

Life cycle assessment of advanced building materials towards NZEBs

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Abstract. Buildings are responsible for 40% of energy consumption annually in Europe, along with the respective greenhouse gas emissions. To mitigate these impacts, intensive research is ongoing in the sector of the Nearly Zero-Energy Buildings (NZEBs). However, as it is expected that the operational energy of future buildings becomes greener and more efficient, impacts related to the embodied energy of building materials becomes of more significance. Thus, choices on building materials are of crucial importance as they affect the energy performance of the building envelope and its environmental impacts. The objective of this study was to implement preliminary Life Cycle Assessment (LCA) on new advanced building materials, with the final scope to achieve lower embodied carbon in NZEBs. The materials examined are concretes and aerogels for wall façades. Design of sustainable advanced materials and building envelope components is expected to improve the overall energy performance of buildings, including NZEBs. The study findings provide clear evidence on the necessity for further research on the topic, as lack of embodied impacts' data of novel materials is presented in literature and adds to the discussion around NZEBs.

1 Introduction

As Europe targets to become climate neutral by 2050 [1], efforts have been intensified during the last decade to mitigate greenhouse gas emissions from different economic activities. In this challenge, the European Commission pays special attention to the building sector, as it accounts for 40% of energy consumption annually, along with 36% of associated emissions [2]. The recently launched EC initiative of the Renovation Wave provides a perfect opportunity for all related stakeholders to rethink their decarbonization approach. As about 85% of the existing buildings will be standing in 2050, with less than 1% undergoing energy efficient renovation every year [3], renovation towards NZEBs unlocks significant potential

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to meet the EU climate goals. However, renovation for a climate-neutral Europe, needs to address the energy efficiency and carbon intensity of buildings over their whole life cycle. As solutions for decarbonization of buildings' operational energy gain ground, the embodied energy of building materials becomes of more significance. In this context, the EU project "iclimabuilt" [4] aims to develop and upscale advanced building materials to reach NZEBs balance. To assure materials' sustainability, LCA will be performed in the project framework.

2 Embodied Emissions and Product Stage of building materials

As electricity decarbonizes and buildings turn to more energy efficient, their operational energy is gradually reduced; therefore, their embodied energy and embodied carbon, become of more significance. Research shows that the share of embodied energy in the buildings' life cycle can even reach 74% to 100% for NZEBs [5] and embodied carbon can represent 40% to 70% of whole life carbon in a new low carbon building [6]. While embodied emissions occur to all life cycle phases of the built assets, emissions released before the building use stage are expected to be responsible for half the total carbon footprint of a new building [7], with particularly the product stage of materials estimated to be the main carbon contributor [8]. So, to mitigate the whole life carbon of buildings, research on embodied carbon of building materials' manufacturing needs to be intensified, mainly when it comes to new building materials which lack of respective data.

3 NZEB Advanced Materials

Cellular Lightweight Concrete (CLC) is a lightweight cementitious material that principally consists of a combination of cement, sand (optionally), water, and foam. Its thermal conductivity and price can become comparable with these of Expanded Polystyrene. If silica aerogel is added, the thermal conductivity can reach $30 \text{ m}\cdot\text{W}/(\text{m}\cdot\text{K})$. CLC is non-flammable and is not releasing toxic gases when heated. As it consists 99% of mineral components, it can be used as secondary source, i.e., feedstock for cement production [9, 10].

The new high-performance composite Textile Reinforced Concrete (TRC) is created by combining corrosion-resistant reinforcement structures made of carbon fibres in the form of mats and bars with sustainable concrete compositions. The material properties of TRC allow reducing drastically the thickness of the inner and outer layers of sandwich elements due to its high mechanical performance and durability. By reducing the concrete cover, enormous concrete savings and the associated emissions savings can be achieved [11], making TRC an excellent candidate material for concrete-based facades. This study focuses on the assessment of the concrete used in the TRC, while the carbon fibre mat will be assessed at a later stage.

Aerogels are lightweight nanomaterials that due to the fine and open-pore structure resulting in low densities, can reach very low thermal conductivities, about $15 \text{ m}\cdot\text{W}/(\text{m}\cdot\text{K})$ [12, 13]. Aerogels assessed in this study are: i) silica, ii) cellulose with ammonia solution and iii) cellulose with sodium hydroxide solution. Supercritical drying by CO_2 extraction is applied in the manufacturing process, as considered to be safer and more environment-friendly than other drying processes, applicable in all gel kinds [12].

4 LCA Methodology

4.1 Goal and Scope

The applied LCA methodology in this study is in accordance with the international standards of ISO 14040 and ISO 14044 [14, 15] and the European standards EN 15804:2012+A1:2013

and EN 15978:2011 [16, 17]. The goal of the study was to perform preliminary LCA of the potential environmental impacts of advanced building materials, with the scope to achieve lower embodied carbon in NZEBs. The study follows a “cradle to gate” approach, so it implements LCA at the Product Stage (A1-A3) of building materials, according to the classification of the life cycle stages of building materials based on European standards [16]. When implementing LCA on a building component, the Functional Unit (FU) for thermal insulation products is usually defined as: “Thermal insulation of 1m² of a building element, with an insulation thickness that gives a thermal transmittance U_c of the element as defined in the vertical rules, with a design life span of 50 years”. However, this study is a preliminary LCA oriented to building material level. The examined materials are shown in Table 1, with the FUs considered and with the iclimabuilt partners responsible for material development.

