Applied Energy 258 (2020) 114107

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation☆

Martin Röck[a], Marcella Ruschi Mendes Saade[b], Maria Balouktsi[c], Freja Nygaard Rasmussen[d], Harpa Birgisdottir[d], Rolf Frischknecht[e], Guillaume Habert[f], Thomas Lützkendorf[c], Alexander Passer[a,*]

[a] Working Group Sustainable Construction, Institute of Technology and Testing of Construction Materials, Graz University of Technology, Waagner-Biro-Straße 100/XI, 8020 Graz, Austria

[b] LIRIDE (Interdisciplinary Research Laboratory on Sustainable Engineering and Ecodesign), Department of Civil and Building Engineering, University of Sherbrooke, 2500 boul de l'Université, Sherbrooke J1K 2R1, QC, Canada

[c] Centre for Real Estate, Chair for Sustainable Management of Housing and Real Estate, Karlsruhe Institute of Technology, Kaiserstr. 12, 76131 Karlsruhe, Germany

[d] Danish Building Research Institute, Aalborg University, A. C. Meyers Vaenge 15, 2450 Copenhagen SW, Denmark

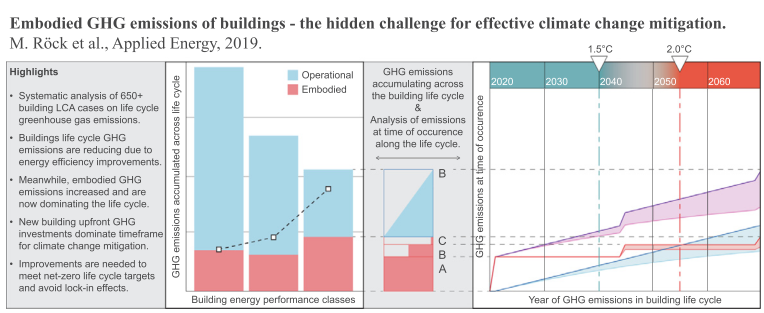
[e] treeze Ltd., Kanzleistrasse 4, 8610 Uster, Switzerland

[f] Institute of Construction of Infrastructure Management, Chair of Sustainable Construction, ETH Zurich, Switzerland

HIGHLIGHTS

- Systematic analysis of 650+ building LCA cases on life cycle greenhouse gas emissions.
- Buildings life cycle GHG emissions are reducing due to energy efficiency improvements.
- Meanwhile, embodied GHG emissions increased and are now dominating the life cycle.
- New building upfront GHG investments dominate timeframe for climate change mitigation.
- Improvements are needed to meet net-zero life cycle targets and avoid lock-in effects.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Life cycle assessment (LCA)
Construction
Buildings
Embodied carbon
Greenhouse gas (GHG) emissions
Environmental impacts

ABSTRACT

Buildings are major sources of greenhouse gas (GHG) emissions and contributors to the climate crisis. To meet climate-change mitigation needs, one must go beyond operational energy consumption and related GHG emissions of buildings and address their full life cycle. This study investigates the global trends of GHG emissions arising across the life cycle of buildings by systematically compiling and analysing more than 650 life cycle assessment (LCA) case studies. The results, presented for different energy performance classes based on a final sample of 238 cases, show a clear reduction trend in life cycle GHG emissions due to improved operational energy performance. However, the analysis reveals an increase in relative and absolute contributions of so-called 'embodied' GHG emissions, i.e., emissions arising from manufacturing and processing of building materials. While the average share of embodied GHG emissions from buildings following current energy performance regulations is approximately 20–25% of life cycle GHG emissions, this figure escalates to 45–50% for highly energy-efficient buildings and surpasses 90% in extreme cases. Furthermore, this study analyses GHG emissions

☆ This research is related to IEA EBC Annex 72 - Assessing Life Cycle Related Environmental Impacts Caused by Buildings - http://annex72.iea-ebc.org.

* Corresponding author.
E-mail addresses: martinroeck@protonmail.com (M. Röck), alexander.passer@tugraz.at (A. Passer).

https://doi.org/10.1016/j.apenergy.2019.114107
Received 30 June 2019; Received in revised form 18 October 2019; Accepted 8 November 2019
Available online 28 November 2019

at time of occurrence, highlighting the 'carbon spike' from building production. Relating the results to existing benchmarks for buildings' GHG emissions in the Swiss SIA energy efficiency path shows that most cases exceed the target of 11.0 $kgCO_2eq/m^2a$. Considering global GHG reduction targets, these results emphasize the urgent need to reduce GHG emissions of buildings by optimizing both operational and embodied impacts. The analysis further confirmed a need for improving transparency and comparability of LCA studies.

1. Introduction

1.1. The role of buildings in responding to the climate crisis

The potential consequences of the climate crisis and the effects it has already triggered are prompting an intensive examination of the necessity of and possibilities for reducing anthropogenic greenhouse gas (GHG) emissions. The relevance and pressing nature of this topic is highlighted by the integration of climate change mitigation measures into the globally recognized Sustainable Development Goals (SDGs) [1], the alarming reports of the Intergovernmental Panel on Climate Change (IPCC) [2] and the commitments to national GHG emission reduction measures within the framework of the United Nations Climate Change Conference of the Parties (COP) [3].

The relevance of 'buildings' and the 'construction industry' in this context is highlighted, for example, in the yearly status reports published by UN Environment, the International Energy Agency (IEA) and the Global Alliance for Buildings and Construction (GABC). These reports make it clear that *"building construction and operations [account for] 36% of global final energy use and 39% of energy-related carbon dioxide (CO2) [emissions]"* [4].

In recent reports [2,5], the IPCC identified 'buildings' as an essential field of action for a number of reasons. First, building operations worldwide account for 28% of energy-related GHG emissions [4]. These emissions from building operation arise from the energy used for heating and/or cooling, hot water supply, ventilation and air conditioning, lighting, and process-related climate-relevant GHG emissions, i.e., the release of refrigerants and blowing agents (HFC- and PFC-gases). Second, because 'buildings' are responsible for a massive amount of current GHG emissions, they also have significant potential to reduce GHG emissions through improved operational energy efficiency. In this context, the IPCC states that *"1.5 °C-consistent pathways require building [GHG] emissions to be reduced by 80–90% by 2050, new construction to be fossil-free and near-zero energy by 2020"*, and the need for *"an increased rate of energy refurbishment of existing buildings to 5% per annum in OECD countries"*[5].

Thus far, efforts to improve building-related GHG emissions focus mainly on increasing energy efficiency to reduce operational energy demand and on increasing the use of renewable energy carriers. Eventually, the aim is a net-zero energy and emissions balance in the use phase of buildings. In addition to conserving non-renewable energy sources, pursuing these goals should support the reduction of GHG emissions across the life cycle of buildings. The tightening of legal requirements regarding energy efficiency in building operation has led to, e.g., growing awareness among actors in the construction and real estate industry, increased development of related construction products and systems, and the establishment and improvement of various information and design support tools. Altogether, these measures have successfully contributed to a decline in the energy demands of building operation, thus shifting the environmental hotspots to other stages in the life cycle of buildings [6].

1.2. Shifting focus from efficiency in operation towards a full life cycle perspective

Currently, a large part of the scientific community in the field of buildings and energy research focuses on optimizing the so-called 'operational' energy use of buildings and, more recently, on the associated GHG emissions. However, given the full life cycle of buildings, energy use and GHG emissions occur for reasons that extend beyond building operation. Energy is required for the manufacturing of construction products; it is 'invested' in the construction of new buildings and in modernization and replacement measures; and it is consumed by transport and construction processes as well as during the dismantling and disposal of buildings and materials. The field of buildings and energy research can build on previous work on embodied energy from the twenties and eighties of the last century [7–10]. In particular, the publicly available results of IEA ECBCS Annex 31 *Energy-related environmental impacts of buildings* [11] and IEA EBC Annex 57 *Evaluation of Embodied Energy and CO_2eq for Building Construction* [12] are highly relevant.

The life cycle assessment (LCA) methodology, internationally standardized in the 1990s, aims at quantifying the environmental impacts of products and processes throughout their entire life cycle, i.e., from

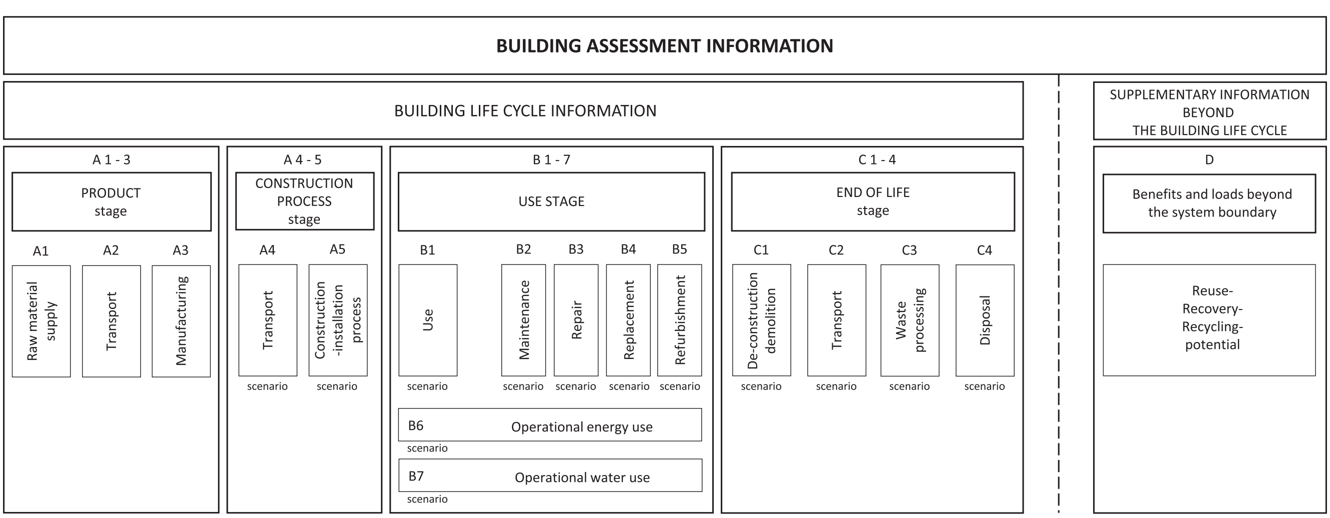


Fig. 1. Display of modular information for the different stages of building assessment (acc. EN 15978).

