Renewable and Sustainable Energy Reviews 94 (2018) 1142–1152

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

The carbon footprint of buildings: A review of methodologies and applications

Andriel Evandro Fenner[a,*], Charles Joseph Kibert[a], Junghoon Woo[a], Shirley Morque[a], Mohamad Razkenari[a], Hamed Hakim[a], Xiaoshu Lu[b]

[a] *Powell Center for Construction and Environment, M.E. Rinker School of Construction Management, University of Florida, Gainesville, FL, United States*
[b] *College of Construction Engineering, Jilin University, Changchun Jilin 130026, China*

ARTICLE INFO

Keywords:
Built environment
Carbon footprint
Carbon emission assessment
Life-cycle assessment methodologies

ABSTRACT

The carbon emissions associated with the built environment represent the dominant fraction of the total carbon footprint of society. As a result of the intense debate over how to address climate change, Life-Cycle Carbon Emissions Assessment and carbon footprint standards such as the PAS2050, ISO/TS 14067, and the GHG Protocol, are receiving increased attention. However, carbon emission calculations often vary in terms of boundaries, scope, units of greenhouse gas emissions, and methodologies. There is not an internationally accepted method for measuring, reporting, and verifying GHG emissions from existing buildings in a consistent and comparable way. In support of developing a standardized approach, this paper reviews current methodologies for carbon footprint accounting and outlines the inconsistencies of most life-cycle carbon assessments studies. The paper also aims to present the cutting-edge knowledge about emissions resulting from buildings during their life-cycle. The conclusion of this research, after a comprehensive literature review and critical analysis, is that there is a need for a clear, accessible and consistent method to assess the carbon emissions from buildings. The findings in this paper can also support and facilitate the discussion of the meaningful targets required to reduce carbon emissions.

1. Introduction

Dealing with climate change and its consequences for the environment has been one of the biggest challenges of modern life. In fact, most current sustainable strategies are intrinsically associated with the intention of reducing our overall carbon footprint. The built environment is, by far, the dominant sector responsible for the total carbon footprint in our society [1], mostly because it represents the intersection of the three main emitters: energy, transportation, and buildings [2]. While commercial and residential buildings release around 40% of total electricity-related GHG emissions in the US [2,3], additional emissions are derived from the extensive use of raw materials, industrial processes to manufacture building products, and subsequent transportation of these products [4]. Additionally, a number of different daily activities also contribute to the built environment carbon footprint, such as the type of transportation used by people to go to work, perform home duties, or for leisure.

The Life-Cycle Assessment (LCA) of buildings has become an essential tool for minimizing the environmental impacts of construction and enabling the construction sector to move towards sustainability. LCA is the best-known method for evaluating the impacts related to the different phases of a process. LCA does benefit the decision-making process that supports the development of sustainable initiatives throughout the life cycle of the building, including building planning, construction, operation, renovation, and deconstruction [5,6]. Due to the increasing incidence of global warming problems, the Life-Cycle Carbon Emission Assessment (LCCO$_2$A), a subsection of the traditional LCA, is receiving greater attention recently.

Overall, carbon emissions can be measured in three ways: (1) considering carbon dioxide alone; (2) including the six gases identified by Kyoto Protocol, i.e. CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6; or (3) including numerous GHG emissions specified by the Intergovernmental Panel on Climate Change (IPCC) framework. The IPCC framework [7], established to facilitate the reporting of carbon emissions in compliance with the Kyoto Protocol, is the most frequent method used. In this method, GHG emissions are reported considering the individual

---

Abbreviations: CO_2, Carbon dioxide; CH_4, Methane; N_2O, Nitrous oxide; CFC, Chlorofluorocarbon; HCFC, Hydrochlorofluorocarbon; HFCs, Hydrofluorocarbons; PFCs, Perfluorinated chemicals; SF_6, Sulfur hexafluoride

[*] Corresponding author.

E-mail address: fenner@ufl.edu (A.E. Fenner).

https://doi.org/10.1016/j.rser.2018.07.012
Received 8 December 2017; Received in revised form 9 March 2018; Accepted 1 July 2018
1364-0321/

Table 1
Most common GHG emissions associated with building construction and their respective GWP impacts, lifetime, and typical use. Adapted from [2,8,9].

Greenhouse Gas (GHG)	Atmospheric lifetime (years)	GWP (100-year lifetime)	Most typical sources in the building environment
Carbon Dioxide (CO_2)	50–200	1	Fossil fuel combustion from activities including electricity generation, manufacturing, transportation, and solid waste combustion.
Methane (CH_4)	12	25	Natural gas and fossil fuel combustion, enteric fermentation, solid and organic waste, and coal mining.
Nitrous Oxide (N_2O)	114	298	Industrial activities, combustion of fossil fuels, solid waste, and wastewater treatment.
CFC-11 (CCl_3F)	45	4750	Refrigeration, aerosol insulation, propellants, solvents, and air conditioning.
CFC-12 (CF_2Cl_2)	100	10,900	
HCFC-22 ($CHClF_2$)	12	1810	
Hydrofluorocarbons (HFCs)	Up to 270	Up to 14,800	Air conditioning, refrigerants, manufacture of foam-blowing agents for insulation, fire extinguishing systems, and aerosols.

impacts of each GHG gas by using the Global Warming Potentials (GWP) of gases expressed in units of kilograms of carbon dioxide equivalent (kg-CO_2eq). Table 1 shows the most common GHG emissions associated with building construction and their respective GWP impacts.

