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Coupling MFA and LCA

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Full length article

Temporally dynamic environmental impact assessment of a building stock: Coupling MFA and LCA

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ABSTRACT

In this study, MFA and LCA are coupled in a prospective analysis of the environmental impact of a building stock at a Danish university campus. The existing buildings are mapped and future growth is identified to create a dynamic LCA inventory. The prospective model is applied in a case study to determine the accumulated environmental impacts associated with the growth of the campus building stock from 2023 to 2050.

The findings indicate that the national decarbonization of electricity and heat supply from 2023 to 2035 will deliver notable impact reductions, however the reduction in the overall impact of the building stock by 2050 will be counteracted by growth in new buildings and potential renovation activities. If decarbonization continues post-2035, impact will decrease for particularly global warming potential. The results allow identification of environmental impact hotspots, both spatially and temporally. This supports the development of mitigation strategies to reduce environmental impacts.

1. Introduction

According to the United Nations (UN) (2019), the global urban population is projected to grow by 2.5 billion people between 2018 and 2050, and with this comes an increasing need for housing and infrastructure in urban areas (United Nations Habitat, 2017). In 2015, all 193 UN member states pledged to pursue the UNs 17 goals for sustainable development (SDGs) until 2030. Target 11.1 under SDG-11 on Sustainable Cities and Communities reads that “by 2030, universal access to adequate, safe, and affordable housing and basic services should be ensured” (United Nations, 2015). Since this commitment was made, the majority of world regions have reported a consistent increase in built-up area per capita (United Nations, 2021). Buildings are estimated to be responsible for 40 % of all materials consumed in the global economy (Mirabella et al., 2019), and the energy needed to construct and operate buildings globally, cause 12 % of the total anthropogenic GHG emissions (IPCC Working Group III, 2022). This highlights buildings and building stocks as central in mitigating climate change and other environmental impacts. To ensure that mitigation actions have the highest degree of relevance and effectiveness, it is key that current impacts, as well as expected future impacts, are quantified.

To evaluate the effectiveness of mitigation strategies on future impact levels, assessments should take a prospective modeling approach, and include dynamic variables to ensure that interactions between urban material flows and socioeconomic activities are accurately integrated and mapped (Lanau et al., 2021). In the context of buildings and building stocks, Röck et al. (2021) define a model as (a) spatially dynamic, when a differentiation is made based geography or climate, in e.g. building characteristics, (b) temporally dynamic, when changes over time are considered, e.g. in demand for space or technological innovation, and (c) spatially and temporally dynamic when changes are considered over both time and space. Some of the most commonly assessed dynamic variables in studies of buildings and building stocks are related to the occupants and their behavior, evolution in energy mix, climatic changes and technological evolution (Su et al., 2021).

A dynamic perspective can be integrated into assessments of urban areas through ‘material flow analysis’ (MFA). MFA provides a systematic assessment of flows and stocks within a temporally and spatially defined system, e.g. a city or urban area (Brunner and Rechberger, 2004). MFA

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can be used in both retrospective and prospective analyses of building materials in cities (Augiseau and Barles, 2017). A shortcoming of MFA is that emissions embodied in raw materials or products entering the system are not accounted for (Goldstein et al., 2013; Goldstein and Rasmussen, 2017). Therefore, MFA is often coupled with life cycle assessments (LCA). LCA is an ISO-standardized methodology for assessing environmental impacts associated with all life cycle stages of a product or system (International Organization for Standardization, 2006). LCA introduces a full life cycle perspective into MFA, thus accounting for activities up- and downstream of the MFA system boundaries. LCA also complements MFA by adding an environmental extension by translating flows into environmental impact potentials for the system's metabolism.

While a dynamic perspective is more common in MFA studies on material stocks in the built environment (Lanau et al., 2019), most LCA studies on building stocks still adopt a static modeling approach focusing solely on the current stock or sometimes comparing to a future state (Mastrucci et al., 2017). This finding is echoed by Anand and Amor (2017) and Su et al. (2017) who highlight dynamic LCAs as a new addition to the pool of LCA studies on buildings, however a highly relevant development from the traditional static LCA, where impacts that – in the case of buildings – occur over many decades, are aggregated to an average annual score.

Both Röck et al. (2021) and Mastrucci et al. (2017) found that a majority of LCA studies on building stocks focus only on residential buildings, and Bahramian and Yetilmezsoy (2020) found that non-residential buildings often have markedly higher environmental impacts than residential buildings, due to higher operational energy consumption. With the majority of existing studies focusing on residential buildings, there is a risk of overlooking important contributors to the total environmental impact the built environment.

Finally, in reviews of environmental impacts of buildings (Anand and Amor, 2017), building stocks (Lotteau et al., 2015; Mastrucci et al., 2017; Röck et al., 2021) or cities (Petit-Boix et al., 2017), it is a consistent finding that most studies focus on global warming potential (GWP) and primary energy use (PE). This limited impact coverage in existing literature, introduces a risk of burden shifting among impact categories when developing policies and planning mitigation strategies.

As a contribution to the growing field of dynamic LCA applied at neighborhood level, this work demonstrates how the environmental impact of a building stock can be assessed over a time period of 27 years (2023 to 2050) by developing and applying a prospective and dynamic MFA-LCA model with a spatially differentiated and temporally dynamic life cycle inventory. The MFA-LCA model is considered to be in accordance with the definition of "temporally dynamic" in Röck et al. (2021), as future technological developments are modelled over time as well as annual developments in demand for space.

To advance the current knowledge on the impact of non-residential building stocks, we apply the model to the case of a university campus that is taken as a proxy for a neighborhood with mixed building functions, i.e. including buildings with both residential, recreational, and educational use. Campuses often encompass many of the same functions as a small community, and hence, for the purpose of this paper, we argue that as a proof of concept, a campus is relevant to investigate as a proxy for a neighborhood. The impact assessment covers 18 environmental impact categories, thus providing new knowledge on the temporal development in the environmental impacts of building stock outside of GWP and highlighting possible burden shifting between impact categories as a result of an evolving building stock. The campus considered is the Technical University of Denmark (DTU) Lyngby Campus, which covers an area of roughly one square-kilometer and currently includes a building stock of nearly 530,000 m^2.

2. Materials and methods

Fig. 1 outlines how the MFA framework is coupled with the LCA framework to build the MFA-LCA model applied in this work. The approach follows the methodological framework of LCA (International Organization for Standardization, 2006) with the four main steps: (1) goal and scope definition, (2) inventory modeling, (3) impact assessment, and (4) interpretation. The second step, namely the inventory modeling, is adapted from the normally static LCA approach where all inputs (resources) and outputs (emissions) are simply compiled across the considered time frame (Finnveden et al., 2009), by using time-dependent flows linked to a geographical location to produce results, which can be differentiated both temporally and spatially. Section 2.1 describe the goal and scope definition and Section 2.2 detail the inventory modeling. Supporting Information I, Section 1.1 and 1.2, provide further details on the modeling approach.

2.1. Goal and scope definition

As described in Section 1, the object of the assessment is the building stock at a university campus over a period of 27 years (2023 to 2050). The functional unit (FU) was defined as the *"operation, maintenance and renovation of the existing building stock and new construction of 157,000 additional square meters of building area on the DTU Lyngby Campus from*

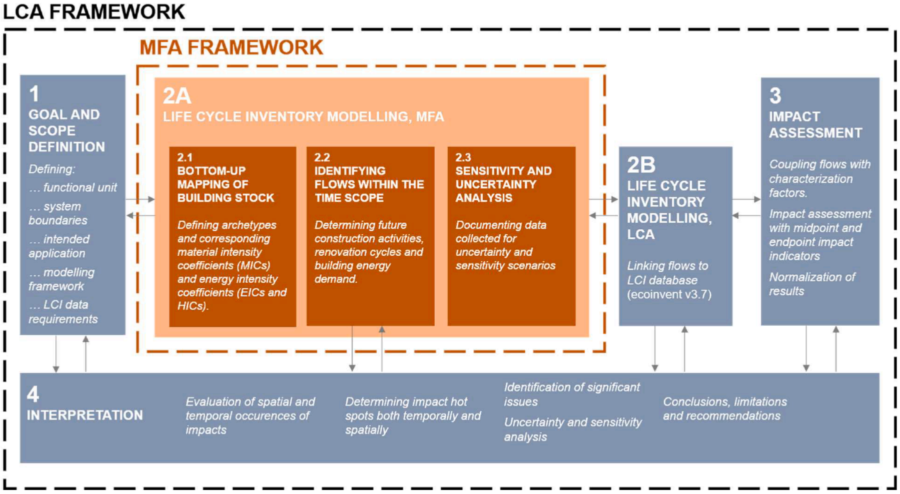


Fig. 1. Outline of the methodological approach applied. Material flow analysis (MFA) is applied in the life cycle inventory (LCI) step of the life cycle assessment (LCA) methodology. The MFA framework allows a temporal and spatial differentiation of the process flows, hence creating a temporally and spatially dynamic life cycle inventory.

