that all energy efficient retrofitting is considered that is cost-effective when the specific building component must be renovated. If different ESMs and packages are cost-effective in the same year, the packages containing the individual ESMs are preferred. Scenarios 1 and 2 are further limited by restrictions regarding yearly investment capacity and a yearly cap on the share of the stock that can be renovated. The limitation on share of the stock being renovated is a proxy for factors such as available workforce and planning procedures. These limitations are given to the model as a maximum total heated floor area (HFA) in the city of Gothenburg being renovated per year ($m^2_{HFA}$/year) and as a maximal annual investment per HFA renovated per year [€/($m^2_{HFA,}$ year)]. The limitations are not applied for each building but rather to groups of owners divided in three categories; the municipal housing company, housing associations and private property owners. Two levels of limiting factors are used, one based on current trends and one with a more ambitious uptake in renovation measures. Limitation A is based on average investments in energy efficiency measures of the municipality housing company (7.5€/$m^2$ HFA) [43] and on the national average renovation rate of roughly 1% [44]. Limitation B uses a higher investment ceiling of 10.0€/$m^2$ HFA and a higher capacity for renovation resulting in 2.5% of HFA being renovated. The limiting factors are denoted with A or B to indicate lower or higher levels used with scenario 1 and 2 for a total of four outcomes as can be seen in Table 1. A limit for maximum annual investment is applied first for all property owner groups and years. The calculations are performed for each year of the scenario. The purpose of this is to guarantee that all property owner groups invest in energy efficient renovations to their maximum capacity. If the resulting annual investment is over the limit, the least cost-effective investment is postponed until the next year. If the annual investment is lower than the limit, all investments are made and the difference between the maximal and the actual investment is saved until the next time step, enabling property owners to save up for a larger investment.

**Table 1**
Description of scenarios and limitations for investment capacity and annual share of the stock to be renovated.

| Scenario | Renovation logic | Investment capacity | Renovation capacity |
|---|---|---|---|
| 1A | EOL | 7.5€/$m^2$ HFA | 1% of HFA |
| 1B | EOL | 10€/$m^2$ HFA | 2.5% of HFA |
| 2A | EOL and cost-effective | 7.5€/$m^2$ HFA | 1% of HFA |
| 2B | EOL and cost-effective | 10€/$m^2$ HFA | 2.5% of HFA |

**Table 2**
Description of energy saving measures used and related input parameters.

| ESM Number | ESM description | Input parameter affected (and its value after renovation) | Included in package | Lifetime (years) |
|---|---|---|---|---|
| 1 | Increased insulation of floor/basement | U-value floor (0.30 W/m$^2$K) | 1, 4 | 40 |
| 2 | Increased insulation of facades | U-value wall (0.30 W/m$^2$K) | 1, 4 | 40 |
| 3 | Increased insulation of attics/roofs | U-value roof (0.25 W/m$^2$K) | 1, 4 | 40 |
| 4 | Replacement of windows | U-value window (2.0 W/m$^2$K) | 1, 2, 4 | 40 |
| 5 | Upgrade of ventilation systems with heat recovery | SFP (2.0 kW/(m3,s)), η (0.75) | 2, 4 | 20 |
| 6 | Installation of efficient lighting equipment (leading to 25% reduction in electricity consumption) | Lighting (0.51 W/m$^2$ HFA) | 3, 5 | 5 |
| 7 | Installation of efficient appliances (leading to 25% reduction in electricity consumption) | Appliances (2.1 W/m$^2$ HFA) | 3, 5 | 15 |
| 8 | Reduction in power used for the production of hot water | Hot-water (2.0 W/m$^2$) | 4, 5 | 15 |
| 9 | Installation of PV panels | 10% of roof surface | – | 25 |
| 10 | Installation of PV panels | 30% of roof surface | 4 | 25 |
| 11 | Installation of PV panels | 50% of roof surface | – | 25 |
| 12 (P 1) | Retrofitted envelope and windows | Includes ESMs 1-4 | 4, 5 | |
| 13 (P 2) | Retrofitted ventilation and windows | Includes ESMs 4-5 | 4, 5 | |
| 14 (P 3) | Improved lighting and appliances | Includes ESMs 6-7 | 5 | |
| 15 (P 4) | Reduced heating demand | Includes ESMs 1–5, 8 and 10 | 5 | |
| 16 (P 5) | Comprehensive energy renovation | Includes ESMs 1–8 and 10 | – | |