'cradle-to-grave' [13–16]. This approach provides a sound methodological basis for calculating energy consumption and assessing resource depletion, GHG emissions and other environmental indicators over the full life cycle of buildings [17–20].

Due to methodological developments in recent years, the application of LCA has been successfully facilitated in the construction industry. Increasingly, manufacturers of construction products publish LCA data for their products using Environmental Product Declarations (EPD) [21–23] and other formats, the establishment of which follows international standards such as ISO 14040/14044 [24]. In a European context, the related standards for the sustainability of construction works are EN 15978 ('Assessment of environmental performance of buildings') and EN 15804 (stating the core rules of establishing EPDs). Fig. 1 presents the general structure and definition of stages in the life cycle of buildings according to the European standard for the sustainability of construction works, assessment of the environmental performance of buildings (EN 15978).

1.3. Challenges and misconceptions regarding life cycle-related GHG emissions

There are systemic reasons for the lack of attention paid to embodied impacts in building-related energy research thus far. The energy consumption and GHG emissions that arise in the life cycle of buildings are cross-sectoral issues. Top-down statistics and environmental considerations are typically broken down by economic sectors. The 'buildings' sector includes all activities related to the operation of buildings, whereas the construction of these very same buildings is attributed to the 'industry' sector. Today, the production of construction products used for new buildings and for the refurbishment of existing ones represents 11% of global overall energy- and process-related GHG emissions, with more than half of these emissions related to the manufacturing of steel and cement [25]. The most recent IPCC report aimed to overcome this division by including a short discussion of embodied energy in buildings [5].

One of the reasons embodied impacts have seldom been considered in policy making is the misconception that factors other than operational energy demands and GHG emissions are negligible aspects of a building's environmental performance. Now considered outdated, earlier studies showed that for typical buildings, the ratio of embodied to operational impacts was approximately 1:10. Therefore, the embodied contribution to life cycle energy was within the uncertainty range of the energy demand forecast for building use and thus not considered relevant [26]. However, this situation has changed dramatically. In recent years, several studies have demonstrated the growing importance of embodied impacts, both relative to their contribution to life cycle-based performance and in absolute terms [27–30]. Among the topics investigated and discussed are the relative and absolute values of the embodied impacts as well as how to identify related benchmarks [31–33]. In some countries, there are initial standards that identify benchmarks for embodied and operational GHG emissions, e.g., the Swiss SIA [34,35]. Studies often use only one or a few buildings to examine how individual building and site characteristics affect the magnitude of the embodied GHG emissions or their contribution to life cycle GHG emissions; few studies have investigated a larger number of buildings [32]. Examples of the parameters commonly analysed are (i) the type of building and its use [36,37]; (ii) site-specific properties (e.g., country, climatic zone, seismic zone) [38,39]; (iii) the energy performance standard [40,41]; (iv) construction method (choice of main building materials (e.g., for structural system, envelope, internal walls) [36,42–44]; and (v) the size and shape of the building (e.g., floor area, number of stories, general shape) [32,36].

However, as shown in Table 1, studies investigating the matter have thus far been limited regarding the number and variety of studies compared; they are often limited to one building type and are limited in scope with regard to temporal and spatial representativeness. To date, no studies have systematically investigated recent trends in the contribution of embodied and operational impacts across the life cycle of buildings. The present paper aims to analyse the relative and absolute relevance of operational and embodied GHG emissions across different geographical locations, building types and energy performance standards.

1.4. Research questions

Building on the state of the art as described above, the following research questions are investigated:

I. What is the historical trend and current state-of-the-art with regard to the contribution of embodied versus operational GHG emissions in the life cycle of buildings?
II. Is there a clear and causal trade-off between operational and embodied GHG emissions, or can buildings have both below-average operational and below-average embodied GHG emissions?
III. How does a consideration of the temporal distribution, i.e., time of occurrence of GHG emissions in the life cycle of buildings, influence conclusions in the context of the climate crisis?

2. Material and methods

2.1. Systematic compilation of scientific literature

The collection of published information and subsequent analysis of the documents were performed following the structured protocol for Systematic Literature Review (SLR) and the 'snowball' approach [45,46], a complementary strategy to assure relevant sources are not left out which consists of checking the reference lists of papers and reports collected via the initial protocol. Based on the previously defined research questions, the authors systematically searched the publicly available literature using the following keyword string: [(LCA OR life cycle assessment) AND buil* AND embodied]. The search was performed on 'Scopus', checking for the presence of selected terms in

Table 1
Overview of previous studies documenting embodied GHG emissions and the parameters that affect them.

Paper(s)	Number of buildings	Analysed parameter(s) affecting embodied GHG
De Wolf, Iuorio and Ochsendorf, 2014	3	Construction method (choice of main building materials)
De Wolf et al., 2015	200	Construction method (choice of main building materials)
Chastas, Theodosiou and Bikas, 2016	90	Energy performance standard
Cobîrzan et al., 2017	2	Site-specific properties
Hossain and Ng, 2018	37	Type of building and use
Koezjakov et al., 2018	25	Energy performance standard
Ng et al., 2016	1	Site-specific properties
Passer, Kreiner and Maydl, 2012	5	Construction method (choice of main building materials)
Säynäjoki, Heinonen, Junnila, et al., 2017	116	Construction method (choice of main building materials); Size and shape of building
Simonen, X Rodriguez and De Wolf, 2017	1007	Size and shape of building

the paper's abstract, title or keywords, limiting results to English-written papers only. The search criteria further predicted the exclusion of grey literature (e.g., conference proceedings, master's and/or doctoral theses, books/chapters), and no time boundaries were set. In addition, the authors used the snowball approach to identify publications that are relevant but may have not shown up in the systematic search. This approach was executed by (i) checking the reference list of each sampled paper, (ii) assessing case studies listed in European technical reports, and (iii) consulting experts in the field for additional input regarding relevant LCA studies. The database search was finalized in July 2018, but additions via the snowball method continued through March 2019.

The scientific papers that matched the initial search criteria were then transferred to a reference management software, where, following the SLR method, they went through three filtering phases: (i) a title analysis, (ii) an abstract analysis and (iii) a full paper in-depth analysis and data extraction. Filtering was carried out conservatively, i.e., by retaining – up until the final screening phase – papers for which it was uncertain whether they could contribute to answering the research questions (iii). Fig. 2 illustrates the phases of database search and filtering, showing the number of studies remaining after each phase.

A total of 369 papers matched the initial search. After the first filtering round (title-based), 20 papers were excluded. The abstract analysis led to the elimination of 168 papers. Finally, after a full paper investigation, the final paper sample was composed of 94 files, encompassing 325 case studies. The snowball approach added 331 case studies to the review, documented in 43 scientific papers, 9 reports, 2 master theses and one book. An overview of all studies compiled for this analysis, and the studies contained in the final sample, can be found in the supplementary information (Table S1).

To extract information from the studies in the final sample, a data extraction table was established to systematically collect relevant metadata, building-related and method-related information, as well as energy and GHG emissions from sampled papers and technical reports (Fig. 2). The information collected in the data extraction table fed the meta-analysis, which allowed for a joint discussion of the findings, as well as an in-depth analysis of GHG emissions across buildings' life cycles as reported in the identified studies.

2.2. Data transformation and classification

2.2.1. Harmonization procedure

For the analysis of absolute embodied GHG emission (EGHG) values, all results collected in this study have been harmonized to the common reference unit $kgCO_2eq/m^2a$, which expresses GHG emissions in kg CO_2 equivalent per square metre (m^2) of gross floor area (GFA) normalized across a 50-year Reference Study Period (RSP).

Due to the aim of applying a harmonization procedure towards a common floor-area-based reference unit, the sample of LCA results was limited to studies reporting the GHG emissions either per m^2 GFA or m^2 NFA (net floor area) or, at least, providing the information necessary to calculate any of these two areas (e.g., building plans). In other words, studies that only vaguely defined the functional equivalent were excluded from the final sample. In the case of the studies that only reported the m^2 NFA, the results were converted to m^2 GFA using a net-to-gross adjustment factor, as described in the following. The definitions 'usable floor area' and 'gross internal floor area' were considered to be equivalent to the NFA definition. As a general rule, GFA indicates the total constructed area, while NFA refers to the area inside the building and excludes the area covered by the outer walls of a building (ISO 6707-1).