2023 to 2050″. In 2023, the building stock at DTU Lyngby campus covered nearly 530,000 m^2, and it is the ambition of the DTU administration to have expanded the building stock by 157,000 m^2 by 2050. Student and staff consumption of e.g. food, beverages, office supplies, and other goods are not included either. Finally, technical building installations, e.g. ventilation systems, heating systems, sewers or electrical wiring are excluded as well. Simplified system boundaries are shown in Fig. 2. The life cycle inventory (Step 2) was modeled with an attributional approach. The background system is modeled based on ecoinvent v3.7 (Wernet et al., 2016) using the cut-off system model. The processes from ecoinvent used to model the background system (see Table S3 in Supporting Information II), i.e. extraction of raw materials for building materials and the treatment of building waste, all represent an average European context. Technological developments in e.g. production and construction technologies occurring over the 27-year time scope are addressed in five sensitivity scenarios described in Section 2.2.3 and Supporting Information I, Section 1.3. The current projections for the national heat and electricity grid mixes in Denmark are modeled c.f. the description given in Supporting Information I, Section 1.2. The modelled mix can be found in Table S4 in Supporting Information II. The impact assessment in Step 3 is done with LCIA methodology ReCiPe 2016 v1.1 (Huijbregts et al., 2017) at both midpoint and endpoint, as well as normalized against a global average person-equivalent (PE) in 2010. In Step 4, the results are presented and discussed, including an investigation of whether impacts are decoupled from the growth of the campus. Furthermore, Step 4 presents the conclusions, recommendations, and limitations of the study.

2.2. *Inventory modeling*

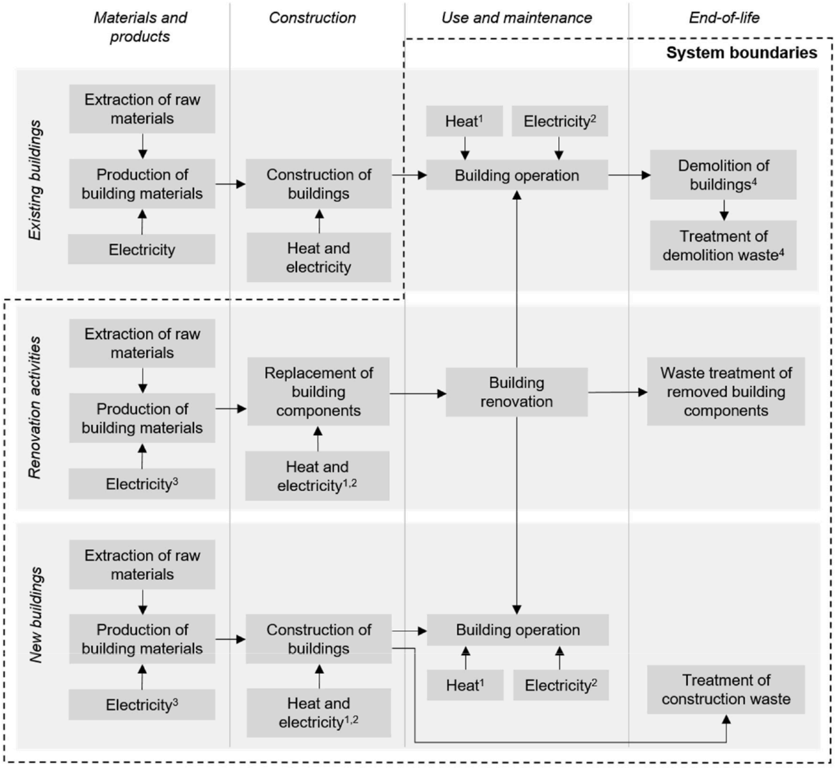
As illustrated in Fig. 1 the next step is to apply the MFA approach and construct dynamic inventories, starting with a bottom-up mapping of the existing building stock, followed by an identification of the flows modelled as dynamic and occurring within the time scope.

2.2.1. *Bottom-up mapping of the existing building stock*

To build a dynamic inventory that can be integrated with the LCA framework, the material stock already existing within the system boundaries is mapped. Mapping provides an overview of material hot spots, i.e. geographical locations where potentially recyclable resources are abundant. A common approach to mapping building stocks in MFA is by assigning each individual building to an archetype representing key characteristics of a group of buildings (Mastrucci et al., 2017). This approach has previously been demonstrated by e.g. Lanau and Liu (2020) and Li et al. (2022), who defined material intensity coefficients (MICs) for 30 building archetypes covering the entire building stock in the municipality of Odense in Denmark. Details on the how the mapping and archetype definition was done can be found in Supporting Information I, Section 1.2. Table 1 provides an overview of the archetypes defined. A MIC for each of the archetypes was defined and the average electricity and heat consumption for each archetype was defined as the electricity intensity coefficient (EIC) and heat intensity coefficient (HIC). A detailed description of how this was done can be found in Supporting Information I, Section 1.2. The MIC are reported for each archetype in Supporting Information II, Table S1.

2.2.2. *Modeling of static and dynamic flows within time scope*

In the inventory modeling, some flows are modelled as static, while others are modelled as temporally dynamic. Flows modelled as static include the operational electricity and heat consumption, the outside climatic conditions, building and material service lives, as well as technological advancements in material production and waste treatment. The flows modelled as dynamic include the growth in the building stock, the electricity and heat grid mix, construction waste, and the



[1]Provided by the Danish average heat mix in year n (n = 2023…2050)
[2]Provided by the Danish average electricity mix in year n
[3]Only relevant in Scenario 1 (see Section 2.2.3). Provided by the European average electricity mix in year n.
[4]Only relevant in Scenario 4

Fig. 2. System boundaries of the assessed system.

Table 1
Building attributes used to define the 11 building archetypes used in the current study, as well as the area, service life and EIC and HIC of each archetype.

Construction year[b]	Main structural material[a,b]	End-use[b]	Windows share[c] [%]	Archetype	Total area, 2023 [m^2]	Service life[d] [years]	Electricity intensity coefficient[e] [kWh/m^2]	Heat intensity coefficient[e] [kWh/m^2]
Before 2000	Concrete	Recreational	10–50	1	48 813	100	51.1	111.0
	Bricks	Research activities	0	2	13 480	80	133.2	112.9
			10–50	3	196 166	80	81.1	138.0
			51–80	4	19 077	80	71.6	122.3
		Education	10–50	5	32 879	100	96.6	109.4
			51–80	6	44 256	100	48.0	125.4
After 2000	Concrete	Residential	10–50	7	14 281	120	40.8	133.5
	Steel	Research activities	0	8	3 290	80	177.4	144.3
			10–50	9	65 194	80	114.3	100.1
		Education	51–80	10	36 811	100	90.9	87.4
	Wood	Residential and research activities	20–80	11	18 536	80	114.4	56.2

[a] All buildings have a concrete foundation and ground slab. Differences in the main structural material therefore refer to beams, columns, exterior load bearing walls, and slabs.

[b] No buildings built before 2000 with wood or steel as the main structural material and therefore this category does not exist in the table. Similarly, no buildings with a dedicated recreational end-use has been built since 2000 and therefore this category does not exist either.

[c] Calculated as the area of the windows divided by the surface area of the exterior walls (excluding wall area below ground).

[d] Assigned based on end-use from Haugbølle et al. (2021).

[e] Measured data from meters on-site at DTU Lyngby Campus, average of the buildings in the archetype.

energy consumed during construction (the latter two are modelled as static in the business-as-usual (BAU) scenario, see more details in 2.2.3). The flows relevant to fulfilling the functional unit can be grouped into materials and construction activities, renovation and demolition activities, and building operations. The modelled flows associated with each of these activities are described briefly in the next section, with further details in Supporting Information I, Section 1.2.