### 2.2. Energy saving measures

The ESMs used are presented in Table 2 below. ESMs 1–4 are assumed to be in line with the requirement of the Swedish building regulation in force [45] of an average thermal transmittance (Um) of the building envelope of 0.4 W/m$^2$ K, and ESM 5 is based on the values for Specific Fan Power (SFP) for extract and supply air with heat recovery established in the regulation. ESMs 6–8 are based on the literature [42]. ESMs 1–8 are typical renovation measures and have been exhaustively studied before in Swedish buildings [46,47]. Finally, ESMs 9–11 are based on [48,49] respectively. In addition, the measures are combined in five packages where packages are chosen as described under Scenario modelling. The cost of measures is based on [42] (ESM 1–8) and [48] (9–11). For energy costs, consumer prices in 2015 have been used [50]. To account for increased efficiency over time, the investment cost is assumed to annually decrease by 0,5% and the efficiency to annually increase by 0,5% compared to 2015 levels. Additionally, reapplication of measures related to lighting, appliances and aerator taps are assumed to have diminishing returns and energy savings are reduced by 50%.

### 2.3. Life-cycle assessment

The LCA is carried out using the software SimaPro V8.0.5.13 and the database Ecoinvent V3.1 with the goal to investigate environmental impacts due to changes in the MFB stock of the City of Gothenburg until 2050. European data is used when available, in other cases global data is used in the assessment. The environmental impact is assessed for all construction related measures (1–5 and 9–11) using 15 of the ReCIPe [51] V1.12 mid-point categories, omitting land related impacts. Interior measures such as lighting and appliances are omitted due to data availability. The material use for construction measures is based on a library of common renovation measures on the Swedish market [52,53]. For measures relating to façade insulation and windows, several options are considered. Windows have been differentiated according to frame material (wood/aluminium) and additional façade insulation have three different implementations, all using mineral wool, depending on the original wall make-up. To assess GHG emissions from energy use in the building-stock, data for the local energy provider is used for district heating (65 $gCO_2eq/kWh$) and the Swedish market mix is used for electricity (131.2 $gCO_2eq/kWh$) [54]. Future changes to the energy system are not considered and neither is the impact of new construction. The assessment is carried out in accordance with relevant standards [32,55], using life-cycle stages A1-A3 (raw material supply, transport and manufacturing) and B6 (operational energy use) with the functional unit being the 5901 MFB used in the assessment. The environmental impact of renovation measures and energy use until 2050 is assessed to coincide with long-term goals set by the City of Gothenburg.

## 3. Results

The change in yearly energy use until 2050 for the different scenarios can be seen in Fig. 1. This includes delivered energy for heating, hot-water and electricity use. The total energy use is 3009 GWh/year for the initial state of the stock and changes in energy use over time is modest in all scenarios except for scenario 1B with a 23% reduction. The limiting factors have a significant impact on reductions in energy use which increase by a factor of 4.7 for scenario 1 and 5.8 for scenario 2. While the total energy use is reduced, measures regarding energy efficient lighting and appliances reduce the electricity use and thus internal loads which in turn increase heating demand. As heating is generally provided via district heating, there is a shift from electricity use to district heating. This is particularly the case for scenario 2 where a large portion of the energy savings relate to reduced electricity use. While the total energy use for scenario 2 decreases by 0.7% (scenario 2A) and 4.1% (scenario 2B) respectively, the yearly energy use for district heating increases by 70 GWh/year until 2050 in both cases.