All values of the sample were transformed to the common reference unit $kgCO_2eq/m^2a$ by dividing, where necessary, with the reference study period and square metres stated in each study. As previous studies have showed, differences in the building life span as well as in the reference study period could lead to significant variations in the results [47,48]. Hence, following this initial harmonization, a two-step procedure was employed. First, the total sample of annualised EGHG values was normalised for a 50-year reference study period using Formula (1).

$$EGHG_{norm1} = EGHG\left(\frac{RSP}{50}\right) \quad (1)$$

where

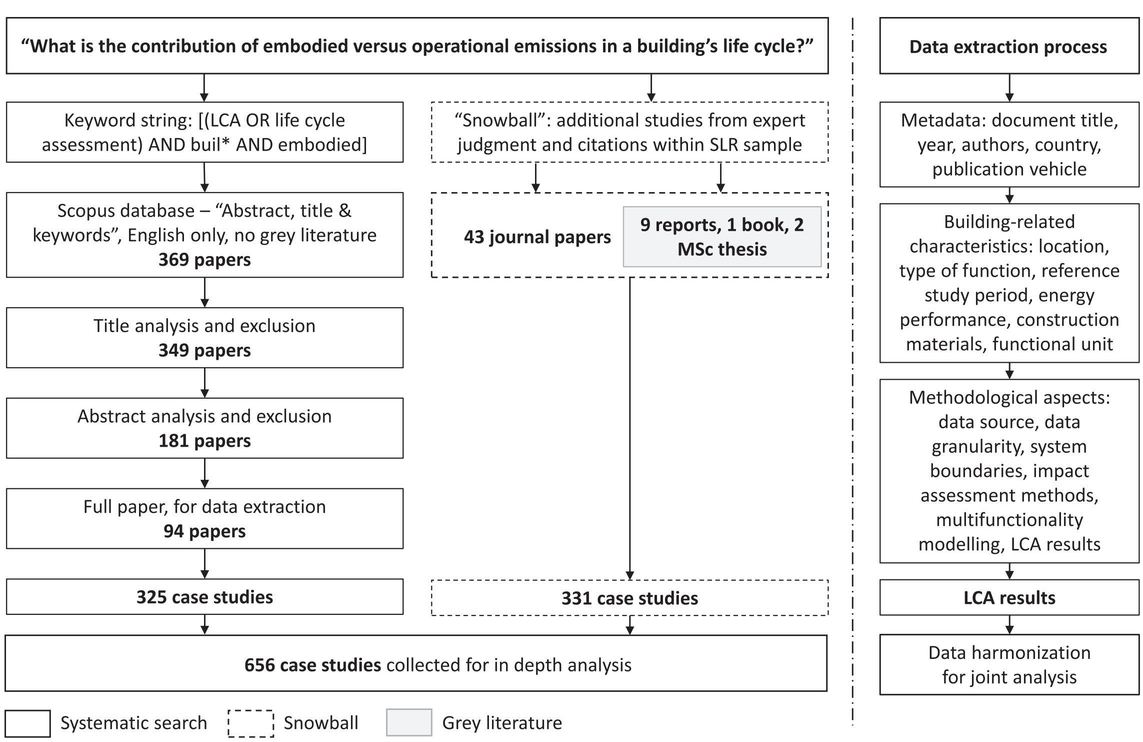


Fig. 2. Overview of systematic search and data analysis.

$EGHG_{norm1}$ = Annualized EGHG value after the 50-year normalization ($kgCO_2eq/m^2a_{50}$)
RSP = Reference study period considered in the investigated study

Second, using Formula (2) for building cases where only the NFA was known, the $EGHG_{norm1}$ values were converted into GFAs by applying a constant of 0.8 m^2 NFA per m^2 GFA (in line with [49]). However, the specific net-to-gross floor-area conversion factor may differ across countries and building types due to differences in building codes and architectural practices [36].

$$EGHG_{norm2} = 0.8EGHG_{norm1} \quad (2)$$

The relative figures (i.e., share of embodied GHG emissions) were obtained by converting EGHGnorm1 values from step 1 into percentages.

2.2.2. Data classification

The final sample dataset was analysed with regard to the building type, energy performance standard and location. For building types, a two-category division into residential and office buildings was employed. For the energy performance classification, the building cases were categorized into three different types of energy performance:

(a) 'New advanced' buildings (i.e., studies assessing passive houses, low-energy buildings or near/net zero energy or emission (NZEB) buildings);
(b) 'New standard' practices (i.e., buildings following current standards regarding operational energy performance, which are in place as legal requirements in most of the countries investigated), or
(c) 'Existing standard' buildings, i.e., constructed before the tightening of legal requirements for building operation (these 'existing standard' buildings make up the majority of the building stock).

For the latter two types, a point in time was defined before which buildings were considered to have a different level of energy performance. This time point was defined following a 'rule of thumb' regional approach and giving the label 'existing standard' to the following:

- All existing building cases built prior to 2005 for Europe and Australia. This date was chosen as critical for these two regions because a few years earlier, stricter energy standards began to be introduced, i.e., the first version of the Energy Performance of Buildings Directive (EPBD) in Europe in 2002 (updated in 2010) [50] and a '4-star' requirement in the Building Code of Australia in 2003 [51]
- All office buildings built prior to 2007 and residential buildings built prior to 2009 for the USA. The selection of these two dates is also based on the introduction of tighter energy standards in the US around that period of time, i.e., ASHRAE 90.1:2007 [52] and the 2009 International Energy Conservation Code (IECC)

Although each country has a different history with respect to enforcing stricter energy efficiency regulations and standards, defining a different point in time for each country included in the review was not feasible. For the classification of location-based climate zones, the widely applied Köppen-Geiger climate classification (1980–2016) [53] was applied, focusing on its five main zones: (A) Tropical; (B) Arid; (C) Temperate; (D) Continental; (E) Polar.

2.2.3. Exclusion criteria and data quality requirements

One challenge identified in the screened literature was that a significant share of the published papers, surprisingly, either do not report their data sets in sufficient detail to allow an analysis of their scope or, in some cases, report implausible results. This limitation reduced the number of eligible results that could be included in the analysis to 583 cases. The systematic analysis focuses on studies investigating 'New buildings' (calculated GHG emissions of new building models and archetypes) and 'Existing buildings' (impacts of buildings already in operation) and was limited to residential and office buildings. All papers dealing with 'refurbishment' cases were excluded because, from a methodological point of view, they do not allow comparison with the results of new construction cases. This restriction reduced the dataset to 401 cases. Therein, studies reporting only embodied energy (EE) but no embodied GHG emissions (EGHG) were excluded because a 'general' conversion factor from primary energy to GHG emissions does not exist and a regional conversion based on the various differences in construction material use, fuel type or year was not feasible. The final dataset for the analysis of global trends was composed of 238 building cases based on 54 studies.

It is important to note that in many papers, the results were not provided in numerical terms but only given in graphs and charts. Although the extracted values from these papers are thus only visual approximations, they are accurate enough for the purposes of the present study and therefore were considered in the analysis if all other inclusion criteria were met.

Although the harmonization of the reference unit and reference study period of the results analysed in this study enables general comparison, the results are still influenced by the studies' diversity regarding building type, climate, scope in relation to the included life cycle stages, type of LCI data, etc. As these parameters could not be fully harmonized, they indicate a source of systematic uncertainty.

2.3. Final sample meta-analysis

The meta-data analysis of the studies contained in the final sample, as presented in Table 2, shows that the majority of case studies within the final sample come from European countries (74%), followed distantly by Asian countries (15%) and Oceania (6%). Cases from North America, South America and other regions make up only a minor fraction in this sample (sum of 5%). This distribution explains why the majority of case studies were located in either a Temperate (C) (64%) or Continental (D) climate (25%). The analysis thus revealed a clear research gap regarding studies from the Americas as well as from tropical countries more generally. This gap in the analysis is notable considering how outside temperature can affect heating and cooling energy demand during a building's use phase. In terms of building type and energy performance, the final sample is hence composed of office (52) and residential buildings (186), mostly adopting current standards in

Table 2
Number of cases in the final sample (and total of initially eligible but excluded cases) sub-divided based on, e.g., building's type of function, energy performance class, world region and climate zones (acc. Köppen-Geiger definition).

Type of function		Energy performance		World region		Climate zone	
Residential	186 (416)	Existing Standard	67 (89)	Europe	175 (388)	Tropical (A)	10 (27)
Office	52 (83)	New standard	111 (274)	Asia	35 (77)	Arid (B)	12 (18)
other	- (84)	New advanced	60 (159)	Oceania	15 (60)	Temperate (C)	153 (393)
		n/a	- (61)	North America	4 (21)	Continental (D)	59 (138)
				South America	7 (24)	Polar (E)	1 (1)
				other	2 (13)	n/a	3 (6)

energy performance, i.e., 'New standard' and 'New advanced' buildings.

For the reference study period (RSP) applied throughout the different studies, an RSP of 50 years was the predominant choice (approximately 60% of the sample). The preference for this specific estimation is consistent with the depreciation principles for construction investments [54].

3. Results and discussion

3.1. The increasing importance of embodied GHG emissions

The analysis of life cycle GHG emissions in the collected building cases makes clear that with increasing energy efficiency in buildings, the relevance of embodied GHG emissions is increasing in both relative and absolute terms as shown in Fig. 3.