According to the DTU campus development strategy, the student and staff population is projected to increase by 2 % annually (DTU, 2022) and as mentioned in Section 2.1, the university administration's official plan for campus development entails an increase in the building stock by 157,000 m^2 from 2023 to 2050 (DTU, 2022). The growth in building stock is modelled as a function of the growth in population. The population in 2050 is determined based on the population in 2023 and the annual population increase of 2 %, cf. Eq. (1). From this, the building area added per new user is found and assumed to be constant from 2023 to 2050 (Eq. (2)). Therefore, the building area added in year, *i*, can be found from Eq. (3).

$$P_{T,i} = P_{T,2017} * 1.02^{i-2017} \tag{1}$$

$$A_{NP} = \frac{A_N}{P_N}, \; P_N = P_{T,2050} - P_{T,2023} \tag{2}$$

$$A_{N,i} = \left(P_{T,i} - P_{T,2023}\right) * \frac{A_N}{P_N} \tag{3}$$

Where:
$P_{T,i}$ is the total population in year $i = 2023\ldots2050$
$P_{T,2017}$ is the total population in 2017 (17,200 persons)
A_{NP} is the needed area per new user
A_N is the total area added from 2023 to 2050 (157,000 m^2)
P_N is the total new population added from 2023 to 2050
$A_{N,i}$ is the cumulated area added in year $i = 2023\ldots2050$

All new square meters were modelled as Archetype 10 and 11, and the new buildings were therefore modelled with the EIC of Archetype 10 and 11. The flows associated with the materials and construction activities cover the production of building materials needed to expand the building stock every year as determined by Eq. (3), including an additional 10 % of all building materials, added to account for construction waste (Danish Center for Energy Savings in Buildings, 2020). Heat and electricity consumption during the construction processes is covered here, as well as the treatment of construction waste. The renovation and demolition activities are modelled as 40-year cycles following a normal probability distribution function with 99 % of the renovations occurring within a 35 to 45 year period. Renovation cycles were modelled to follow 40-year cycles as the majority of the building materials replaced in a renovation have a service life of 40 years in a Danish context according to Haugbølle et al. (2021). The 40-year cycle for a given building starts from its year of construction. The effect of possible energy renovations that may lower the operational energy consumption is not investigated in this work, as this perspective is covered extensively in other literature (Brown et al., 2014; Mastrucci et al., 2020; Nemry et al., 2010; Pauliuk et al., 2013; Wang et al., 2015; Zhang et al., 2021). Production of new building materials added and treatment of old materials removed is considered. Demolition of the buildings is assumed to be unlikely given the architectural heritage value of the oldest buildings, and the fact that the younger buildings without any such value will only reach an age of 60 years within the time scope considered. According to Haugbølle et al. (2021), buildings used for offices, education and housing are estimated to have a life span of 80 to 120 years, thus exceeding the time scope. The electricity and heat grid mix that cover the operational electricity and heat demand were modelled following the projected year-by-year development of electricity and heat mix in Denmark (Danish Energy Agency, 2022).

2.2.3. *Sources of uncertainties and scenario definition*

Given the prospective nature of the assessment, several assumptions in the modeling of the future are potentially critical to the resulting environmental impact potential. Five major assumptions in the prospective modeling were deemed particularly uncertain and were therefore isolated and evaluated individually in five scenarios, to investigate their effect on the conclusions obtained. Following the logic of Heijungs (1996), particular interest should be paid to parameters that are both highly uncertain and which contributes markedly to the results. The five parameters and corresponding scenarios are not an exhaustive list of parameters that can be considered uncertain, but these were deemed to be the five most uncertain in this particular study. Further details on the uncertainties that motivate each scenario are provided in Supporting Information I, Section 1.3. Table 2 provide an overview of each scenario. Uncertainties in the background processes were investigated through a Monte Carlo simulation with 1000 iterations. A lognormal distribution was assumed for all processes. The 95 % confidence interval are reported for all results in Supporting Information II, Tables S8–S11.

Table 2

Overview of the business-as-usual scenario and the five scenarios investigated.

	Construction waste[a]	Construction energy[b]	Building demolition[c]	Direct energy decarb.	Indirect energy decarb.
Business-as-usual (BAU)	10 %	Heat: 0.24 kWh/m^2 Electricity: 13.5 kWh/m^2	No demolitions	2023–2035, constant post-2035[d]	No decarb.
Scenario 1: Assumed that the majority of the building materials are produced within Europe, and as fossil fuels are planned to be removed from the electricity grid mix across Europe (European Commission, 2021), affecting impacts associated with material production. Only investigated for global warming potential as a proof of concept, but could be expanded to other impact categories, e.g. by using the PREMISE tool (Sacchi et al., 2022).	BAU	BAU	BAU	BAU	From 2023–2030, constant post-2030
Scenario 2: Due to lack of data on the actual amount of materials lost during construction of buildings, the current best estimate was used. Future technological advancements may reduce this, and the modelled construction waste therefore follows a year-by-year decrease to reach a total decrease of 25 % from 2023 to 2050.	2023 … 2050 = 10%…7.5 %	BAU	BAU	BAU	BAU
Scenario 3: Measured data from a Danish construction site in 2021 was used. This estimate could potentially be reduced in the future due to technological advancements. Therefore, the energy consumed during the construction phase follows a year-by-year decrease to reach a total decrease of 25 % from 2023 to 2050.	BAU	2023 … 2050 *Heat:* 0.24 … 0.18 kWh/m^2 Electricity: 13.5 … 10.1 kWh/m^2	BAU	BAU	BAU
Scenario 4: The likelihood of demolitions may be challenged, and demolition is modelled for the buildings used for research activities despite their architectural heritage value. These buildings are replaced by new buildings modelled as A10 and 11.	BAU	BAU	Demolition included for A2, A3, A4, A8, A9	BAU	BAU
Scenario 5: Current available projections (as of March 2023) for the Danish heat and electricity grid mix does not go beyond 2035, but fossil fuels are expected to be completely phased out by 2050. Therefore, the remaining fossil fuels in the 2035 mix are replaced by wind turbines, photovoltaics, biomass and heat pumps.	BAU	BAU	BAU	Decarb. from 2023 to 2050	BAU

[a] Danish Center for Energy Savings in Buildings (2020).

[b] Measured data from another construction site in Denmark in 2021.

[c] Haugbølle et al. (2021).

[d] Official projections from the Danish Energy Agency does not go beyond 2035.

3. Results and discussion

In the following sections we present the results obtained with the MFA-LCA model, discuss interpretations and conclusions based on the findings, and present the most important limitations of the work. Finally, a set of recommendations is provided based on the obtained results.

3.1. *Spatially differentiated inventory and impact assessment results*

Fig. 3A-E illustrate the spatially differentiated life cycle inventory focusing on the building stock in the neighborhood in 2023. It is not known specifically where future buildings (built between 2023 and 2050) will be located, and it is therefore not possible to generate Fig. 3A-E for a later decade. Fig. 3F-H show the accumulated climate change impact per square meter in 2030, 2040 and 2050.

Considering both Fig. 3C and E, the buildings with very little insulation per square meter (less than 3 kg/m^2) tend to have a higher heating demand. However, Fig. 3F-H do not indicate that the buildings with the highest heating demand (as per Fig. 3E) will be notable impact hotspots in 2030, 2040 or 2050. Considering both Fig. 3D and F-H suggests that the buildings that are impact hotspots are the buildings that have a high electricity consumption per square meter. However, the heating impacts of the entire building stock may still contribute more to the total impact than the electricity consumption, but Fig. 3 suggests that a few buildings are main contributors to the total electricity impact. This insight could allow decision makers to target these specific buildings and investigate if their electricity consumption can be reduced without compromising the use of the building. To reduce the overall impact of the building stock, it may still be a practical solution to reduce heating demand. An approach could be to identify the buildings with a high heating demand and insufficient insulation, and initiate targeted energy renovations.

Fig. 3A-C provide insight into the material stocks on-site. In total, there are nearly 69,000 tons bricks and more than 280,000 tons concrete stocked within the campus boundaries. The new buildings planned to be built between 2023 and 2050 will increase the size of the new material stocks within the case study area. Section 3.2 demonstrates that there will be substantial potential impacts linked to the production of the virgin materials needed to expand the building stock as planned. One possible solution to reduce future emissions from virgin material production could be to ensure that new buildings are designed for disassembly (Eberhardt et al., 2018), i.e. extracting and reusing components and materials in another context, if a building is demolished. For instance, Kakkos et al. (2020) found that a change in the Swiss construction practice to design-for-disassembly and material recovery could reduce the global warming potential of the Swiss building sector with 68–117 kt CO_2 eq. over a four-year period.

