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Normalising and assessing carbon emissions in the building sector: A review on the embodied CO_2 emissions of residential buildings

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ABSTRACT

Towards zero emission and zero energy buildings, literature reviews highlight the importance of embodied energy and embodied carbon emissions. The current review analyses 95 case studies of residential buildings, as an effort to identify the range of embodied carbon emissions and the correlation between the share of embodied energy and carbon for different levels of building's energy efficiency. The assessment identifies a range of embodied carbon emissions between 179.3 $kgCO_2e/m^2$-1050 $kgCO_2e/m^2$ (50-year building lifespan) that reflects a share between 9% and 80% to the total life cycle impact. That same share follows similar trends with the respective for embodied energy and ranges between 9% and 22% for conventional, between 32% and 38% for passive and between 21% and 57% for low energy buildings, while the normalised results indicate a sensitivity for the share of operating emissions that relates to the electricity mix. Considering the deviation of the results, even though a two-step normalisation procedure increases the homogeneity and comparability of the sample, the differences in the electricity mix, in LCI databases or even in the overall building design could not be neutralised and confirm the need for further standardisation in LCA.

1. Introduction

Towards zero energy and emission buildings, there is a correlation between the embodied impact and the increase in the initial and recurring use of materials [1], as they involve energy-intensive steps [2]. Moreover, using technical installations, such as photovoltaic panels or energy efficient HVAC systems, is highlighted as an important contributor both to the embodied Global Warming Potential (GWP) impact and embodied energy in the life cycle of a zero energy building [3]. The majority of national and international regulations focus on reducing the operating environmental impact while international literature indicates an increasing importance of the embodied impact in terms of energy [4] and carbon emissions [2,5]. Reviews in Life Cycle Energy Analysis (LCEA) of buildings [6–9] indicate a decrease in operating and an increase in embodied energy considering the different levels of building's energy efficiency [6,9]. The final share of embodied energy to the total life cycle of residential nearly zero energy buildings (nZEBs) ranges between 74% and 100%, with a gap of 17% when compared to low energy buildings [6]. A share of embodied carbon emissions that could be extracted by previous reviews ranges between 10% and 80% [5] and of embodied GHG between 7% and 49% [2] respectively and indicates its wide range and important contribution to the total life cycle impact. The European legislation for the nZEB, defined via the recast of the European Directive 2010/31/EE (EPBD recast) [10], the Delegated Regulation 244/2012 [11] and its accompanying guidelines [12], is characterised by an *"incompleteness"* considering the embodied impact but provides its potential assessment with an extension of the system boundaries [12]. National standards and legislations, such as Minergie A [13] and ZEB-OM, ZEB-COME and ZEB-COMPLETE [14], even though they follow a Life Cycle Assessment (LCA) perspective and account embodied energy and embodied material emissions respectively, they use the on-site electricity production as a counterweight to compensate the embodied impact. Most major Building Sustainability Assessment Tools [15–22] consider embodied impacts with direct and indirect approaches [23] but with an underrating of the LCA through their weighting set [23,24]. Moreover, literature acknowledges the increasing embodied impact, by considering embodied energy in the life cycle energy and rating of nZEBs [25], in the sustainability [26] and environmental (in carbon and energy) assessment of building retrofitting [27] or even in the extension of EPBD recast to a life cycle perspective [23]. Nevertheless, for a future and equal consideration of the embodied impact and before extending standards and policies for the building's efficiency and sustainability into a total LCA perspective, the need for an embodied protocol [28], for further standardisation in LCA in order to create a robust database [29] and for a more comprehensive presentation of the results [6], should first be concerned. As

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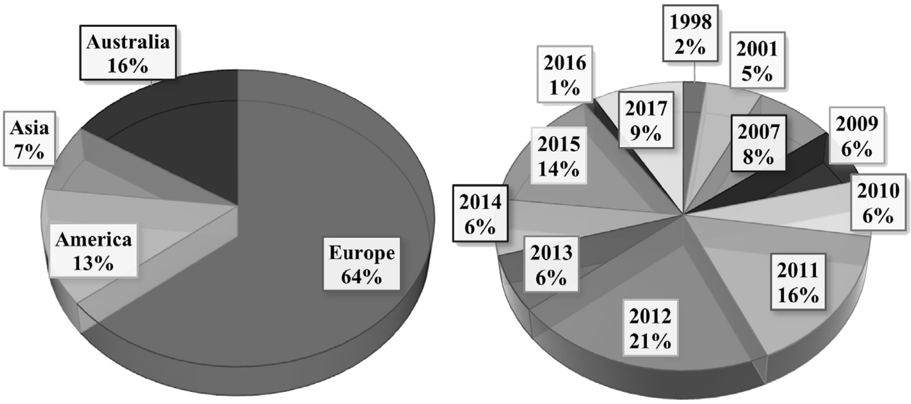