While the literature abounds with carbon footprinting schemes involving commercial buildings, federal buildings, educational buildings, and households [10], the carbon emission calculations often diverge in terms of boundaries, scope, greenhouse gas (GHG) units, and methodologies. For example, Chau et al. [6] reported that the use of primary or secondary energy is not always explicit in the carbon footprint calculations. Additionally, some studies have been focusing on particular materials [11], systems or processes [12], while others have reported comparisons of whole building [6]. Furthermore, the life cycle carbon assessment of buildings has been simplified in several studies, such as omitting transportation emissions for light materials and short distances, thus providing only a general picture of GHG emissions [13]. Beyond all these differences, each project has its own characteristics, such as climate zone, building type, and local regulations, that directly affect the total carbon emissions for each building [6]. Therefore, the comparison of GHG emissions is compromised by the lack of a clear and consistent methodology [14]. In addition, several indirect emissions sources that may represent a significant share of the carbon footprint of buildings, such as the transportation of tenants, are often ignored by most studies.

This study aims to improve our understanding of the overall GHG emissions associated with buildings during their life-cycle. The specific objectives are: (1) a review of current carbon footprint methodologies for buildings; (2) an outline of the inconsistencies of life-cycle carbon assessment studies and the challenges of drawing comparisons among buildings; (3) a state-of-the-art understanding of GHG emissions in the built environment; and (4) a discussion of the need for a clear, accessible and consistent method to assess the carbon emissions of buildings.

2. Methodologies for assessing carbon emissions from buildings

2.1. Life-cycle assessment methodologies

Measuring and reporting GHG emissions from buildings is critical for producing significant and cost-effective strategies. Although carbon emission methodologies vary among countries, the foundation framework is usually the well-established Life-Cycle Assessment (LCA) process. LCA is typically considered a “cradle-to-cradle” approach, where products are systematically assessed over their entire life (e.g. raw material extraction, manufacturing, operations, and end-of-life disposal and recycling). In the last few years, there has been an increased interest in LCA methods to evaluate buildings and products in order to design efficiently and with environmentally preferable materials [5,6].

The ISO 14000 environmental management standard series was implemented in the 1990's, with the 14040-series concentrating on LCA methodologies [15]. The standard's major characteristic is its four-stage framework: (1) *scope definition*, which identifies the goals and boundaries, functional units, and main definitions; (2) *inventory analysis,* which collects data about energy and material flows for each stage of a product life-span; (3) *impact assessment*, which classify, aggregate, and characterize several midpoints and endpoint environmental impacts by means of weighting and normalization methodologies; and (4) *interpretation*, which is used to interpret results and assist in the selection of environmentally-friendly products and to provide project recommendations.

In a broad sense, there are three types of LCA approaches: Process-Based, Economic Input-Output (EIO), and Hybrid. Fig. 1 shows the number of publications in peer-reviewed journals that referred to each of these LCA methodologies and the top ten field of research. The data does not show the number of papers applying each methodology, rather it indicates the popularity of each method over the time. A systematic search was conducted on the Web of Science database from 2000 to 2017 cross-referencing keywords such as “life-cycle assessment” with

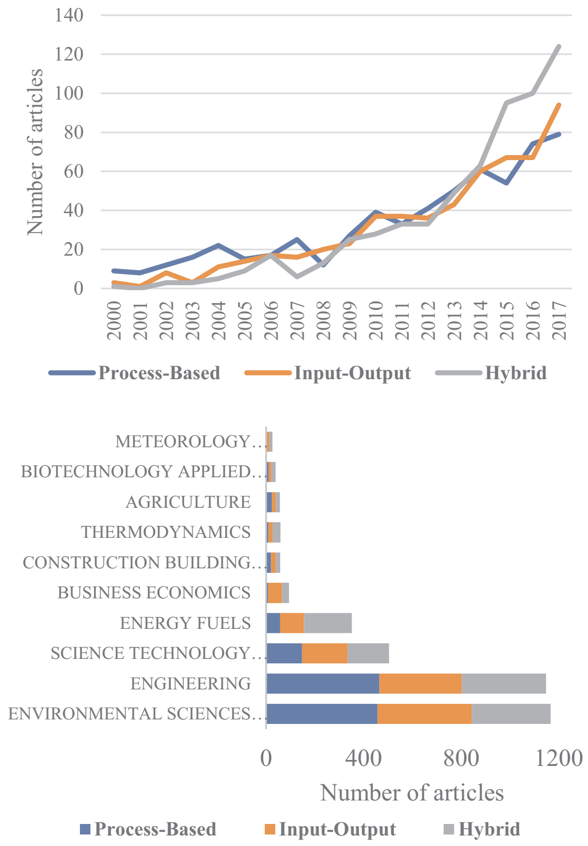

Fig. 1. Trends in publications for process-based, EIO, and hybrid methodologies.