Having access to knowledge on the spatial distribution of resources and energy consumption, allows decision-makers to develop targeted strategies and prioritize hot spots, which can help ensure that time and resources are spent efficiently. Fig. 3A-C highlight that buildings are clusters of valuable resources that may end up as waste if no actions are taken to avoid this. The materials in existing buildings also represent significant amounts of environmental impacts that have already occurred. Buildings should be considered as valuable material stocks that can and should be utilized in the future. After preservation, the first

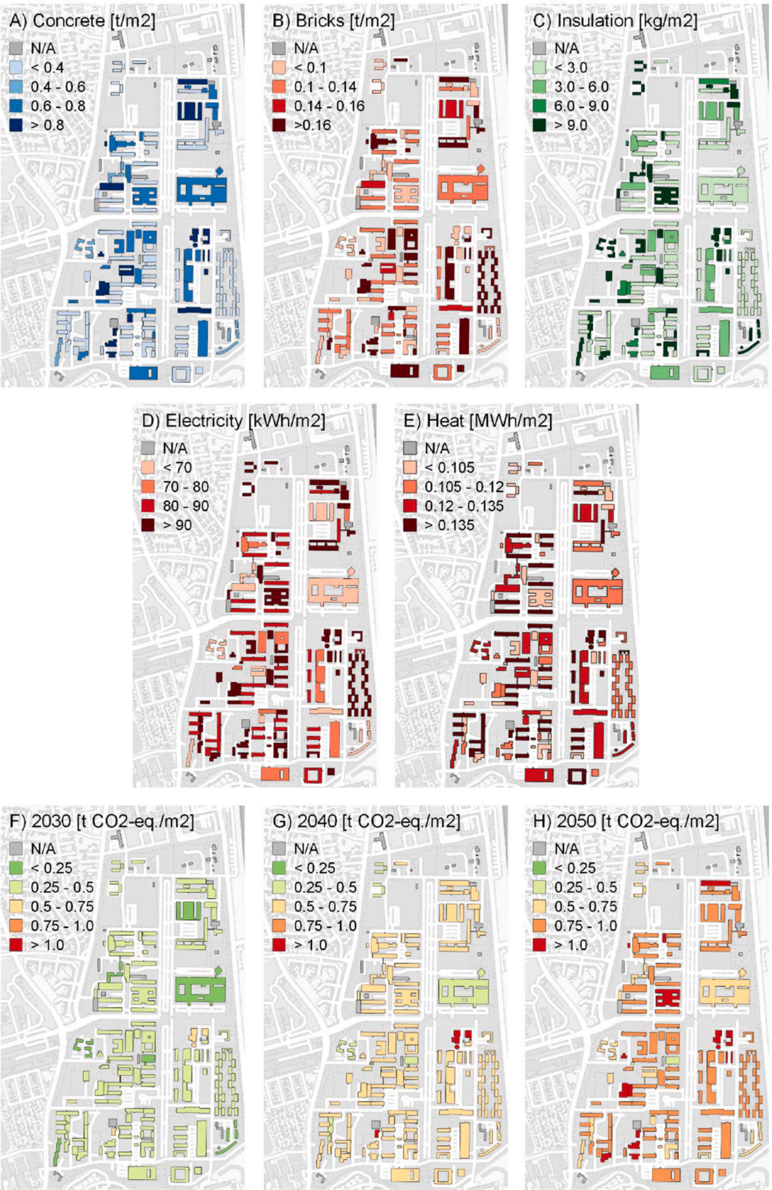


Fig. 3. Spatial mapping of material stocks, operational energy demand and climate change impacts. A-C provide information on the material content of the buildings (concrete, bricks and insulation), D-E illustrate the electricity and heat consumption of the buildings, and F-H show accumulated climate change impact in 2030, 2040 and 2050 in t CO_2-eq. per square meter.

priority should be to reuse components directly as they are – this could for instance apply to structural elements such as beams and columns, if they can still deliver the same structural abilities and comply with building regulations. The second priority should be to recycle materials, and the final option should be to 'downcycle' materials, e.g. crushed structural concrete serving as a road filler at end-of-life.

3.2. Evolution of environmental impacts over time

Fig. 4A-D show the environmental impact of the entire neighborhood area over time on three main areas of protection, namely damage to ecosystems, damage to human health and damage to resource availability in the BAU scenario. Fig. 4A shows the life cycle contribution to ecosystem damage (available for human health and resource availability in Supporting Information II, Table S9), and Fig. 4B-D show the impact contribution to endpoint damage.

3.2.1. Overall temporal trends

The overall reduction in the campus' impact from 2023 to 2050 is minor, due to the increasing impact from building renovations and construction of new buildings. For damage on ecosystems and resource availability, the overall impact decreases by 2.5 % and 1.5 %, respectively. For human health damage, the impact increases by 13.5 %, primarily driven by the increase in human carcinogenic toxicity and human non-carcinogenic toxicity (see Section 3.2.4). Fig. 4A shows that the total ecosystem damage decreases from 2023 to 2035 due to the decarbonization of the electricity grid mix, but the steady addition of new buildings as well as a wave of renovations occurring post-2040 cause the overall impact to increase from 2040 to 2050.

Fig. 4A shows that neither the end-of-life stage for material waste and materials disposed of in renovations nor the energy usage during construction has a notable impact on ecosystem damage. The former contributes with less than 1 % across the considered time scope, while the latter contribute with less than 0.01 %.

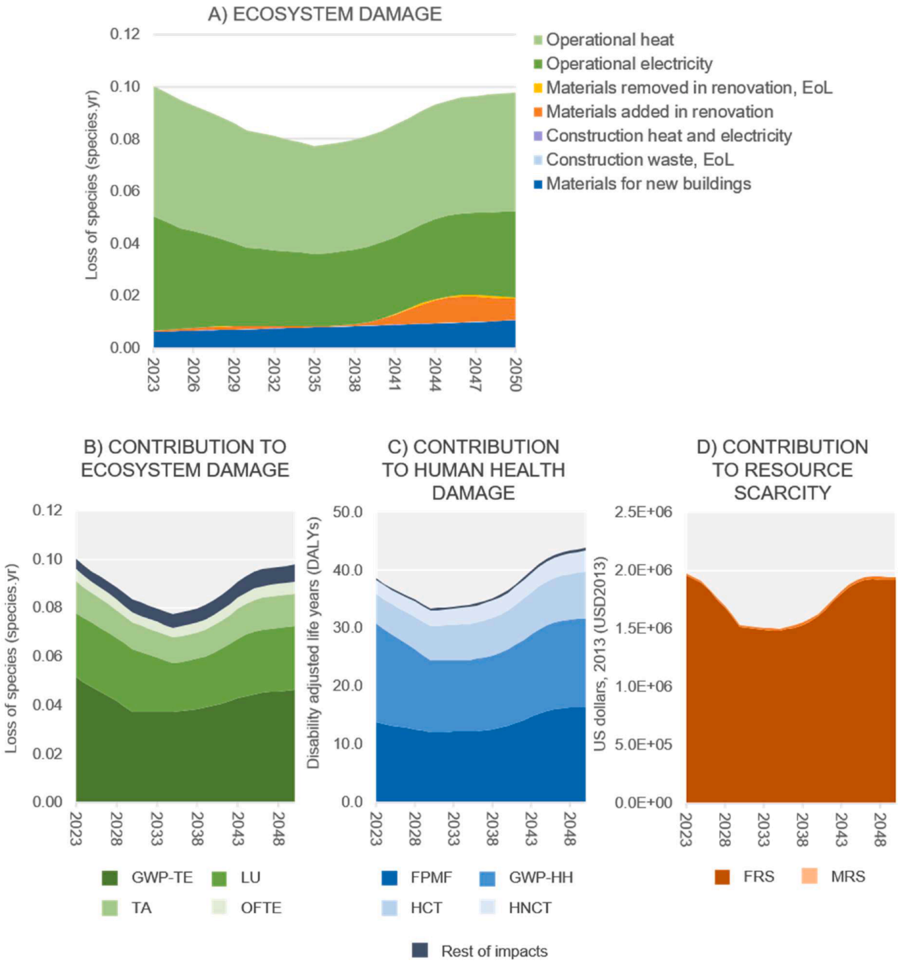


Fig. 4. Impact results at endpoint aggregated into the area-of-protection 'ecosystem damage' (Figure A), with the impact contribution differentiated across life cycle stages. Figures B, C and D show the contribution of the endpoint categories to each area-of-protection. GWP-TE = Global warming potential, terrestrial ecotoxicity, LU = Land use, TA = Terrestrial acidification, OFTE = Ozone formation, terrestrial ecotoxicity, FPMF = Fine particulate matter formation, GWP-HH = Global warming potential, human health, HCT = Human carcinogenic toxicity, HNCT = Human non-carcinogenic toxicity, FRS = Fossil resource scarcity, MRS = mineral resource scarcity.

3.2.2. *Consequences of growth in building stock*

Reflecting the modelled annual increase in the building stock, the impact due to production of building materials and components are steadily increasing. In 2023, the impacts embodied in new building materials were 6.2 %, 10.2 % and 10.2 % of the total emissions for damage on ecosystems, human health and resource availability, respectively, increasing to 10.8 %, 15.3 % and 15.3 % in 2050. This indicates that impacts embodied in material production will be of increasing relevance in the future.