The yearly GHG emissions from energy use until 2050 is shown in Fig. 2. For 2015, GHG emissions from the MFB stock is 204 $ktonCO_2eq$/year. The reduction in GHG emissions over time follows the pattern of energy use but with a larger total reduction, reflecting the shift from electricity use to district heating. For example, the reduction in GHG emissions for scenario 1B increases to 31% compared to the reduction in energy use of 23% until 2050.

In Fig. 3, the number of buildings that employ measures and packages described in Table 2 for the different scenarios is shown. As stated previously, the uptake of measures favours reduction in electricity use through energy efficient lighting (measure 6) and appliances (measure 7). Due to the limited technical lifetime, appliances are changed in most buildings twice as the total number of buildings in the stock is 5901 and the measure is implemented in 9872 cases. For scenario 1, individual measures are favoured over packages while in scenario 2, the opposite occurs. In scenario 1, the uptake of measures 1–10 is similar regardless of limiting factors while measure 11 is significantly impacted. For scenario 2, the effect of limiting factors is more evenly distributed among the different measures due to the use of package solutions. In total, a package is applied twice for scenario 1A and 1B each while a package of measures is used 1504 times for scenario 2A

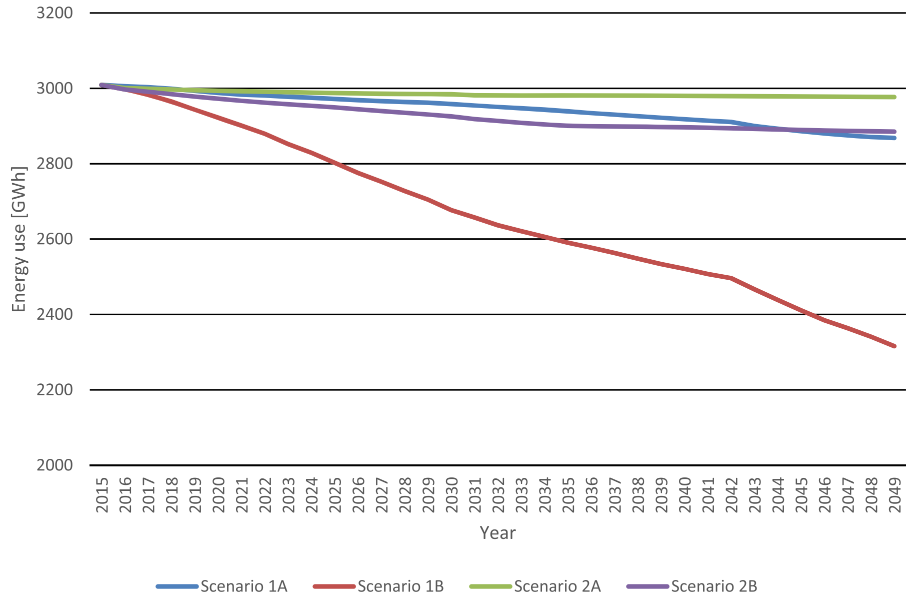


**Fig. 1.** Yearly energy use in the MFB stock until 2050 for the different scenarios.

and 3619 times for scenario 2B. The investment capacity is more limiting than share of the stock to be renovated in both scenarios. The relatively small change in limiting factors between the scenarios have a large impact on the uptake of measures where an increase in investment capacity from 7.5 to 10 €/$m^2$ HFA increases the number of implementations of a certain measures by roughly a factor 5.

In Fig. 4, the environmental impact of construction related measures is given using 15 of the ReCIPe mid-point categories. All impact categories have been normalised against scenario 1A to highlight trends. Results tend to follow the trend in uptake of measures where an increase in limiting factors result in a factor five increase in environmental impact. Scenario 1A and 1B show similar trends while scenario 2A largely follows the same trend as scenario 2B. As such, the limiting factors does not affect what measures are implemented but rather to what extent. While scenario 1B achieved the largest reduction in energy use, scenario 2B have a larger environmental impact from material use. This is due to what measures are implemented in the different scenarios where scenario 1 favours appliances which are not included in the environmental impact assessment regarding material use.