4.2 LCI Data Collection

Primary data collection took place by tailor-made Life Cycle Inventory (LCI) questionnaires, addressed to the iclimabuilt partners. Such data are not analytically presented here due to the principle of confidentiality. Background LCI data were sourced from the professional database Ecoinvent v3.7.1, considering the European conditions in terms of electricity and water inputs. Proxy values through peer-reviewed literature were used when necessary.

4.3 LCIA

The Life Cycle Impact Assessment (LCIA) was implemented by the SimaPro software v9.1.1.7. According to the European standards recommendations [16], seven environmental impact categories, presented with their units, were selected to assess the materials examined. LCIA was implemented using the CML-IA (baseline) method, since it is included in SimaPro and covers the seven impact categories selected for the LCIA:

- Global warming potential (100a) (kg CO₂ eq)
- Ozone depletion (kg CFC-11 eq)
- Acidification potential of soil and water (kg SO₂ eq)
- Depletion of abiotic resources (elements) (kg Sb eq)
- Depletion of abiotic resources (fossil fuels) (MJ)
- Photochemical ozone creation potential / oxidation (kg C₂H₄ eq)
- Eutrophication potential (kg PO₄ eq)

5 Results

The LCIA results for each building material examined in terms of contribution to the Global Warming Potential (GWP) are presented in Table 1.

Table 1. GWP of building materials assessed – Product Stage (A1-A3)

iclimabuilt materials	iclimabuilt partners	GWP (kg CO ₂ eq / FU)	FU
CLC	RISE	0.574	1 kg
Concrete for TRC	HTWK	0.133	1 kg
Silica Aerogel	TUHH	0.88	1 L
Cellulose Aerogel (ammonia)	TUHH	0.87	1 L
Cellulose Aerogel (sodium)	TUHH	0.85	1 L

The following figures present the LCIA results in the form of staked 100% graphs for all impact categories addressed. Results are presented as normalized, due to confidentiality.

Legends show the material and energy inputs and outputs for each examined material. Fig. 1 presents the LCIA results for the CLC. According to the environmental hotspot analysis, the cement raw materials represent the largest share for all impact categories, contributing to GWP by 87%. The foaming agent mainly contributes to Eutrophication and Photochemical oxidation, while other materials affect Abiotic depletion (fossil). The GWP results of the CLC assessed are compared to literature on foam concretes [18, 19] in Table 2, showing that the results of this study lie in the same levels with similar studies. Fig. 2 presents the LCIA results for the concrete assessed, used in the TRC. The hotspot analysis shows that cement raw materials present the largest share for all impact categories, except Eutrophication, contributing to GWP by 92%. Other materials contribute with 10% to 18% to Ozone depletion, Acidification, Abiotic depletion (fossil) and Photochemical oxidation. Generated waste is the main contributor to Eutrophication with 60%, with cements' contribution 37%. Required electricity and water are not significant to any of the impact categories assessed.

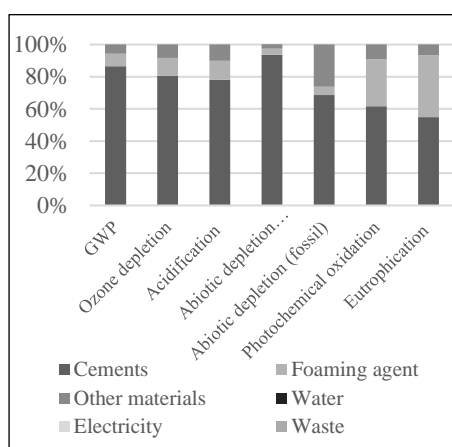


Fig.1. LCIA results for the CLC

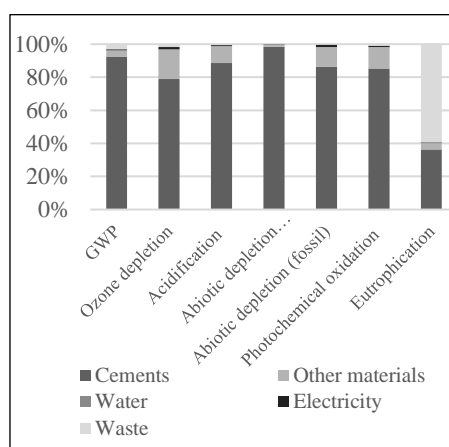


Fig.2. LCIA results for the TRC

Table 2. GWP of different types of foam concrete – Product Stage (A1-A3)