It should be noted that the growth in building stock has been modelled as constant over time rather than concentrated occurrences a specific point in time. This modeling choice was made due to a lack of knowledge on when specific buildings will be added to the building stock in the future. This does, however, have an important effect on the temporality of impacts, as the actual environmental impacts will likely not occur as a steady increase over time, but rather as a pulse, when a new building is added to the building stock. Access to more detailed information on the planned building activities would improve the temporal differentiation of impacts even further and thus allow even more detailed analysis of temporal hotspots.

To reduce impacts associated with production of virgin materials, reused building materials and components can potentially replace impact-heavy materials such as concrete, steel and mineral wool insulation. Additionally, buildings are often demolished before the end of their service life, which could be overcome with a – typically less impacting – refurbishment. Other strategies could be to adapt the building layout to accommodate more users, e.g. by reducing hallway areas, and using building materials efficiently, i.e. avoiding excessive use of impact-heavy structural materials (e.g. steel and concrete) by optimizing the structural design (Arup and C40, 2019).

The impact of renovations increases dramatically after 2040 where the large pool of buildings built in the 1960s and early 1970s (more than 300,000 m^2s) reach their second renovation cycle (the first having occurred in 2000–2010). With the steady addition of new buildings, the environmental impacts associated with renovations will be of increasing importance. It should, however, be noted, that the renovations may aid in avoiding unnecessary demolitions, which would ultimately lead to higher environmental impacts (see Section 3.3).

3.2.3. *Effects of national decarbonization on "Ecosystem damage"*

The expected decarbonization of the electricity and heat mix leads to a reduction in damage on ecosystems by 24.5 % and 27.5 %, respectively, from 2023 to 2035. However, as the building stock grows post-2035 and no further decarbonization is modelled in the BAU scenario, the impact of the operational electricity consumption increases 18.6 % from 2035 to 2050, resulting in a net decrease in the impact from operational electricity consumption of 10.4 % from 2023 to 2050. For operational heat, the net decrease from 2023 to 2050 is 20.3 %.

This demonstrates that while environmental benefits associated with a technological development in renewable electricity sources are achieved across impact categories, the full benefits are to some extent counteracted by the steady increase in building demand. This suggests that the campus administration will potentially need to consider more active means or mitigation strategies to ensure that their environmental impact will not dramatically increase, if they expect to maintain a steady growth in users and building stock. It is likely that decarbonization will continue post-2035 (discussed in Section 3.3), but at some point, no further decarbonization can be done and if the building stock is still growing, the total impact will increase.

3.2.4. *Contribution to endpoint damages*

Fig. 4B-D show that a few impact categories are responsible for the greatest share (>95 %) of the endpoint damage. Fig. 4B shows that particularly global warming effects on terrestrial ecosystems (GWP-TE) drives the decrease in damage on ecosystems from 2023 to 2035. LU decreases a bit, however, the remaining impact categories (hereunder freshwater, marine and terrestrial ecotoxicity) increase marginally from 2023 to 2035, but the substantial decrease in GWP-TE outweighs this.

For human health damage (Fig. 4C), the decrease in global warming effects on human health (GWP-HH) deliver almost the entire decrease in human health damage from 2023 to 2030. The impact on human carcinogenic and non-carcinogenic toxicity (HCT and HNCT) increase steadily from 2023 to 2050, caused by the production of building materials.

This highlights that some impact categories are essential to reduce endpoint damage. Strategies delivering reductions on global warming potential, land use and fine particulate matter formation should be prioritized. However, it is essential that other impact categories are still monitored to ensure that the environmental burden is not shifted across environmental impact categories.

3.3. *Scenario analysis and decoupling impact from growth*

In Fig. 5, the total impact per capita in 2050 is normalized against the impact of a global average person in 2010. Finally, Fig. 5 also shows how each of the scenarios compare to the BAU-scenario. Fig. 6 shows the development from 2023 to 2050 across 18 impact categories at midpoint level relative to the growth in user population.

3.3.1. *Comparing impact trends across scenarios*

Fig. 5E shows that the global warming potential is not reduced markedly in Scenario 1 compared to the BAU scenario, thus indicating

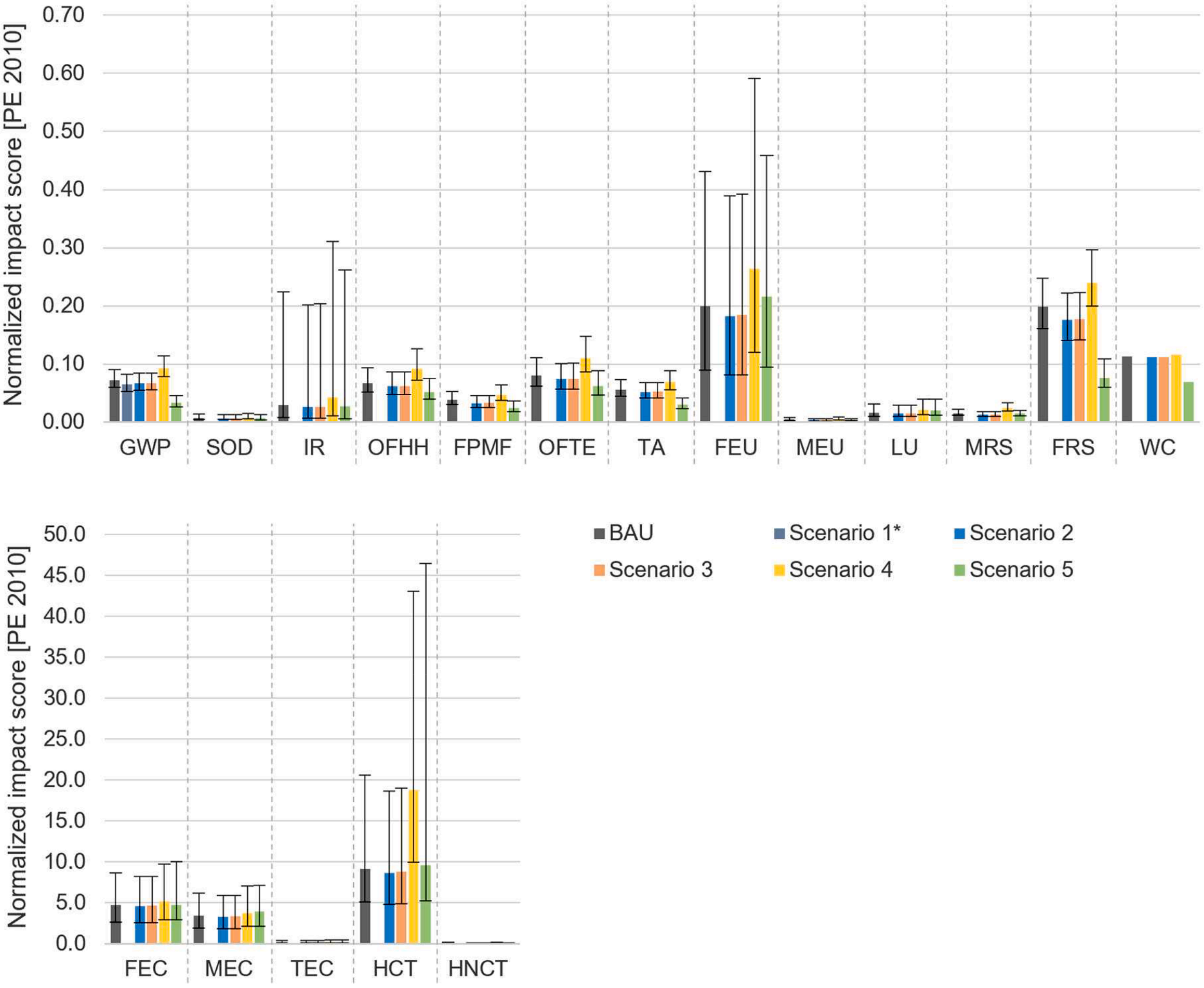


Fig. 5. Total per capita impact in 2050 externally normalized against the impact of a global average person in 2010 for the business-as-usual scenario (BAU) and the five sensitivity scenarios. Toxicity impacts are presented separately from the other impacts, as the normalized impact results for these are uncertain, and considered to be potentially largely overestimated (Laurent and Hauschild, 2015). The error bars indicate the 95 % confidence interval for the results. The * indicate that the results in scenario 1 are only calculated for GWP, for all other impact categories the result is not available. FEC = Freshwater ecotoxicity, FEU = Freshwater eutrophication, FPMF = Fine particulate matter formation, FRS = Fossil resource scarcity, GWP = Global warming potential, HCT = Human carcinogenic toxicity, HNCT = Human non-carcinogenic toxicity, IR = Ionizing radiation, LU = Land use, MEC = Marine ecotoxicity, MEU = Marine eutrophication, MRS = Mineral resource scarcity, OFHH = Ozone formation (human health), OFTE = Ozone formation (terrestrial), SOD = Stratospheric ozone depletion, TA = Terrestrial acidification, TEC = Terrestrial ecotoxicity, WC = Water consumption.