In Figs. 5 and 6, the environmental impact of all construction related measures for scenario 2 until 2050 is given using 15 of the ReCIPe mid-point categories. All impact categories have been normalised relative to individual measures to highlight trade-offs. As the results are based on the total uptake of measures, it is not a comparison of individual measures but rather serves to compare the total relative impact across the building-stock until 2050. Only scenario 2 is highlighted as scenario 1 is heavily biased towards interior measures not accounted for in the LCA, leaving only PV panels to account for environmental impact. The results for scenario 2A and B show that installation of PV panels dominates most impact categories with a share of 50% or more for nine of the 15 impact categories. In addition, PV panels account for more than 75% of the environmental impact regarding ozone depletion potential, terrestrial ecotoxicity and water depletion for scenario 2A. Scenario 2A and B follow the same general trends but due to a larger uptake of insulation related measures for scenario 2B, the relative impact of PV panels is slightly lower. As the uptake of insulation related measures are evenly distributed due to the use of package solutions, they are more comparable. Replacement of windows has the largest

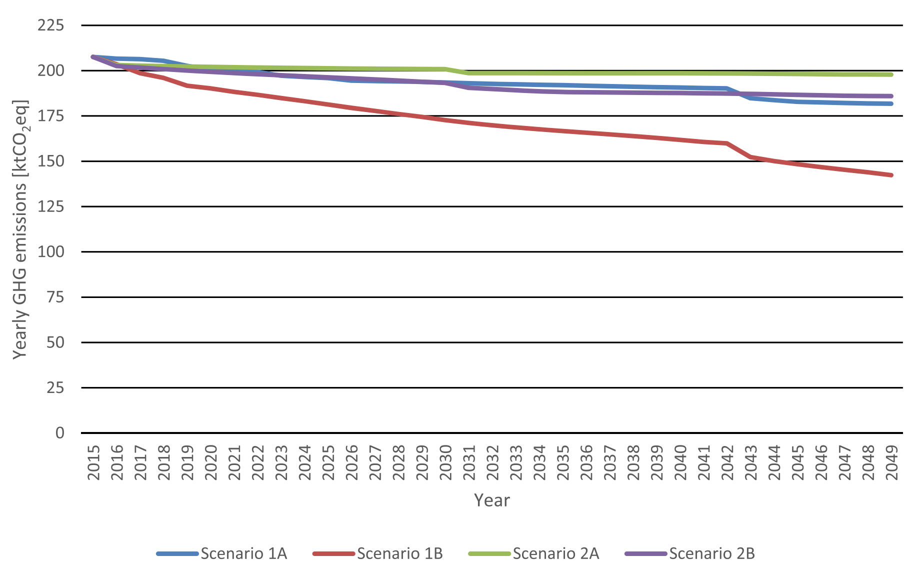


**Fig. 2.** Yearly GHG emissions from the MFB stock until 2050 for the different scenarios.

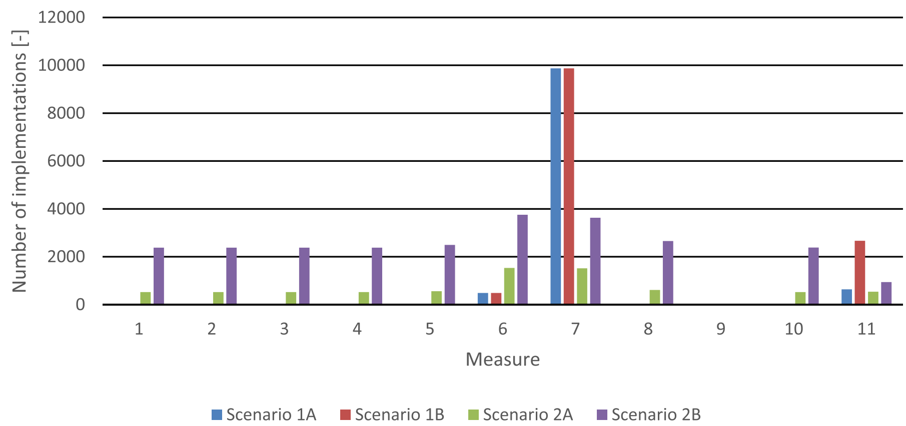


**Fig. 3.** Uptake of measures until 2050 for the different scenarios.

relative environmental impact followed by insulation of facades. Roof insulation has a consistently low environmental impact with around 3–5% while insulation of floor or basement has an environmental impact ranging from 3 to 10% with the exception for marine eutrophication where it is responsible for 64% of the environmental impact for scenario 2A and 69% for scenario 2B. Upgrade of ventilation system with heat recovery have a relatively low environmental impact across all categories, peaking at 10% for metal depletion for scenario 2B.