Fig. 1. Geographical and time allocation. 95 case studies of residential buildings.

analysing buildings with life cycle assessment is *"one of the most complex applications of LCA"* [30], the related uncertainty and comparability are issues of concern, extended discussion and analysis in international literature. A clear definition of the system boundaries and the functional unit (reference area and building lifespan) are *"still central questions"* [31] that relate to uncertainty, while the same uncertainty is also identified in the impact metrics, the Life Cycle Inventory (LCI) databases or even in the building typology and the electricity mix. Variations in embodied energy calculations indicate a need for a comprehensive system boundary model [32], as *"a correct system boundary is important to meet the robustness of the model outcomes"* [2] while its potential simplification needs further consideration and analysis [33,34]. Moreover, a whole LCA is stated as a path to a better understanding of the effect of alternative material choices [35] in the different phases of a building's life cycle [36], choices that usually relate to uncertainties regarding to the functional unit or even to the reference service life of materials [37–39], that suffer from great discrepancies between LCA studies [2,5,9]. The variation in the functional unit proves the comparison between LCA case studies or even with benchmark values as a difficult task [40]. Even though a normalisation procedure could decrease these differences [8], the diversity related to the use and quality of LCI data/databases [6,30,40–42], to building typology [43–46] and to climate [7,47,48] and energy mix [46,47,49–52] dependency of results, are only topics for discussion in international literature as they cannot possibly be neutralised in a review and indicate a need for further research as a step closer to comparability [6] and to *"uniform embodied-LCA calculations"* [42].

As most of previous literature reviews focus on the relative magnitude of embodied carbon emissions and consider large scale projects (office and commercial buildings), the current review analyses and assesses the embodied emissions (carbon dioxide equivalent-CO_2e) of residential buildings in order to enhance the results of a few but very important relative surveys and to validate the outcomes of a previous companion review [6]. An extended search in the international literature outcomes to a sample of 95 case studies of residential buildings, from around the world, which are analysed thoroughly for the total range of embodied carbon emissions and by considering the sensitivity of results to the building structure, the functional unit, the LCI databases and the energy mix. Therefore, a two-step normalisation procedure, that follows the principles of Product Category Rule for buildings (PCR 2014:02) [53] and the workflow of the companion review [6], attempts to minimise the discrepancies between LCA case studies and to increase the potential comparability of the sample. Moreover, an in-depth analysis attempts to reveal even more issues of uncertainty compared to the previous review and to prove once more that uncertainties and incomparability in LCA studies indicate a need for further standardisation. Finally, an additional analysis for both embodied carbon emissions and embodied energy, depending on different levels of building's energy efficiency, validates the potential correlation between the two different indicators and roadmaps towards the nearly zero target.

2. Materials and methods

2.1. Case studies of residential buildings

The sample consists of 95 case studies of residential buildings from Europe, Asia, Australia and America (Canada, United States, South America) with a publication year that varies between 1998 and 2017 (Fig. 1).

Even though international literature consists of a wider range of case studies, the mismatch on the main indicators used for the current analysis, the lack of a detailed description of the system boundaries and results or even more the differentiation in the calculation metrics (Section 2.3), led to their exclusion from the main sample. Moreover, it should be stated that the consideration of every literature case study could not be possible due to limited access to the original data and publications. In LCA, comparability is a significant issue that usually relates to uncertainty. The previous companion review highlights the functional unit (reference area and building lifespan), the energy metrics, the publication year and the system boundaries as important issues of comparability and main aspects of a normalisation procedure [6]. The preliminary analysis (Section 2.2) of the current sample indicates a significant variation in the building structure, the functional unit, the LCI databases and the energy mix. Thus, a detailed recording, analysis and presentation of all the aforementioned features follow in Table 1.

2.2. Preliminary analysis

A preliminary analysis of the main sample indicates a variation in the system boundaries, the functional unit, the building structure combined with secondary materials that have a high mass contribution to the overall building weight, the energy mix and the LCI databases and LCA methods.

2.2.1. System boundaries

LCA in the building sector quantifies the environmental impact from the life cycle of a building, within the framework of ISO 14040 [111], ISO 14044 [112] and of standards (EN 15978 [113], EN 15804 [114]) that encompass its main principles towards a sustainable construction. The boundaries define which of the upstream, core and downstream processes (Fig. 2) are part of the product system [111], with cradle to gate (A1-A3, Fig. 2), cradle to site (A1-A5, Fig. 2) and cradle to grave (A1-A5&B1-B7&C1-C4&D, Fig. 2), as the most common approaches in LCA of buildings.

The definition of the system boundaries could be subject of different scopes or of data availability [32], resulting in a lack of comparability