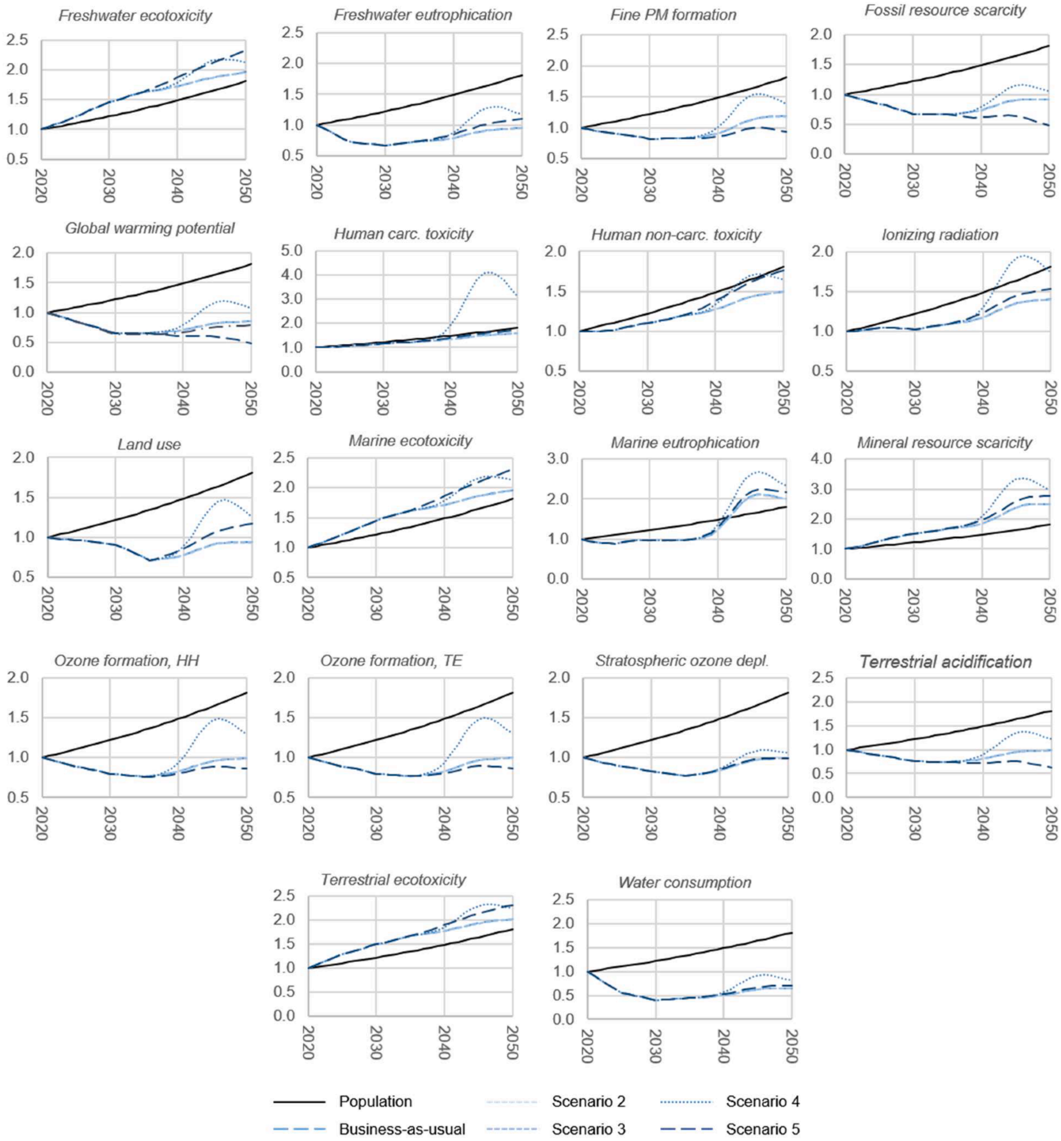


Fig. 6. Development in impacts at midpoint compared to development in user population for impacts at midpoint. If the growth in impact intensity is less than the growth of the user population, there is a trend of relative decoupling. If the impact intensity is declining, while the user population is growing, there is a trend of absolute decoupling. If the growth in impact intensity is more than the growth of the user population, there is no decoupling.

that the projected European decarbonization of electricity production will have minor effects on the overall impacts of building stocks. However, the potential of the expected decarbonization is only modelled from 2023 to 2030, and if the decarbonization continues post-2030, greater reductions will potentially be achieved. The reductions in waste generation and energy consumption during construction (Scenario 2 and 3) lead to minor changes from the BAU scenario for all impact categories.

The impact increases for all impact categories in Scenario 4, peaking in 2045 when the number of potential building demolitions peak. This indicates that demolishing existing buildings and replacing them with new buildings are not preferable from an environmental perspective. Although the newer archetypes (10 and 11), assumed to be replacing the demolished buildings, have lower operational heating consumption, this environmental benefit is outweighed by the environmental impact embodied in the new materials needed to replace the demolished buildings.

Considering Scenario 5, the divergence from the BAU scenario varies from a reduction of 0.2 to 48 %, and an increase of 7.7 to 25.0 %. The impact is lower in Scenario 5 for 11 impact categories, e.g. fine particulate matter formation and global warming potential. The decrease in Scenario 5, is due to the removal of fossil fuels from the electricity and heat grid mix post-2035, i.e. a reduction in emissions of greenhouse gasses (CO_2, CH_4, N_2O) contributing to global warming potential, and $PM_{2.5}$ contributing to fine particulate matter formation. For the remaining seven impact categories, the impact is higher in Scenario 5 than in the BAU scenario. This is most pronounced for land use, where the impact is 25.0 % higher in Scenario 5, due to the increased share of heat produced from biomass incineration, which in Scenario 5 is modelled to account for more than a third of the heat production in 2050.

3.3.2. Normalization of impacts

For the majority of the impact categories the life cycle impacts correspond to less than 10 % of the total annual average impacts of a global citizen in the year 2010. Exceptions include freshwater eutrophication, fossil resource scarcity, freshwater, marine and terrestrial ecotoxicity, and human carcinogenic toxicity. For freshwater eutrophication, the majority of the impacts are caused by long-term emissions related to mine tailings, which are not considered in the used normalization references and therefore the impacts will appear to be considerable compared to the global citizen reference (for freshwater eutrophication more than 25 % in all scenarios). For the toxicity-related impact categories (freshwater eutrophication, marine and terrestrial ecotoxicity, and human carcinogenic toxicity), the large observed impacts may appear as the impact assessment of the toxicity-categories considers long-term emissions, while the normalization references do not. Additionally, the toxicity normalization references may be linked to uncertainty issues that will lead to overestimated normalized results for the toxicity impact categories (Laurent et al., 2011, Heijungs et al., 2007).

The impact of both stratospheric ozone depletion, marine eutrophication and mineral resource scarcity are less than 2 % of the total annual average impacts of a global citizen in the year 2010, highlighting that although the impact of e.g. mineral resource scarcity increase by more than 100 % from 2023 to 2050, the actual size of the impact is in fact minor in a larger societal context. This is also observed for land use. However, the expected decarbonization until 2050 (Scenario 5) increases the impact by 25 % compared to the BAU scenario, the normalized score is just increased from 2.1 % to 2.7 % of a global average citizen's annual impact in 2010. The values in Fig. 5 indicate that global warming potential, fossil resource scarcity, ozone formation (human health and terrestrial ecotoxicity), represent the most dramatic impacts compared to a global average person's annual impact in 2010 (excluding impact categories with the previously described normalization uncertainties). For all of these categories, Scenario 5 represents a decrease in impact compared to the BAU scenario (13 %–48 % decrease).

3.3.4. *Decoupling impacts from growth*

As described in Section 2.2.2, the building stock is planned to grow to meet the needs of a growing user population. In this study, the growth in 18 different impacts at midpoint is related to user population growth. If there is a separation between the temporal development in one parameter (impact) from the other parameter (population), this can be referred to as 'decoupling'. In the following, we differ between three types of decoupling: (1) no decoupling, where impact grow to the same extent or faster than population, (2) relative decoupling, where the growth in impact is lower than the growth in population, and (3) absolute decoupling, where impact are steady or declining while the population grows. In Fig. 6, the BAU scenario and the five additional scenarios are compared to the growth in user population.