In Fig. 7, the cumulative climate impact for scenario 2 due to energy savings until 2050 and material use for the ESMs is given as kt$CO_2$eq saved for the different scenarios and limiting factors. In both cases, the net effect of renovation measures results in a decreased climate impact. The GHG emissions saved equates to one year of current GHG emissions levels for scenario 2A and 2B. The relation between saved GHG emissions from decreased energy use and GHG emissions from material use differs between the two limiting factors. In scenario 2A, the lower investment capacity and renovation rate results in fewer measures being implemented resulting in lower environmental impact from the material use. For scenario 2B, the increased investment capacity and renovation rate allows for larger reductions during the use phase although this is entirely offset due to increased material use. As such, further measures reducing energy use will have a marginal climate impact and trade-offs relating to other impact categories should be considered.

## 4. Discussion

In this paper, we have investigated the environmental impact of ESMs of the existing MFB stock in the City of Gothenburg until 2050 using business-as-usual scenarios. The use of business-as-usual scenarios highlights the limited impact current renovation rate and measures will have with a reduction in energy use of up to 23%. In comparison, energy use for space heating and hot-water due to new construction has been estimated to result in a 20% increase [12]. As the measures used are conservative, a more aggressive renovation strategy could be investigated as the marginal costs are likely to be small. This is especially important to consider with regards to lock-in effects [25]. The use of a business-as-usual scenario provides results on the general trend for the entire stock studied while the relative impact of specific measures requires a detailed building centric focus. In addition to energy use, yearly GHG emissions from energy use for the different scenarios is reduced by up to 31%. The application of an LCA shows that the environmental impact related to material use is low in comparison to achieved reductions due to energy use under business-as-usual scenarios. However, as not all stages in the lifecycle is accounted for and only construction related measures are considered, further studies should include a wider scope including the environmental impact of interior changes as well as broader scope of life-cycle stages including EOL. Also note that the comparatively low impact related to material use is based on conservative measures and the environmental impact of