Fig. 3a presents the outcome of the analysis of the average of GHG emissions across the life cycle of the buildings investigated in absolute terms (i.e., $kgCO_2eq/m^2a$), distinguishing between embodied and operational GHG emissions (stacked bar graph). Furthermore, Fig. 3a shows the relative contribution (percentage) of embodied GHG emissions in buildings' life cycle GHG emissions (line graph). The figure presents these values for both residential and office buildings combined as well as separately for each of these building types. The results are further distinguished into three 'energy performance classes', ranging

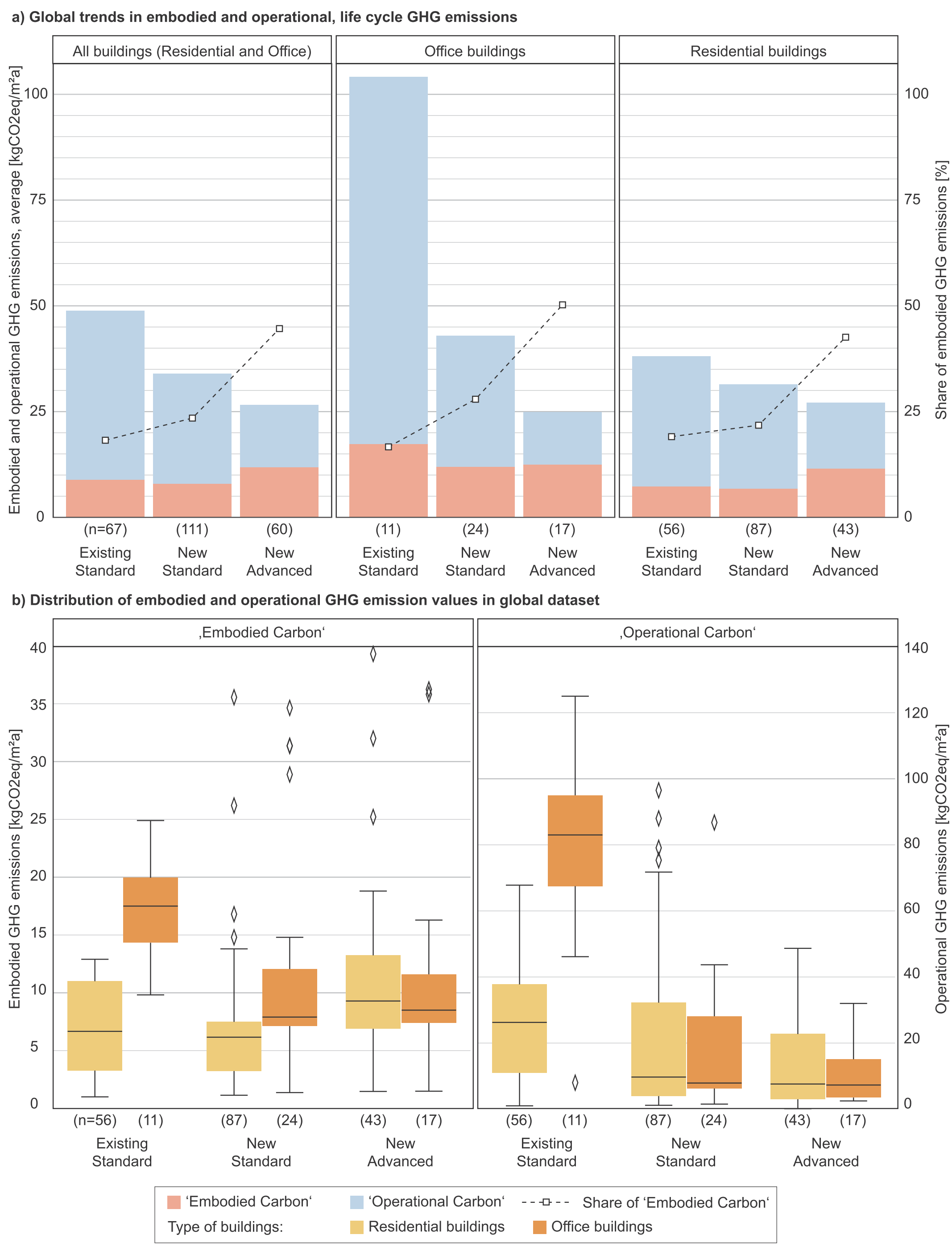


Fig. 3. Global trends in buildings' life cycle GHG emissions (a), and distribution of GHG emission values (b) for residential and office buildings by energy performance class.

from 'existing standard' buildings to 'new standard' and 'new advanced' buildings', as defined in the section 2.2. Focusing on this embodied GHG emissions share, there has been a global escalation of the contribution of embodied GHG emissions in both residential and office buildings – from ~20% to ~50% in new advanced buildings, surpassing 90% in extreme cases. This relative increase in embodied GHG emissions is mainly because operational GHG emissions have dropped in the transition from existing buildings to buildings with new and advanced standards. These trends can be observed for both building types, i.e., in office and residential buildings. These results are consistent across different locations, i.e., there are similar trends in studies from Europe or Asia as well as in the full set of globally distributed LCA studies.

At the same time, embodied GHG emissions have, in absolute terms, either not declined or have even increased. Our analysis shows that this increase in embodied GHG emissions in absolute terms can be observed as an overall trend for residential buildings, where embodied GHG emissions have been increased on average, from approximately 6.7 $kgCO_2eq/m^2a$ for existing buildings to 6.7 and 11.2 $kgCO_2eq/m^2a$ in new and advanced residential buildings. The same trend is not found for the investigated office buildings, where in absolute terms, a decrease and levelling of embodied GHG emissions can be observed, from approximately 17.3 $kgCO_2eq/m^2a$ for existing buildings to 11.6 or 12.0 $kgCO_2eq/m^2a$ for new or advanced office buildings.

Investigating the distribution of data in more detail, as shown in Fig. 3b, values of both operational and embodied emissions are found to vary widely even for buildings of the same type and energy performance class. The absolute values for GHG emissions embodied in new buildings with standard and advanced energy performance, ranges from approximately 3.3–13.3 $kgCO_2eq/m^2a$ for residential buildings and 7.1–11.6 $kgCO_2eq/m^2a$ for office buildings (1st to 3rd quartile).

Complete descriptive statistics and related values can be found in Table S2 of the supplementary information. Furthermore, the distribution of embodied and operational GHG emissions is presented for cases from Europe and Asia in Figures S1 and S2, respectively. Potential aspects driving these differences are discussed in the section 3.5.

A critical investigation of these results reveals that the GHG emission peak for existing office buildings globally is mainly driven by results obtained from Input-Output (IO)-based LCA studies of office buildings in Japan [55] and the United States [56]. These two studies provide more than ninety percent of the 'existing' office building cases in the sample, while most of the other building cases use the Ecoinvent database (i.e., a generic database containing average environmental datasets about construction materials) either exclusively or in combination with regional data sources. An overview of the wide variety of data sources used by the studies contained in the final sample is provided in the supplementary information (Table S3). IO-based LCA studies, in general, are known to yield impact results at a higher level than process-based studies [36,57], which could explain why these studies report higher GHG emissions. The methodological differences between following a bottom-up (process-based) or a top-down (IO-based) approach arise at the very beginning of an LCA study, defining early modelling choices and paths to be taken by the LCA practitioner.

3.2. Life cycle GHG emission metrics of individual building cases

The life cycle performance of a building in terms of its environmental impact depends on various factors, as laid out earlier. Furthermore, the building function, related requirements for thermal comfort, and its occupational patterns during use, including user behaviour, influence life cycle impacts and, for that matter, GHG emissions.

Fig. 4 gives an overview of the individual results from the investigated studies by showing the total life cycle GHG emissions over the share of embodied GHG emissions. Coloured areas provide an approximation of clusters representing the energy performance classes. Note that to provide a clearer picture of the situation, we have limited the y-axis to 100 $kgCO_2eq/m^2a$, hence omitting a small number of extreme results (occurring for reasons discussed in the methodology section). We observe a spread of life cycle-related GHG emissions ranging from below 10 $kgCO_2eq/m^2a$ up to more than 90 $kgCO_2eq/m^2a$. However, we can also clearly see a trend in which the energy efficient buildings, where operational energy consumption has been reduced (indicated by a higher share of embodied GHG emissions), have overall lower emissions across the life cycle. This result confirms the previous observation arguing that the improvement of energy efficiency in buildings did reduce overall GHG emissions (Fig. 3). Moreover, when zooming in on buildings with low life cycle GHG emissions in the reference study period (lower than 20 $kgCO_2eq/m^2a$), it becomes evident that the share of embodied GHG emissions tends to increase from existing standard buildings to new standard and new advanced buildings.

This result is striking because it shows that it was and is possible to design low life-cycle-emissions buildings with all types of standards. However, buildings built with existing standards relied on smaller embodied GHG emissions and a higher contribution of operational energy and related GHG emissions. In contrast, for similar total GHG emissions, the buildings with newly advanced standards show a substantially higher share of embodied GHG emissions, which means that most of the GHG emissions saved through energy efficiency measures have been lost or even outweighed through extra emissions from building materials and technical systems.

Fig. 4 clearly shows a shift in the origin and therefore the timing of occurrence of GHG emissions from existing to advanced buildings. The results confirm that there is a general tendency towards a higher share of embodied GHG emissions, which, in the current analysis, correlate with lower total GHG emissions in the building's life cycle. At the same time, the results show that it is possible to achieve low total emissions without necessarily increasing the share of embodied GHG emissions.

As will be discussed in more detail, the results of LCA studies of individual building cases are influenced by a variety of parameters and methodological choices. However, across all these varieties, which are in part due to the large number of studies analysed, we see clear trends and consistent results in the average values shown in Fig. 3 and when investigating the clusters of individual studies' results as shown in Fig. 4. The results are therefore considered robust because they show consistent trends across studies from different geographical contexts, climate zones and building types.

3.3. European residential buildings and benchmark comparison

To improve the understanding of individual buildings' performance, we investigate the relation of the best-practice examples in this analysis and existing benchmarks for buildings' GHG emissions.