For half of the impact categories, e.g. fossil resource scarcity and stratospheric ozone depletion, the development in all scenarios from 2023 to 2035 follows a trend of absolute decoupling. The remaining half either follow a trend of no decoupling, e.g. marine ecotoxicity, or relative decoupling, e.g. marine eutrophication. This represents the influence of the expected decarbonization discussed in Section 3.2.3.

The scenarios start to divert from each other post-2035 when the renovations and, in scenario 4, demolitions start occurring. In the BAU scenario the development either follows a relative decoupling, e.g. global warming potential, or shows no decoupling, e.g. fine particulate matter formation. If the impacts associated with material production are a hotspot for a given impact category, the renovations occurring post-2035 will lead to no decoupling occurring for this impact category. If material production are not an impact hotspot, the BAU scenario will follow a trend of relative decoupling post-2035. In Scenario 2 and 3, the majority of impact categories follow a trend of relative decoupling.

Scenario 4 amplifies the impacts associated with renovating buildings in the BAU scenario, by demolishing and rebuilding some of the existing buildings instead of renovating them. Scenario 4 shows a wave of impacts occurring because of the demolitions, peaking in 2047 followed by a decline until 2050. Seven impact categories show a trend of absolute decoupling from 2023 to 2050 in Scenario 5. Notably, for these impact categories, the reductions linked to the decarbonization of the electricity and heat production outweigh the increase in impacts associated with the renovations.

Fig. 6 and the results discussed in Section 3.2 indicate that it may be necessary to address the growth in the building stock to ensure that impacts are effectively decoupled from growth. While the area-to-user-ratio is already expected to decrease from 2023 to 2050 given the official plans of the campus administration, it may be necessary to reduce this ratio even further. Avoiding construction of new buildings and reducing operational energy in the existing building stock could potentially be the most efficient way of reducing impact across all impact categories. Reducing consumption (e.g. of building materials and energy) rather than relying only on technological improvements – which can be linked to rebound effects that lead to little or no actual impact reductions – is increasingly considered a necessary step towards a sustainable development (IPCC Working Group III, 2022).

In this work, some of the uncertainties linked to future technological developments are addressed in the five scenarios investigated. For most of the parameters investigated, the conclusion is that the model, the results and the conclusions drawn hereof are not very sensitive to changes in these parameters, and thus the unavoidable uncertainties in assessments of future conditions linked to these parameters are considered acceptable. The aim was to model the surrounding society (with the technologies and resources available at a given time) as accurately as needed, but as simple as possible. Future work could expand how the surrounding society (i.e. background system) is modelled over time.

For the flows modelled as static, described in Section 2.2.2, e.g. operational heat and electricity consumption, it was deemed too speculative to make assumptions about how future building users will behave and how technologies may improve in the coming decades. Su et al. (2021) highlight that there is a methodological need for formal cut-off criteria to determine when flows should be modelled as dynamic, i.e. based on contribution to total impact, to ensure consistency between dynamic LCAs on buildings.

Finally, a next step could be to consider the results obtained in this study in an absolute perspective, i.e. compare the environmental pressure of the considered building stock to the carrying capacity of the Earth systems. Based on this it would be possible to determine whether any environmental boundaries are exceeded, and which mitigation strategies have the potential to reduce impacts sufficiently. The model presented in this work could furthermore support future studies in evaluating specific mitigation strategies, e.g. material substitution or energy renovations.

When running the Monte Carlo simulations, the water consumption balance (withdrawals minus releases) in the background system is disturbed by the assigned random values and hence lead to negative impact values for water consumption, and therefore the uncertainty range for water consumption is not reported as the values are meaningless.

4. Conclusions and recommendations

This work demonstrates a prospective environmental impact assessment of a building stock using a coupled MFA and LCA model with temporally dynamic variables. The results highlight the effects of changes in both the internal and external systems that affects the environmental performance of buildings. The assessment expands the existing, and currently limited, focus on purely residential building stocks, and cover mixed building functions. The results thus provide valuable new insights on the performance of non-residential building stocks. The findings furthermore contribute to filling the existing knowledge gap on other impacts than global warming potential, currently the only type of impact covered in the majority of impact assessments of buildings and building stocks. Thereby, the results presented in this study reduces the risk of burden shifting as a full impact coverage is included.

In this work, the building stock at a university campus was chosen as the object of the case study. As this building stock is under one common administration, detailed data was available for both building material composition and energy consumption for a large share of the buildings. This improved the data representativeness markedly, and thus the quality of the results. Access to this type of data would likely not be possible for other types of building stocks, e.g. an urban neighborhood. Here, the model would have to rely on more generalized archetypes and this would potentially increase uncertainties and reduce model representativeness.

The study presents the annual impact across five scenarios, each in which one uncertain parameter is modified separately to evaluate the sensitivity of the conclusions obtained towards changes in these parameters. The findings suggest that only the parameters investigated in Scenario 4 and 5 have a pronounced effect on the conclusions. For the majority of the impact categories, potential building demolition (Scenario 4) has a notable effect on the impact scores between 2040 and 2050 compared to the business-as-usual scenario.

The results indicate that while the expected national decarbonization of electricity and heat supply will reduce overall damage on ecosystems from 2023 to 2035, the growth of the building stock and a wave of renovations occurring post-2040 will result in minor overall reductions from 2023 to 2050. This suggests that decision makers should not rely alone on the expected technological development in the surrounding society, but should consider other means that can reduce the impact of building stocks in the future. The findings suggest that for global warming potential, decarbonization post-2035 (Scenario 5) will ensure that impact on global warming potential continue to decrease until 2050. However, the results also reveal that decarbonization post-2035 will increase the impact on other categories, e.g. land use.

While focusing on just one impact category, e.g. global warming potential, increases the risk of burden shifting, the results presented in this work suggest that some may be more important to include than others. Based on the results presented in Sections 3.2–3.4, it is recommended to prioritize global warming potential, fine particulate matter formation, human carcinogenic toxicity, and land use in assessments of building stocks and potentially including water consumptions and marine eutrophication.

The results presented in this study allow a tracking of emissions across space and time. This temporal differentiation in the occurrence of the impacts allows decision makers to better understand their goal. If the timeliness of the emissions was not considered and a comparison between impacts in 2020 and 2050 was made, the results would appear satisfactory – the impact has been reduced. However, one would overlook that the impacts are in fact on an increasing pathway, which may be unsustainable. Decreasing the growth in user population in this particular neighborhood is not a realistic nor practical solution, as this would merely shift the impact from one location to another, as the user will find somewhere else to meet their need. However, if the environmental impacts of the neighborhood increase faster than its population grows, as is e.g. seen for marine ecotoxicity in Section 3.3.4, the neighborhood will eventually reach an unsustainable level of impact – if not already reached. An absolute decoupling appears realistic for certain impact categories (global warming potential, fossil resource scarcity and fine particulate matter formation) which benefit from the decarbonization of the energy system. However, if the growth in user population continues, the resulting total impact will increase, thus calling for further action to ensure a continuous absolute decoupling.

CRediT authorship contribution statement

Pernille K. Ohms: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Lise Hvid Horup:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – review & editing. **Srinivasa Raghavendra Bhuvan Gummidi:** Conceptualization, Writing – review & editing, Supervision. **Morten Ryberg:** Conceptualization, Writing – review & editing, Supervision. **Alexis Laurent:** Writing – review & editing, Supervision. **Gang Liu:** Conceptualization, Writing – review & editing, Supervision.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2023.107340.

References

Anand, C.K., Amor, B., 2017. Recent developments, future challenges and new research directions in LCA of buildings: a critical review. Renew. Sustain. Energy Rev. 67, 408–416. https://doi.org/10.1016/J.RSER.2016.09.058.

Arup, & C40. (2019). *Building and infrastructure consumption emissions*. 27. https://c40-production-images.s3.amazonaws.com/other_uploads/images/2390_BIC_Report_FINAL.original.pdf?1570401598.

Augiseau, V., Barles, S., 2017. Studying construction materials flows and stock: a review. Resour. Conserv. Recycl. 123, 153–164. https://doi.org/10.1016/j.resconrec.2016.09.002.

Bahramian, M., Yetilmezsoy, K., 2020. Life cycle assessment of the building industry: an overview of two decades of research (1995-2018). Energy Build. 219, 109917 https://doi.org/10.1016/j.enbuild.2020.109917.

Brown, N.W.O., Olsson, S., Malmqvist, T., 2014. Embodied greenhouse gas emissions from refurbishment of residential building stock to achieve a 50% operational energy reduction. Build. Environ. 79, 46–56. https://doi.org/10.1016/j.buildenv.2014.04.018.