Reference	Different types of foam concrete	GWP (kg CO2 eq/kg)
This study	CLC iclimabuilt	0.574
ZIMELE et al. [18]	FM 2.4 MP compressive strength	0.44
ZIMELE et al. [18]	FM 12.5 MP compressive strength	0.68
Lim et al. [19]	CTRLFC = LFC 100% river sand	0.476
Lim et al. [19]	75QDLFC = LFC 75% quarry dust, 25% river sand	0.442
Lim et al. [19]	100QDLFC = LFC 100% quarry dust	0.43

Fig. 3 presents the LCIA results for the silica aerogels assessed, produced by sodium silicate. Even though recycled by 95%, ethanol is the main contributor in most of the impact categories assessed, with a share of 50% to GWP. As shown in Fig. 3, the supercritical CO2 (sCO2) used in aerogel drying presents a share of 28% in GWP and of 40% to Ozone depletion, even though assumed to be recycled by 95%. Sodium silicate mainly burdens Abiotic depletion (elements) with over 90% and contributes to GWP, Ozone depletion and Acidification (over 20%).

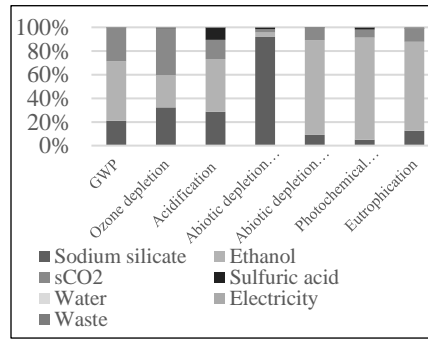


Fig.3. LCIA results for the Silica Aerogel

Fig. 4 presents the LCIA results for the cellulose aerogels assessed, produced using ammonia solution (left) and sodium hydroxide solution (right). In both cases, as in the silica aerogel assessed, even though ethanol is recycled by 95%, it is the main contributor to GWP with a share of 50%. It is also the largest contributor to Abiotic depletion (fossil) and Photochemical oxidation. As shown in Fig. 4, the sCO₂ used in aerogel drying has a share of 28% in GWP, even though assumed to be recycled by 95%. Also, cellulose burdens other categories like Eutrophication and Abiotic depletion (elements), while required electricity and water, and generated waste, are negligible to the categories assessed. In general, the LCIA results of the two types of cellulose aerogels are similar.

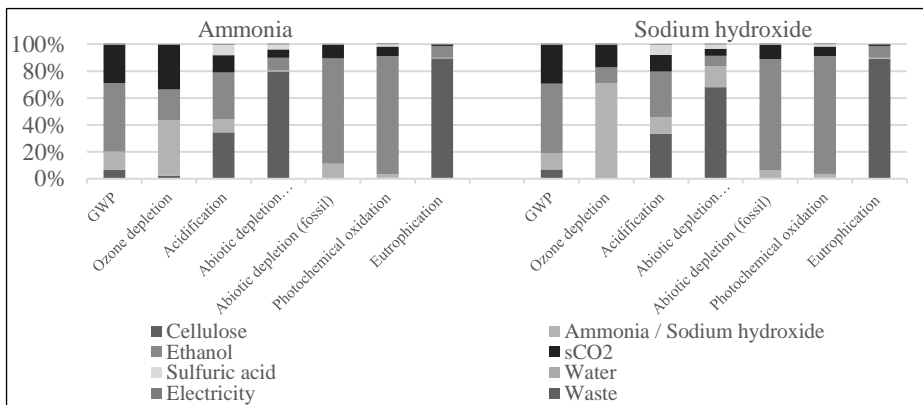


Fig.4. LCIA results for Cellulose Aerogels

6 Conclusions

The objective of this study was to perform the preliminary LCA of advanced building materials that are developed and will be upscaled in the framework of the iclimabuilt EU project towards NZEBs, with lower embodied carbon. For concretes and aerogels examined, results indicated that electricity and water required were not significant to the environmental impact categories assessed, while the waste generated was a main contributor only to Eutrophication and only for the TRC. So, the environmental burden lies in the raw material inputs. Regarding climate change, the GWP of the CLC examined was in line with the GWP levels of other foam concretes in literature.

The concrete for the TRC results in low GWP (0,133 kg CO₂ eq / kg), providing sustainable potential alternative of structural layers for wall façades. No important differences in GWP by the different types of aerogels were identified. However, as cellulose is one of the most promising environmentally friendly compounds for thermal insulation, investigation grows towards environmental improvement of such aerogels. The study also reveals a general necessity to enrich LCI databases for advanced building materials, as there is lack of environmental impacts' data in literature.

7 Future work

Future work in iclimabuilt includes LCA of all project materials and their combinations to provide building envelope products. Their environmental impacts will be further analysed in a specific building context, with their functional characteristics adequately addressed. End-of-Life (EoL) scenarios will be investigated, assessing the feasibility of disassembly options and of alternative construction and demolition (C&D) waste treatment, so that materials and products can be reused in future buildings and thus serve circular economy. As these materials and products are for the moment developed in laboratory and pilot scale, there is still large potential for environmental improvements to be achieved by sustainable design and upscale.

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