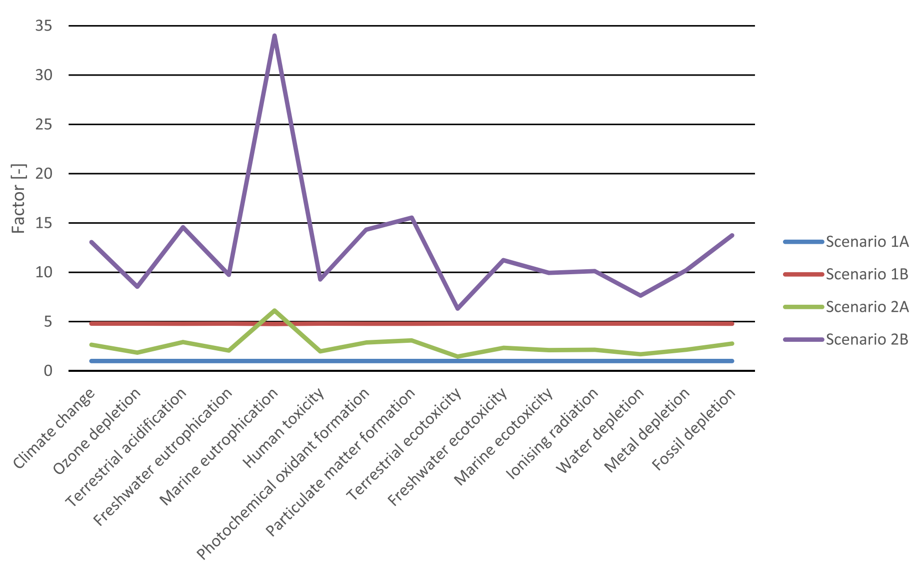


**Fig. 4.** Environmental impact for 15 mid-point categories for the different scenarios, normalised against scenario 1A.

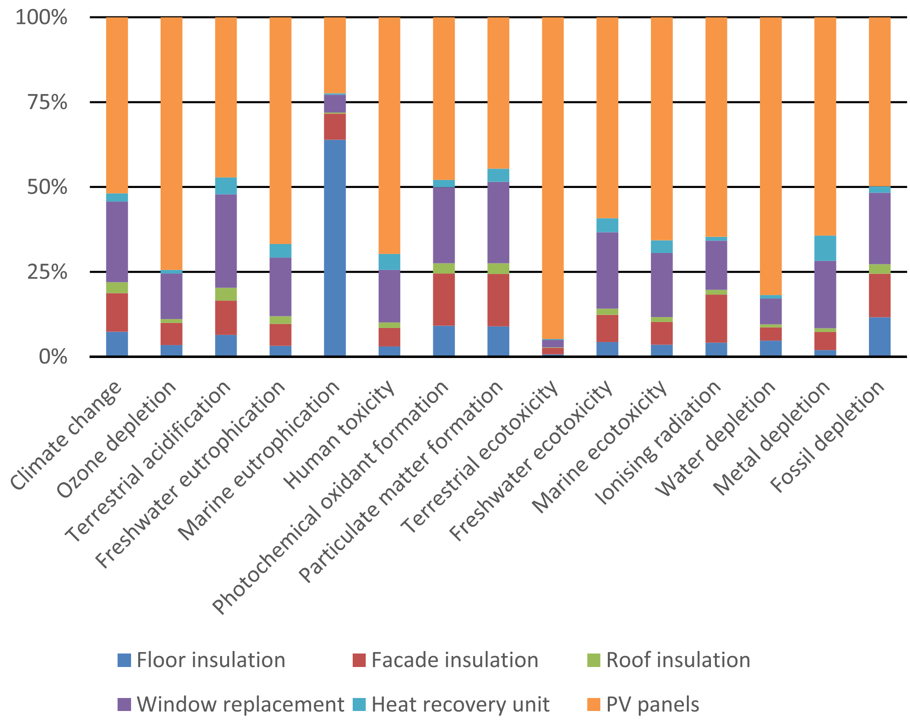


**Fig. 5.** Relative environmental impact of construction related renovation implemented until 2050 measures for 15 mid-point coordinates under scenario 2A.