Brunner, P.H., Rechberger, H., 2004. Material Flow Analysis. CRC Press.

Danish Center for Energy Savings in Buildings. (2020). *Guide om ressourceanvendelse på byggepladsen*.

Danish Energy Agency. (2022). *Klimastatus Og -fremskrivning 2022*. http://www.ens.dk.

DTU. (2022). *Strategic campus plan*. https://campusudvikling.dtu.dk/vision-strategi/lyngby-campus.

Eberhardt, L.C.M., Birgisdóttir, H., & Birkved, M. (2018). *Life cycle assessment of a Danish office building designed for disassembly*. 10.1080/09613218.2018.1517458.

European Commission. (2021). *"Fit For 55": delivering the EU's 2030 climate target on the way to climate neutrality*.

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in Life Cycle Assessment. J. Environ. Manage. 91 (1), 1–21. https://doi.org/10.1016/J.JENVMAN.2009.06.018.

Goldstein, B., Birkved, M., Quitzau, M.-B., Hauschild, M., 2013. Quantification of urban metabolism through coupling with the life cycle assessment framework: concept development and case study. Environ. Res. Lett. 8.

Goldstein, B., & Rasmussen, F.N. (.2017). LCA of buildings and the built environment. In *Life Cycle Assessment: Theory and Practice* (pp. 695–722).

Haugbølle, K., Mahdi, V., Morelli, M., & Wahedi, H. (2021). *BUILD 2021:32 build levetidstabel*.

Heijungs, R., 1996. Identification of key issues for further investigation in improving the reliability of life cycle asssssments. J. Clean. Prod. 4, 159–166.

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22 (2), 138–147. https://doi.org/10.1007/s11367-016-1246-y.

International Organization for Standardization. (2006). *ISO 14040:2006 - environmental management - life cycle assessment - principles and framework*.

IPCC Working Group III. (2022). Mitigation of climate change climate change. *IPCC Sixth Assessment Report*. www.ipcc.ch.

Kakkos, E., Heisel, F., Hebel, D.E., Hischier, R., 2020. Towards urban mining-estimating the potential environmental benefits by applying an alternative construction practice. A case study from Switzerland. Sustainability 12 (12). https://doi.org/10.3390/su12125041. *Switzerland*.

Lanau, M., Herbert, L., Liu, G., 2021. Extending urban stocks and flows analysis to urban greenhouse gas emission accounting: a case of Odense, Denmark. J. Ind. Ecol. 25 (4), 961–978. https://doi.org/10.1111/JIEC.13110.

Lanau, M., Liu, G., 2020. Developing an urban resource cadaster for circular economy: a case of Odense, Denmark. Environ. Sci. Technol. 54 (7), 4675–4685. https://doi.org/10.1021/acs.est.9b07749.

Lanau, M., Liu, G., Kral, U., Wiedenhofer, D., Keijzer, E., Yu, C., & Ehlert, C. (2019). *Taking stock of built environment stock studies: progress and prospects*. 10.1021/acs.est.8b06652.

Laurent, A., & Hauschild, M.Z. (2015). Normalisation. In M. Z. Hauschild & M. A. J. Huijbregts (Eds.), *Life Cycle Impact Assessment* (pp. 271–300).

Laurent, A., Irving Olsen, S., Zwicky Hauschild, M., 2011. Normalization in EDIP97 and EDIP2003: updated European inventory for 2004 and guidance towards a consistent use in practice. Int. J. Life Cycle Assess. 16, 401–409. https://doi.org/10.1007/s11367-011-0278-6.

Li, Q., Raghavendra, S., Gummidi, B., Lanau, M., Yu, B., Liu, G., 2022. Spatiotemporally explicit mapping of built environment stocks reveals two centuries of urban development in a Fairytale City, Odense, Denmark. Cite This: Environ. Sci. Technol. 2022, 16369–16381. https://doi.org/10.1021/acs.est.2c04781.

Lotteau, M., Loubet, P., Pousse, M., Dufrasnes, E., Sonnemann, G., 2015. Critical review of life cycle assessment (LCA) for the built environment at the neighborhood scale. Build. Environ. 93 (P2), 165–178. https://doi.org/10.1016/j.buildenv.2015.06.029.

Mastrucci, A., Marvuglia, A., Benetto, E., Leopold, U., 2020. A spatio-temporal life cycle assessment framework for building renovation scenarios at the urban scale. Renew. Sustain. Energy Rev. 126 (August 2019), 109834 https://doi.org/10.1016/j.rser.2020.109834.

Mastrucci, A., Marvuglia, A., Popovici, E., Leopold, U., Benetto, E., 2017. Geospatial characterization of building material stocks for the life cycle assessment of end-of-life scenarios at the urban scale. Resour. Conserv. Recycl. 123, 54–66. https://doi.org/10.1016/J.RESCONREC.2016.07.003.

Mirabella, N., Allacker, K., Sala, S., 2019. Current trends and limitations of life cycle assessment applied to the urban scale: critical analysis and review of selected literature. Int. J. Life Cycle Assess. 24, 1174–1193. https://doi.org/10.1007/s11367-018-1467-3.

Nemry, F., Uihlein, A., Colodel, C.M., Wetzel, C., Braune, A., Wittstock, B., Hasan, I., Kreißig, J., Gallon, N., Niemeier, S., Frech, Y., 2010. Options to reduce the environmental impacts of residential buildings in the European Union-Potential and costs. Energy Build. 42 (7), 976–984. https://doi.org/10.1016/j.enbuild.2010.01.009.

Pauliuk, S., Sjöstrand, K., Müller, D.B., 2013. Transforming the Norwegian dwelling stock to reach the 2 degrees celsius climate target: combining material flow analysis and life cycle assessment techniques. J. Ind. Ecol. 17 (4), 542–554. https://doi.org/10.1111/j.1530-9290.2012.00571.x.

Petit-Boix, A., Llorach-Massana, P., Sanjuan-Delmás, D., Sierra-Pérez, J., Vinyes, E., Gabarrell, X., Rieradevall, J., Sanyé-Mengual, E., 2017. Application of life cycle thinking towards sustainable cities: a review. J. Clean. Prod. 166, 939–951. https://doi.org/10.1016/J.JCLEPRO.2017.08.030.

Röck, M., Baldereschi, E., Verellen, E., Passer, A., Sala, S., Allacker, K., 2021. Environmental modelling of building stocks – an integrated review of life cycle-based assessment models to support EU policy making. Renew. Sustain. Energy Rev. 151 https://doi.org/10.1016/J.RSER.2021.111550.

Sacchi, R., Terlouw, T., Siala, K., Dirnaichner, A., Bauer, C., Cox, B., Mutel, C., Daioglou, V., Luderer, G., 2022. PRospective environmental impact asSEment (premise): a streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. Renew. Sustain. Energy Rev. 160 https://doi.org/10.1016/J.RSER.2022.112311.

Su, S., Li, X., Zhu, Y., Lin, B., 2017. Dynamic LCA framework for environmental impact assessment of buildings. Energy Build. 149, 310–320. https://doi.org/10.1016/j.enbuild.2017.05.042.

Su, S., Zhang, H., Zuo, J., Li, &.X., Yuan, J., 2021. Assessment models and dynamic variables for dynamic life cycle assessment of buildings: a review. Environ. Sci. Pollut. Res. 28, 199–262. https://doi.org/10.1007/s11356-021-13614-1/Published.

United Nations. (2015). *Transforming our world: the 2030 Agenda for sustainable development*.

United Nations. (2019). *World urbanization prospects: the 2018 revision*.

United Nations. (2021). The sustainable development goals report 2019. *United Nations Publication Issued by the Department of Economic and Social Affairs*, 64. https://unstats.un.org/sdgs/report/2019/The-Sustainable-Development-Goals-Report-2019_Spanish.pdf%0Ahttps://undocs.org/E/2019/68.

United Nations Habitat. (2017). New urban Agenda. In *Developing Domestic Water Security Index in Urban Cities, Bahir Dar City, Ethiopia*.

Wang, Q., Laurenti, R., Holmberg, S., 2015. A novel hybrid methodology to evaluate sustainable retrofitting inexisting Swedish residential buildings. Sustain. Cities Soc. 16 (C), 24–38. https://doi.org/10.1016/j.scs.2015.02.002.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21 (9), 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.

Zhang, C., Hu, M., Sprecher, B., Yang, X., Zhong, X., Li, C., Tukker, A., 2021. Recycling potential in building energy renovation: a prospective study of the Dutch residential building stock up to 2050. J. Clean. Prod. 301, 126835 https://doi.org/10.1016/j.jclepro.2021.126835.