As described in the meta-analysis, most of the data collected in the systematic review are from buildings in Europe. Within this dataset, we observe a more homogenous situation regarding differences in geographical aspects as well as overall technical building standards. In this sense, an analysis is presented below focusing on how the residential buildings in Europe contained in the dataset perform in relation to existing benchmarks for buildings' life cycle performance as well as benchmarks for embodied GHG emissions. The benchmark used for comparison is the Swiss SIA 2040 [35]. The SIA 2040 provides well-established benchmarks for buildings based on the '2000 Watt society' concept. The benchmark provides a life cycle-based target value for buildings, including embodied impacts, operational impacts, and impacts due to so-called building-related mobility. These benchmarks were established following a top-down approach based on a global GHG budget, which was transferred to a budget per capita. According to the Swiss 2000 Watt society principles [58], and according to the German Environment Agency [59], reaching a goal of reducing GHG emissions to 1 t CO_2eq per capita and year by the year 2050 puts us on track to achieve 'climate neutrality'.[1] SIA 2040 further splits this per capita budget into different sectors, such as housing, mobility or private and

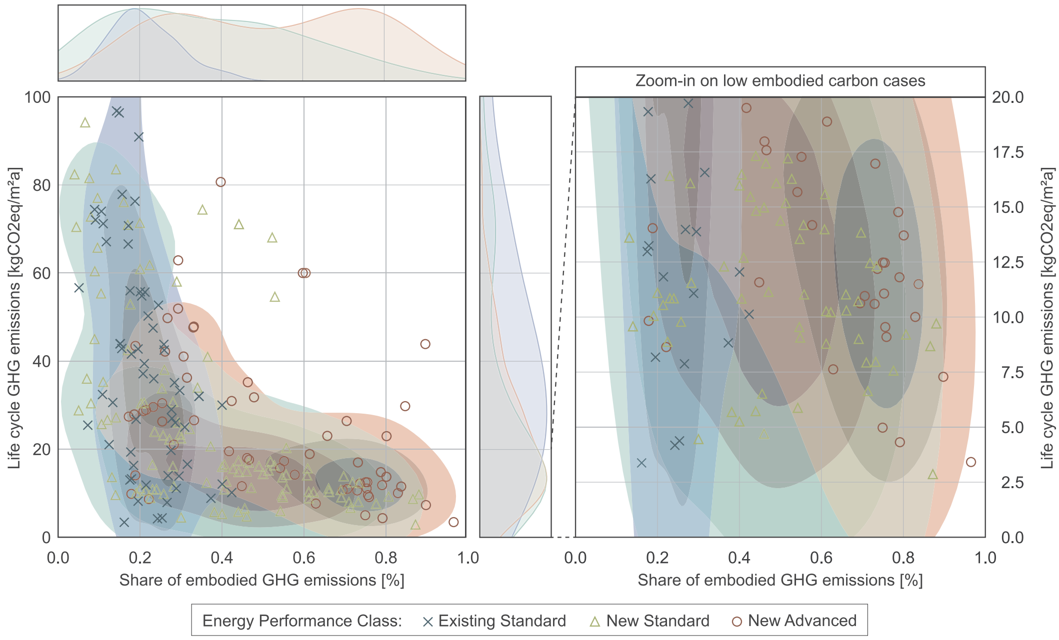


Fig. 4. Overview of individual results regarding GHG emissions across the life cycle and share of embodied impacts, incl. zooming in on the low life-cycle-emissions examples.

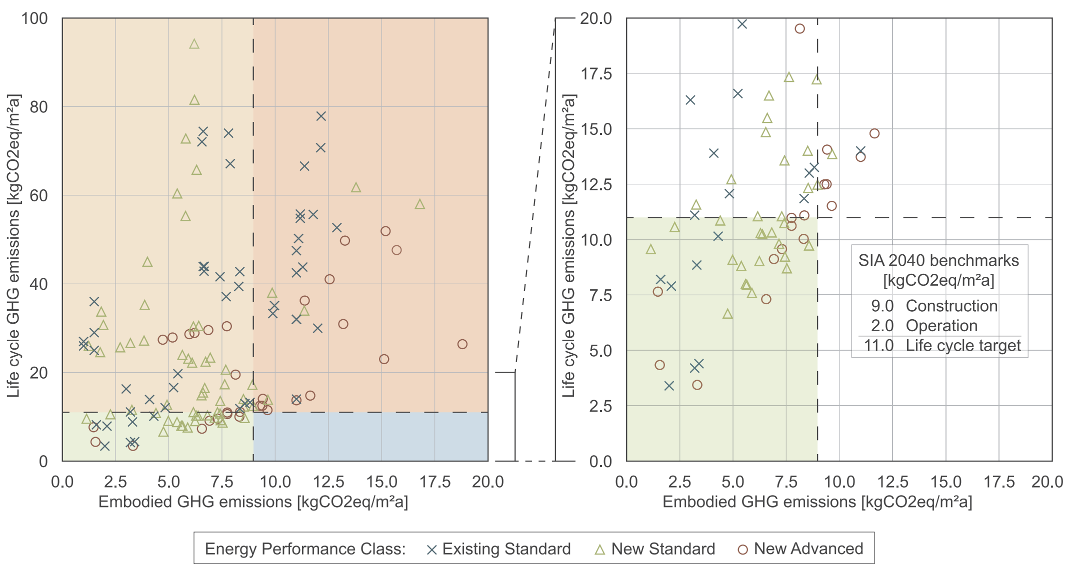


Fig. 5. European residential buildings' GHG emissions across the life cycle and absolute embodied GHG in relation to Swiss SIA 2040 benchmarks.

public consumption. Thirty-six percent of GHG emissions are attributed to housing. Other countries currently have, or are planning to introduce, benchmarks for the GHG emissions of buildings (see [60]), but the 2000 W society benchmark is at this point considered one of the clearer approaches and has already been used by many studies investigating the environmental impacts of buildings [61,62].

Fig. 5 shows the total life cycle GHG emissions of European residential buildings over the amount of embodied GHG emissions and the related benchmarks according to SIA 2040. The figure clearly shows that most of the buildings do not meet the target values. For the vast majority of cases, total life cycle GHG emissions are higher than 11.0 $kgCO_2/m^2a$. This is the case independent of the buildings' energy standard. For all energy performance categories, i.e., existing standards for new standard and new advanced buildings, only a few cases meet the benchmarks. Considering the buildings that do meet the targets, it can be observed that it is not necessarily the buildings with new standards that have a better chance of meeting the targets. This raises the question of the adequacy of building standards, focusing on operational energy efficiency, compared to the targets that need to be achieved to stay at a global temperature increase of 'well below 2 °C'. If new building standards do not necessarily meet the targets, which kind of building requirements, policies and directives have to be implemented to bend the GHG emission curve of buildings? The analysis shows that target values related exclusively to the operational phase are not sufficient for reducing life cycle GHG emissions. It is therefore necessary to develop and implement benchmarks addressing embodied GHG emissions and overall environmental life cycle performance to put buildings on track for ambitious and effective climate mitigation scenarios.

[1] At the time of writing, the 2000 W society benchmarks are under revision. Most likely, the benchmarks will be substantially lowered to comply with the scientific findings of the IPCC 1.5 °C special reports [76].

3.4. Temporal distribution: the 'carbon spike' from initial GHG 'investments'

The importance of addressing embodied GHG emissions is further emphasized when considering the temporal distribution of life cycle GHG emissions due to the 'carbon spike' resulting from building production. In the context of the Paris climate goals and limited GHG emission budgets for achieving net zero GHG emissions globally, as emphasized in the IPCC 1.5 °C special reports [2], emissions across the life cycle of buildings have to be lowered to 'net zero' eventually. Hence, the GHG emissions invested in erecting and modernizing buildings and other infrastructure must be 'cost-effective', i.e., their GHG 'investment' has to contribute to eventually reducing the level of GHG emissions from a whole life cycle perspective. The previous sections showed that investing more in embodied GHG emissions does not necessarily reduce life cycle GHG emissions and that 'advanced' building concepts are not necessarily the most effective way to achieve low life cycle GHG emissions.

To further explore the issue of GHG investment, Fig. 6 illustrates the temporal occurrence of GHG emissions across the building life cycle. The figure draws on the average values for embodied and operational GHG emissions as shown in Fig. 3, partly reversing the normalization and transforming the values to the accumulated sum of embodied and operational GHG emissions across the years of the life cycle. Embodied GHG emissions therein are distributed by allocating GHG emissions across different life cycle stages based on shares from the literature [63]:, i.e., the production and construction process stage (64%); the use stage (maintenance and replacement) (22%); and the end-of-life stage (14%).

Fig. 6 conceptually shows the accumulation of GHG emissions plotted at the time of occurrence on a year-by-year basis for 'New Standard' and 'New Advanced' buildings. In this exercise, all GHG emissions associated with the replacement of construction elements during the use stage are modelled as taking place in one single year, i.e., in year 25 after construction. In reality, both replacement activities and the related GHG emissions would occur at different discrete points in time during the use stage.

The embodied 'carbon spike' occurring in the year of construction (plotted in year 1) relates to emissions from the production of building materials and the construction of the building. Following the findings presented earlier in Fig. 3, on average, this initial GHG investment for 'New Standard' buildings is 253 $kgCO_2eq/m^2$. For 'New Advanced' buildings, the initial investment is 377 $kgCO_2eq/m^2$ on average. Investigating the dataset in detail, the variety of this initial GHG investment for new standard or advanced buildings ranges from 103–423 $kgCO_2eq/m^2$ (1st to 3rd quartile) and surpasses 1250 $kgCO_2eq/m^2$ in extreme cases. The replacement of materials, when summed as one occurrence, generates an additional spike of GHG emissions during the use stage, in the magnitude of on average 87 $kgCO_2eq/m^2$ for 'New Standard' buildings and 132 $kgCO_2eq/m^2$ for 'New Advanced' buildings (based on today's GHG emissions of materials manufacture).

In contrast, operational GHG emissions occur throughout the building life cycle and are plotted on an annual basis, with amounts of 26 kg $kgCO_2eq/m^2a$ for 'New Standard' buildings and 15 $kgCO_2eq/m^2a$ for 'New Advanced' buildings. Assuming constant GHG emission values and plotting over the reference study period (50 years), the accumulating operational GHG emissions exceed the amount of embodied GHG emissions of 'New Standard' buildings after approximately 10 years of operation. For 'New Advanced' buildings, this break-even occurs only in year 35, i.e., after all GHG emissions from replacements have been taken into account. This 'static' approach towards modelling operational impacts can be considered the default procedure in building LCA. However, due to ambitions to increase renewable energy production, the annual GHG emissions related to the energy demand of buildings are expected to decrease. According to the International Energy Agency (IEA), global GHG intensity of energy production fell an average of 2.0% in the period 2014–2018 (International Energy Agency, 2019). Projecting that trend of emission intensity reduction, the actual relevance of GHG emissions from operational energy use will further decrease with time. This trend towards increased GHG emissions efficiency in production is expected to also lower the embodied impacts associated with the future replacement of building materials and the end-of-life treatment of construction materials. However, the figure shows that improvements to material production and end-of-life treatment are less relevant to the accumulated GHG emissions than is the reduction in operational GHG emissions.