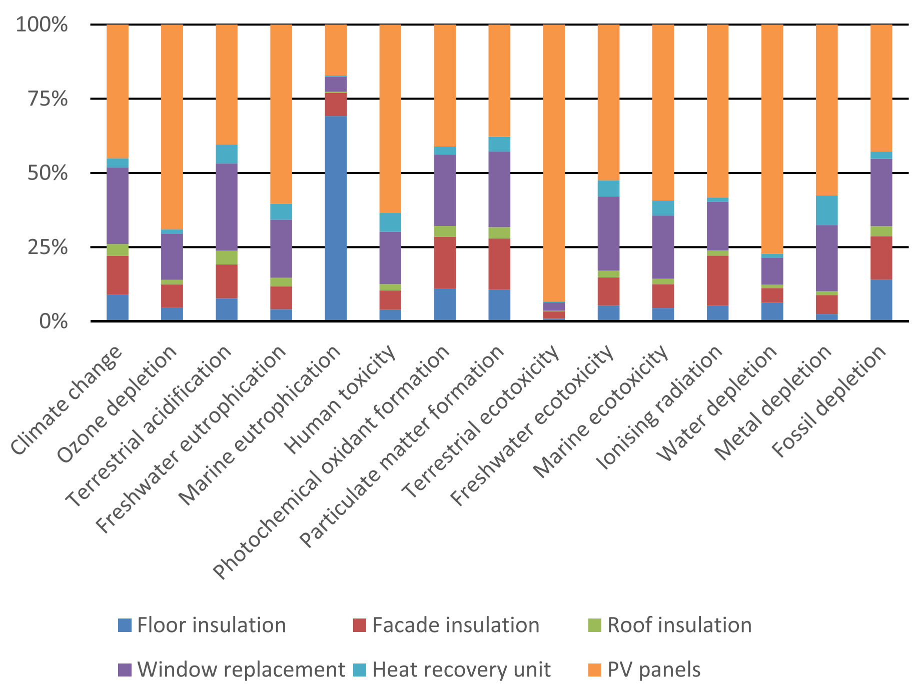


**Fig. 6.** Relative environmental impact of construction related renovation measures implemented until 2050 for 15 mid-point coordinates under scenario 2B.

a more comprehensive renovation approach needs further assessment to avoid sub-optimization. While this paper focus on the combined environmental impact, a more nuanced approach could be employed where the relative impact of certain measures is highlighted for individual buildings. Furthermore, the possibility of using national rather than global data for the environmental impact assessment should be investigated. To provide a solid foundation for many stakeholders involved in the transformation of the existing building-stock, a wide range of mid-point coordinates have been used. In order to better support policymakers or property owners, the possibility to use select end-point indicators or tailored weightings should be further studied. However, it is important to note that environmental impact is only one of many relevant aspects to consider in assessing the effect of renovating the existing building-stock and a wider approach is needed where economic and social aspects are investigated to form a better understanding of the complexities and challenges involved as well as to identify trade-offs.

The state of the building stock is assumed based on economic extent

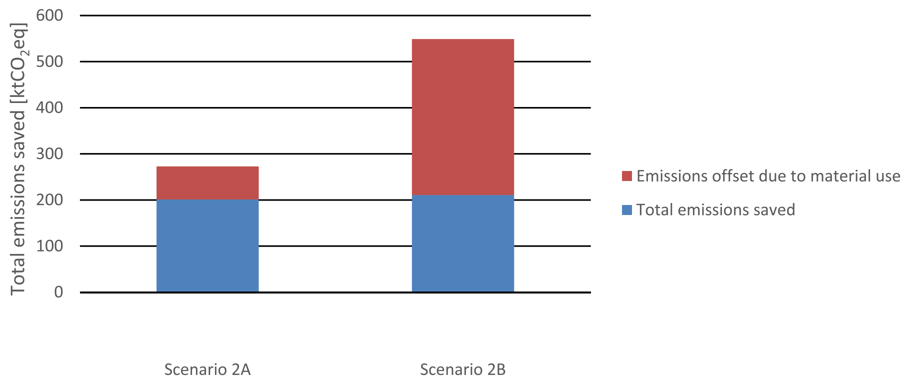


**Fig. 7.** Cumulative climate impact due to energy savings until 2050 and material use for the ESM for scenario 2.

of past renovation activities and the accuracy can be improved by better understanding the current state of individual building components. This could be done using surveys or inspections. In addition, calibration of energy calculations could be performed for each individual building to better assess the current state of the stock [56]. The use of a building specific modelling approach and GIS can be further developed to increase the level of detail of the LCA to account for local impacts as well as to identify local hot-spots and areas with high material concentrations for urban mining [57]. The use of a GIS based modelling approach also enables visualization and communication of results to relevant stakeholders by using maps or 3D-models. In cases where 3D-models of the buildings are not readily available, google earth may be useful in deriving relevant building geometries [58,59]. In addition to increasing the spatial granularity, an enhanced temporal scale could be applied to more accurately assess the environmental impact of energy use. Rather than using yearly averages for GHG emissions, an hourly approach could be used and future changes to the energy supply system could be accounted for [60]. Ideally, additional impact categories can be included in the environmental assessment of energy carriers to provide a more holistic view.