When considering the expected GHG emission reduction of the

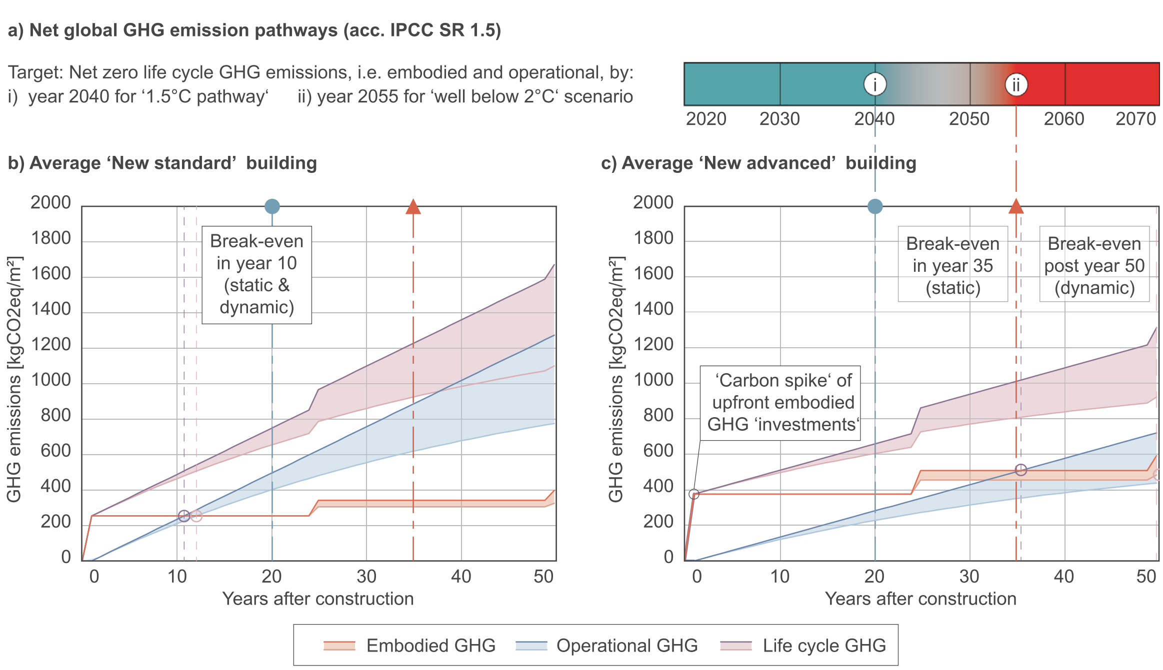


Fig. 6. (a) IPCC GHG emission reduction pathways (acc. [2]) in relation to the temporal distribution of GHG emissions (embodied and operational) across the life cycle of (b) 'New Standard' buildings and (c) 'New Advanced' buildings. Projections for future reduction of emission intensity (hatched areas) are based on a yearly improvement of 2% (acc. IEA [4]).

energy mix in the future, the 'investment' of embodied GHG emissions due to building production is becoming the single most influential source of GHG emissions in the life cycle of buildings (as shown in Fig. 6). In this case, the comparison of embodied versus operational GHG emissions in the life cycle of 'New Advanced' buildings reveals a ratio of approximately 1:1 on average, with embodied GHG emissions dominating the timeframe available for effective climate change mitigation measures.

Furthermore, this analysis also showed that a 2% annual decrease in the GHG emissions intensity of grid energy [4] will only bring about half the emission reductions needed for the net-zero target of 2050. Hence, this demands that the energy sector further accelerate the decarbonisation of energy provision to reach that target. Simultaneously, decarbonisation efforts related to building operation need to further reduce energy demand and GHG emissions from building operation in the future, down to 'near-zero'. The potential strategies for improving energy systems on different scales and through different technologies (e.g., district heating or combined heat and power (CHP) vs. electrification and use of heat pumps on a building level) have to be assessed on a case-by-case basis with regard to their economic and technical feasibility as well as their effectiveness in reducing GHG emissions and other environmental impacts [64–66]. In line with IPCC recommendations, this requires *"new construction to be fossil-free and near-zero energy by 2020"*, and *"an increased rate of energy refurbishment of existing buildings to 5% per annum in OECD countries"*[5]. To achieve the required 'near-zero' energy performance for both new and existing buildings, additional embodied GHG investments in building materials and systems are necessary.

As these embodied GHG emissions are occurring upfront, i.e., at (or prior to) the time of construction, they are exceptionally relevant considering the need to decarbonize the global economy while respecting limited GHG emissions budgets. This situation emphasizes the urgent need to assess and optimize the effectiveness of embodied GHG emissions invested in buildings.

In this paper, the term 'decarbonisation' is used to describe the process of reducing emissions of carbon dioxide (CO_2) and other greenhouse gases (GHG), which is consistent with the wording used by, e.g., the IPCC. Because the GHG emissions reduction is achieved mainly through reduction of fossil fuel based energy provision, the term 'defossilisation' is found more and more in contemporary discourse.

3.5. Limitations and methodological considerations

LCA results are heavily dependent on the methodological choices made by practitioners. Moreover, when applying the method to a complex and long-living system, i.e., an entire building, the number of crucial aspects and scenarios to be considered increases. In these cases, practitioners' preferences and idiosyncrasies, coupled with the peculiarities of the systems that compose a building and their interactions, play a significant role in the LCA's modelling design.

To collectively assess the findings of whole-building LCAs, one must identify certain archetypes that allow the case studies to be compartmentalized into groups. Here, as previously mentioned, the results were divided among others based on the type of function (office or residential), energy efficiency performance, building location and climate zone. Nevertheless, harmonizing the results within those groups was sometimes challenging. The obstacles faced were twofold, related either to varying building and use characteristics or to how the LCA was modelled. The former involves various specificities within a case study, including certain outstanding aspects: (i) the size of the building (number of stories and built area), (ii) the construction materials used (mainly those in the building's structure and envelope), (iii) the location of the building (due to related differences in, e.g., building requirements, climatic context, cultural norms), (iv) the various technical systems used to provide cooling or heating, as well as (v) socio-economic aspects and their influence on, e.g., operational energy consumption, as shown by [67–70]. Even within one category, these factors affect lifecycle impacts and can lead to divergent results.

Regarding methodological choices in LCA, a number of differences can arise and affect comparability. First, the scope of the assessment in terms of the life cycle stages considered greatly affects the outcome regarding environmental impacts. Although all the assessed papers covered (at least) the product stage (A1-A3 according to EN 15978) and the operational energy use (B6), papers that included additional stages were kept in the sample, and the level of data granularity within similar stages might have differed. Furthermore, the differences in the scope of the assessment (i.e., including building components and life cycle stages covered) are critical for comparison. Hence, the extracted LCA results could have been influenced by the varying scopes of the LCA studies performed, which are seldom reported in detail (e.g., by publishing the Life Cycle Inventory (LCI)). Even in cases of similar assessment scopes, it is still likely to have variations in LCA results due to the application of different data sources [71,72]. There is a diverse range of sources (and providers) of LCI data for common building products and processes, and these sources might not always use the same cut-off rules, allocation principles and other underlying assumptions. This diversity results in different emission factors for the same category of building material, product and component. As some authors suggest, data quality indicators can be helpful in this case [73]. In any case, these differences were documented, and the related results went through the same harmonization process as explained in the methodology section.

Another limitation and important aspect of the analysis of published LCA studies is their general lack of transparency. In many cases, basic methodological assumptions were omitted and at times impossible to trace within the publications. The obscurity of key aspects of the LCA leads to superficial results, preventing aggregated analyses that can eventually feed decision making [74]. Thus, comparability was hindered, and for that reason, several papers had to be excluded from the review. LCA studies, even while allowing diverging scopes and some freedom for interpretation, are robust enough to set benchmarks and scientifically grounded public policies regarding the required performance of the built environment if certain key requirements are followed. To properly implement this approach, however, the global scientific community needs harmonized and clear guidelines on how to perform and document whole-building LCAs; such guidelines are long overdue. Proposals for harmonizing the LCA of buildings on an international level can be based on existing standards, e.g., the ISO 14000 series or European EN 15978, and are also being developed, for example, within the ongoing activities of IEA EBC Annex 72 [75].

4. Conclusions and outlook

The study presented in this paper applied a systematic approach to identifying and analysing GHG emissions in the building life cycle. The analysis was based on the systematic review of more than 650 individual building LCA studies, with a final sample of 238 cases fit for evaluation.

The results show that the reduction in life cycle-related GHG emissions is a global trend for buildings that have adopted new energy performance standards for building operation. At the same time, the contribution of embodied GHG emissions increases up to and beyond a ratio of 1:1 (embodied:operational) when we consider a 50-year period. The relevance of embodied GHG emissions further increases when anticipating future reductions in GHG emissions from building operations. This projection assumes current policies, i.e., 'net-zero' GHG emissions from operational energy use due to renewable energy carriers and no (substantial) reduction in embodied GHG emissions (i.e., in construction material manufacture).

The investigation of the temporal distribution of GHG emissions revealed the importance of the initial, upfront 'carbon spike' from the production of building materials and systems. This initial investment of GHG emissions embodied in the investigated 'New advanced' buildings dominates the GHG emissions released in the timeframe relevant for decarbonisation. This result highlights the need to address and reduce operational as well as embodied impacts in the context of limited GHG budgets.

It was further shown that existing life cycle-related benchmarks (for example, the Swiss SIA 2040) can be achieved with different strategies, i.e., high or low embodied GHG emissions, opening the discussion of the effectiveness of ‘GHG investments’.

In conclusion, the results of this study highlight the need to address and further reduce the life-cycle-related GHG emissions of buildings by optimizing embodied emission investments for new construction and promoting ‘carbon-effective’ investments for the refurbishment of existing buildings.

Considering the IPCC-backed call for action towards a global net-zero GHG emissions economy by 2040, profound changes are needed in the construction and use of buildings. First, as an integrated part of the transition in the energy sector, energy systems and technologies implemented for new and refurbished buildings today have to support fossil-free, zero-emission building operation by 2040. Second, attention must be paid to reducing the embodied GHG emissions invested in buildings to net-zero emissions, i.e., industries that produce construction materials need to offer net-zero GHG emission materials by 2040. To support effective climate-change mitigation, embodied GHG missions invested until then must be 'carbon-effective' and respect limited carbon budgets. In this context, aspects of sufficiency and optimization of occupational density as well as other potential strategies for reducing the demands of new construction activity deserve further attention – after all, reducing the area of square metres built is still the most effective way to reduce both embodied and operational GHG emissions.

This crucial transition of the building and construction sector demands a notable and cross-sectoral effort. It requires implementation by building design professionals, and the relevant (construction) industries to decarbonize their production to achieve net-zero embodied emissions for future building construction. Furthermore, building owners and users are urgently challenged to implement activities and practices that further reduce GHG emissions for building operation and to move towards net-zero emissions.

To support this transition in building construction and operation, a clear policy narrative (e.g., introduction of a roadmap and/or regulations) is an important lever with which to enable the concerted action of all industries and actors who influence GHG emissions in the life cycle of buildings.

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.

Acknowledgement

The analysis and results described in this paper relate to ongoing research within the international project IEA EBC Annex 72, which focuses on *Assessing Life Cycle Related Environmental Impacts Caused by Buildings* (http://annex72.iea-ebc.org). The authors would like to thank all participants of the IEA EBC Annex 72 project for their fruitful collaboration. The authors appreciate the contributions to ‘snowball’ studies by Chang U-Chae (Korea Institute of Civil Engineering and Building Technology), Manish Dixit (Texas A&M University) and Sebastien Lasvaux (HES-SO, Switzerland), who provided additional case studies as part of IEA EBC Annex72. We would like to thank TU Graz collaborators Theres Reisinger, Dominik Maierhofer and Nora Hoti for helping with data extraction and illustration. The Austrian contribution is financially supported by the Austrian Ministry for Transport, Innovation and Technology (BMVIT), IEA Research Cooperation via the Austrian Research Promotion Agency (FFG) Grant #864142. Rolf Frischknecht would like to thank Swiss Federal Office for Energy (SFOE), SI/501549-01 for its financial support for preparing and writing this paper. The Danish contribution is funded by the Danish Energy Technology Development and Demonstration Program (EUDP), grant no. 64017-05180. M. Balouktsi and T. Lützkendorf would like to thank the Project Management Organisation Jülich (Projektträger Jülich: PtJ) and the German Federal Ministry for Economic Affairs and Energy (Bundesministerium für Wirtschaft und Energie: BMWi) for funding their contribution to this paper. The authors appreciate the remarks and advice given by three anonymous reviewers, which helped improve the paper substantially.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2019.114107.

References

[1] UN (United Nations). UN sustainable development goals 2015. https://sustainabledevelopment.un.org/sdgs (accessed November 19, 2019).
[2] Intergovernmental Panel on Climate Change (IPCC). Summary for Policymakers. Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty; 2018. ISBN 978-92-9169-151-7.
[3] United Nations. Conference of the Parties Decision. Rep Conf Parties Its Twenty-Fourth Sess Held Katowice from 2 to 15 December 2018 2019:1–13. https://unfccc.int/process/bodies/supreme-bodies/conference-of-the-parties-cop (accessed November 19, 2019).
[4] Abergel T, Dean B, Dulac J, Hamilton I, Wheeler T. Global Status Report - Towards a zero-emission, efficient and resilient buildings and construction sector; 2018. ISBN 978-92-807-3729-5.
[5] de Coninck H, Revi A, Babiker M, Bertoldi P, Buckeridge M, Cartwright A, et al. Strengthening and Implementing the Global Response. Global Warming of 1.5°C. IPCC Special Report; 2018.
[6] Mirabella N, Röck M, Ruschi Mendes Saade M, Spirinckx C, Bosmans M, Allacker K, et al. Strategies to improve the energy performance of buildings: a review of their life cycle impact. Buildings 2018;8:105. https://doi.org/10.3390/buildings8080105.
[7] Friedrich EG, Baurat G, Müller G. Die Bauwirtschaft im Kleinwohnungsbau: kritische Betrachtung der neuzeitlichen Bauweisen und Mitteilung von Erfahrungen mit Baustoffen. Berlin: Wilhelm Ernst & Sohn; 1922.
[8] Gartner EM, Smith MA. Energy costs of house construction. Energy Policy 1976;4:144–57. https://doi.org/10.1016/0301-4215(76)90007-0.
[9] Bekker PCF. A life-cycle approach in building. Build Environ 1982;17:55–61. https://doi.org/10.1016/0360-1323(82)90009-9.
[10] Stein RG, Stein C, Buckley M, Green M. Handbook of energy use for building construction (No. DOE/CS/20220-1). New York (USA): Stein (Richard G.) and Partners; 1980.
[11] International Energy Agency (IEA). IEA EBC Annex 31 - Energy related environmental impacts of buildings; 2001.
[12] International Energy Agency (IEA). IEA EBC Annex 57 Evaluation of Embodied Energy and CO2eq for Building Construction; 2017.
[13] Hellweg S, Mila I Canals L. Emerging approaches, challenges and opportunities in life cycle assessment. Science (80-) 2014;344:1109–13. https://doi.org/10.1126/science.1248361.
[14] European Commission (EC). Guidance for the implementation of the EU Product Environmental Footprint (PEF) during the Environmental Footprint (EF) pilot phase; 2016.
[15] Hauschild MZ, Huijbregts MAJ, editors. Life cycle impact assessment Dordrecht: Springer Science + Business Media; 2015. https://doi.org/10.1007/978-94-017-9744-3.
[16] JRC European commission. ILCD Handbook: Recommendations for Life Cycle Impact Assessment in the European context; 2011. doi:10.278/33030.
[17] Buyle M, Braet J, Audenaert A. Life cycle assessment in the construction sector: a review. Renew Sustain Energy Rev 2013;26:379–88. https://doi.org/10.1016/j.rser.2013.05.001.
[18] Lasvaux S, Achim F, Garat P, Peuportier B, Chevalier J, Habert G. Correlations in Life Cycle Impact Assessment methods (LCIA) and indicators for construction materials: what matters? Ecol Indic 2016;67:174–82. https://doi.org/10.1016/j.ecolind.2016.01.056.
[19] Basbagill J, Flager F, Lepech M, Fischer M. Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. Build Environ 2013;60:81–92. https://doi.org/10.1016/j.buildenv.2012.11.009.
[20] VITO, KU Leuven, TU Graz. PEF4Buildings - Study on the Application of the PEF Method and related guidance documents to a newly office building (ENV.B.1/ETU/2016/0052LV) - Deliverable D3: Report on PEF study of newly built office building; 2018. doi:10.2779/23505.

[21] Passer A, Lasvaux S, Allacker K, De Lathauwer D, Spirinckx C, Wittstock B, et al. Environmental product declarations entering the building sector: critical reflections based on 5 to 10 years experience in different European countries. Int J Life Cycle Assess 2015;20:1199–212. https://doi.org/10.1007/s11367-015-0926-3.

[22] Modahl IS, Askham C, Lyng K-A, Skjerve-Nielssen C, Nereng G. Comparison of two versions of an EPD, using generic and specific data for the foreground system, and some methodological implications. Int J Life Cycle Assess 2013;18:241–51. https://doi.org/10.1007/s11367-012-0449-0.

[23] Hunsager EA, Bach M, Breuer L. An institutional analysis of EPD programs and a global PCR registry. Int J Life Cycle Assess 2014;19:786–95. https://doi.org/10.1007/s11367-014-0711-8.

[24] Klöpffer W. The critical review of life cycle assessment studies according to ISO 14040 and 14044. Int J Life Cycle Assess 2012;17:1087–93. https://doi.org/10.1007/s11367-012-0426-7.

[25] International Energy Agency (IEA), Material Efficiency in Clean Energy Transitions, 2019. www.iea.org/publications/reports/MaterialEfficiencyinCleanEnergyTransitions/.

[26] Ramesh T, Prakash R, Shukla KK. Life cycle energy analysis of buildings: an overview. Energy Build 2010;42:1592–600. https://doi.org/10.1016/j.enbuild.2010.05.007.

[27] De Wolf C, Pomponi F, Moncaster A. Measuring embodied carbon dioxide equivalent of buildings: a review and critique of current industry practice. Energy Build 2017;140:68–80. https://doi.org/10.1016/j.enbuild.2017.01.075.

[28] Häkkinen T, Kuittinen M, Ruuska A, Jung N. Reducing embodied carbon during the design process of buildings. J Build Eng 2015;4:13. https://doi.org/10.1016/j.jobe.2015.06.005.

[29] Dixit MK. Life cycle embodied energy analysis of residential buildings: a review of literature to investigate embodied energy parameters. Renew Sustain Energy Rev 2017;79:390–413. https://doi.org/10.1016/j.rser.2017.05.051.

[30] Ibn-Mohammed T, Greenough R, Taylor S, Ozawa-Meida L, Acquaye A. Operational vs. embodied emissions in buildings - A review of current trends. Energy Build 2013;66:232–45. https://doi.org/10.1016/j.enbuild.2013.07.026.