The limiting factors applied to investment capacity and share of the stock being renovated have a large impact were the uptake of measures is increased by a factor 5. It should be noted that in the current scenarios, only the investment capacity is considered as a limiting factor as it is consistently the main barrier. In future work, other limiting factors could be applied to describe pathways and assess policy measures such as socio-economic impacts of deep renovation [41]. As a building-specific approach to describing the stock enables arbitrary aggregation of results, the methodology used in this paper could be applied to a specific property owner. This would enable tailoring limiting factors to individual stakeholders and with access to maintenance plans, the timing of measures could be optimised [61]. In addition, a property owner view would allow for prioritizing deep renovation from an environmental, financial and socio-economic perspective.

In this paper, factors such as technology development, energy prices and construction costs have been estimated conservatively to be in line with a business-as-usual scenario. Future studies could include a wider analysis on these factors to better understand potential tipping-points and develop alternative scenarios. In addition, a wider range of measures could be used with a larger energy savings potential to highlight the gap between the business-as-usual and best-case scenarios. In addition, the impact of legal requirements on energy use could be investigated to indicate the to what extent it would speed up the urban transformation. Scenario 2B and further measures or measures with a higher material use should be investigated to indicate what the most suitable level of renovation is.

## 5. Conclusions

An explorative LCA on the transformation of the existing MFB stock in the City of Gothenburg under business-as-usual scenarios is used to indicate environmental impacts until 2050, utilizing building-specific information and GIS. By using limiting factors on uptake of renovation measures in terms of investment capacity and annual limits on share of the stock to be renovated, a more robust scenario is achieved while indicating bottlenecks for further reductions in GHG emissions and energy use. To provide a more holistic perspective, 15 of the ReCIPe mid-point indicators have been used and all impact categories have a positive correlation with climate change. Results show yearly reduction in GHG emissions of up to 31% is achievable until 2050 under these scenarios. In some scenarios, the impact of construction materials offset more than half the GHG emissions saved due to reductions in energy use. While GHG emissions from the product stage does not offset greenhouse-gas emission savings until 2050 due to energy savings, interior measures such as appliances and lighting are not accounted for which may further tip this balance. As the environmental impact is evaluated based on total uptake of measures across the stock until 2050, the relative impact of measures is not directly comparable. It should be noted however, that for scenarios that favour construction related interventions, PV panels are responsible for the major part of the environmental impact across the 15 mid-point indicators used.

While trade-offs between environmental impact categories can be highlighted using this approach, it is difficult to provide any specific recommendations in relation to environmental targets set by the municipality. The targets set by the municipality have different timelines, different geographic scope and there is no method for weighing targets against each other. For example, the target relating to climate change is expressed as 3.5 $tCO_2$eq/person by 2035 and net-zero by 2050 while the targets for acidification relates to PH-levels in local lakes and local emissions of $NO_x$ in 2015. As such, further studies are needed where local emissions are accounted for which would also enable normalization to better communicate results to relevant stakeholders. In addition, such studies should account for and highlight environmental impacts that are transferred from a local to a global level.

Current trends in uptake of ESMs will have little effect in reaching targets for reductions in GHG emissions set by the municipality which would have to rely on reductions from other sectors. Further studies could apply a wider scope by incorporating additional sectors in the evaluation. Further improvements to the accuracy and robustness of the LCA can be made by using local data for the impact assessment. Using a more detailed LCA would also enable a similar approach to be applied for large property owners to prioritize renovation measures within their stock.

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