[31] Simonen K, Rodriguez B, Strain L, McDade E. Embodied carbon benchmark study: LCA for low carbon construction; 2017. doi:http://hdl.handle.net/1773/38017.

[32] Simonen K, Rodriguez BX, De Wolf C. Benchmarking the embodied carbon of buildings 2017;1. doi:10.1080/24751448.2017.1354623.

[33] Neururer C, Smutny R, Passer A. Life Cycle analysis as tool for environmental assessment of office and administration buildings - a critical review and evaluation of the LCAs practical feasibility for a future roadmap. In: World Sustain. Build. Conf. 2014 - Conf. Proc.; 2014, p. 63–63.

[34] Swiss Society of Engineers and Architects (SIA). SIA 2040: Effizienzpfad Energie. SIA; 2011.

[35] Swiss Society of Engineers and Architects (SIA). SIA 2040: Effizienzpfad Energie. SIA; 2017.

[36] Säynäjoki A, Heinonen J, Junnila S, Horvath A. Can life-cycle assessment produce reliable policy guidelines in the building sector? Environ Res Lett 2017;12. https://doi.org/10.1088/1748-9326/aa54ee.

[37] Hossain MU, Ng ST. Critical consideration of buildings' environmental impact assessment towards adoption of circular economy: an analytical review. J Clean Prod 2018;205:763–80. https://doi.org/10.1016/j.jclepro.2018.09.120.

[38] Ng TSK, Yau RMH, Lam TNT, Cheng VSY. Design and commission a zero-carbon building for hot and humid climate. Int J Low-Carbon Technol 2016;11:222–34. https://doi.org/10.1093/ijlct/ctt067.

[39] Cobîrzan N, Voinea M, Kopenetz L, Munteanu C, Balog A-A, Tămaş F. Assessment of cost and embodied carbon for masonry structures located in low and high seismic zones. Procedia Eng 2017;181:418–24. https://doi.org/10.1016/j.proeng.2017.02.410.

[40] Chastas P, Theodosiou T, Bikas D. Embodied energy in residential buildings-towards the nearly zero energy building: a literature review. Build Environ 2016;105:267–82. https://doi.org/10.1016/j.buildenv.2016.05.040.

[41] Koezjakov A, Urge-Vorsatz D, Crijns-Graus W, van den Broek M. The relationship between operational energy demand and embodied energy in Dutch residential buildings. Energy Build 2018;165:233–45. https://doi.org/10.1016/j.enbuild.2018.01.036.

[42] De Wolf C, Iuorio O, Ochsendorf J. Structural material quantities and embodied carbon coefficients: challenges and opportunities. Sustain Struct Symp 2014.

[43] De Wolf C, Yang F, Cox D, Charlson A, Hattan AS, Ochsendorf J. Material quantities and embodied carbon dioxide in structures. Proc Inst Civ Eng - Eng Sustain 2015;169:150–61. https://doi.org/10.1680/ensu.15.00033.

[44] Passer A, Kreiner H, Maydl P. Assessment of the environmental performance of buildings: a critical evaluation of the influence of technical building equipment on residential buildings. Int J Life Cycle Assess 2012;17:1116–30. https://doi.org/10.1007/s11367-012-0435-6.

[45] Wohlin C. Guidelines for snowballing in systematic literature studies and a replication in software engineering. In: 18th Int Conf Eval Assess Softw Eng (EASE 2014) 2014:1–10. doi:10.1145/2601248.2601268.

[46] Higgins JP, Green S. Cochrane handbook for systematic reviews of interventions: cochrane book series. vol. Version 5; 2008. doi:10.1002/9780470712184.

[47] Rauf A, Crawford RH. Building service life and its effect on the life cycle embodied energy of buildings. Energy 2015;79:140–8. https://doi.org/10.1016/j.energy.2014.10.093.

[48] Pannier ML, Schalbart P, Peuportier B. Comprehensive assessment of sensitivity analysis methods for the identification of influential factors in building life cycle assessment. J Clean Prod 2018;199:466–80. https://doi.org/10.1016/j.jclepro.2018.07.070.

[49] Commission Directive (EU) 2015/996 of 19 May 2015 establishing common noise assessment methods according to Directive 2002/49/EC of the European Parliament and of the Council; 2015.

[50] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings; 2010.

[51] McLeod P, Fay R. Costs of improving the thermal performance of houses in a cool-temperate climate. Archit Sci Rev 2010;53:307–14. https://doi.org/10.3763/asre.2010.0022.

[52] 90.1 ASSPC. ASHRAE STANDARD Energy Standard for Buildings Except Low-Rise Residential Buildings. vol. 4723; 2009.

[53] Beck HE, Zimmermann NE, McVicar TR, Vergopolan N, Berg A, Wood EF. Present and future Köppen-Geiger climate classification maps at 1-km resolution. Nat Sci Data 2018;5:1–12. https://doi.org/10.1038/sdata.2018.214.

[54] Marsh R. Building lifespan: effect on the environmental impact of building components in a Danish perspective. Archit Eng Des Manag 2017;13:80–100. https://doi.org/10.1080/17452007.2016.1205471.

[55] Suzuki M, Oka T. Estimation of life cycle energy consumption and CO2 emission of office buildings in Japan. Energy Build 1998;28:33–41. https://doi.org/10.1016/S0378-7788(98)00010-3.

[56] Junnila S, Horvath A, Guggemos AA. Life-cycle assessment of office buildings in Europe and the United States. J Infrastruct Syst 2006;12:10–7. https://doi.org/10.1061/(ASCE)1076-0342(2006) 12:1(10).

[57] Säynäjoki A, Heinonen J, Junnonen J-M, Junnila S. Input–output and process LCAs in the building sector: are the results compatible with each other? Carbon Manag 2017;8:155–66. https://doi.org/10.1080/17583004.2017.1309200.

[58] Zimmermann M, Althaus HJ. Haas a. Benchmarks for sustainable construction: a contribution to develop a standard. Energy Build 2005;37:1147–57. https://doi.org/10.1016/j.enbuild.2005.06.017.

[59] Benndorf R, Bernicke M, Bertram A, Butz W, Dettling F, Drotleff J, et al. Treibhausgasneutrales Deutschland im Jahr 2050 – Kurzzusammenfassung; 2013.

[60] Frischknecht R, Balouktsi M, Lützkendorf T, Aumann A, Birgisdottir H, Grosse Ruse E, et al. Environmental Benchmarks for buildings: needs, challenges and solutions [online first]. Int J Life Cycle Assess 2019. https://doi.org/10.1007/s11367-019-01690-y.

[61] Hoxha E, Jusselme T, Brambilla A, Cozza S, Andersen M, Rey E. Impact targets as guidelines towards low carbon buildings: a preliminary concept; 2016.

[62] Wyss F, Frischknecht R, Pfäffli K, John V. Zielwert Gesamtumweltbelastung Gebäude; 2014.

[63] Rasmussen FN, Malmqvist T, Moncaster A, Wiberg AH, Birgisdottir H. Analysing methodological choices in calculation of embodied energy and GHG emissions from buildings. Energy Build 2018;158:1487–98. https://doi.org/10.1016/j.enbuild.2017.11.013.

[64] Victor DG, Abdulla A, Auston D, Brase W, Brouwer J, Brown K, et al. Turning Paris into reality at the University of California. Nat Clim Chang 2018;8:183–5. https://doi.org/10.1038/s41558-018-0103-3.

[65] Eyre N, Baruah P. Uncertainties in future energy demand in UK residential heating. Energy Policy 2015;87:641–53. https://doi.org/10.1016/j.enpol.2014.12.030.

[66] Quiggin D, Buswell R. The implications of heat electrification on national electrical supply-demand balance under published 2050 energy scenarios. Energy 2016;98:253–70. https://doi.org/10.1016/j.energy.2015.11.060.

[67] Longhi S. Residential energy expenditures and the relevance of changes in household circumstances. Energy Econ 2015;49:440–50. https://doi.org/10.1016/j.eneco.2015.03.018.

[68] Besagni G, Borgarello M. The determinants of residential energy expenditure in Italy. Energy 2018;165:369–86. https://doi.org/10.1016/j.energy.2018.09.108.

[69] Brounen D, Kok N, Quigley JM. Residential energy use and conservation: economics and demographics. Eur Econ Rev 2012;56:931–45. https://doi.org/10.1016/j.euroecorev.2012.02.007.

[70] Filippini M, Pachauri S. Elasticities of electricity demand in urban Indian households. Energy Policy 2004;32:429–36. https://doi.org/10.1016/S0301-4215(02)00314-2.

[71] Lasvaux S, Habert G, Peuportier B, Chevalier J. Comparison of generic and product-specific Life Cycle Assessment databases: application to construction materials used in building LCA studies. Int J Life Cycle Assess 2015;20:1473–90. https://doi.org/10.1007/s11367-015-0938-z.

[72] Takano A, Winter S, Hughes M, Linkosalmi L. Comparison of life cycle assessment databases: A case study on building assessment. Build Environ 2014;79:20–30. https://doi.org/10.1016/j.buildenv.2014.04.025.

[73] Anand CK, Amor B. Recent developments, future challenges and new research directions in LCA of buildings: a critical review. Renew Sustain Energy Rev 2017;67:408–16. https://doi.org/10.1016/j.rser.2016.09.058.

[74] Ruschi Mendes Saade M, Gomes V, Gomes da Silva M, Lie Ugaya CM, Lasvaux S, Passer A, et al. Investigating transparency regarding ecoinvent users' system model choices. Int J Life Cycle Assess 2018;23. https://doi.org/10.1007/s11367-018-1509-x.

[75] IEA EBC. IEA EBC Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings; 2019. http://annex72.iea-ebc.org.

[76] Rogelj J, Shindell D, Jiang K, Fifita S, Forster P, Ginzburg V, et al. Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. Global Warming of 1.5°C. IPCC Special Report; 2018.