Building and Environment 72 (2014) 53–62

Contents lists available at ScienceDirect

Building and Environment

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

Scope-based carbon footprint analysis of U.S. residential and commercial buildings: An input–output hybrid life cycle assessment approach

Nuri Cihat Onat, Murat Kucukvar, Omer Tatari*

Department of Civil, Environmental, and Construction Engineering, University of Central Florida, Orlando, FL 32816, United States

ARTICLE INFO

Article history:
Received 17 May 2013
Received in revised form
16 October 2013
Accepted 19 October 2013

Keywords:
Life cycle assessment
Economic input–output analysis
Scope-based carbon footprint
U.S. buildings

ABSTRACT

Analyzing building related carbon emissions remains as one of the most increasing interests in sustainability research. While majority of carbon footprint studies addressing buildings differ in system boundaries, scopes, GHGs and methodology selected, the increasing number of carbon footprint reporting in response to legal and business demand paved the way for worldwide acceptance and adoption of the Greenhouse Gas Protocol (GHG Protocol) set by the World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD). Current research is an important attempt to quantify the carbon footprint of the U.S. residential and commercial buildings in accordance with carbon accounting standards and Scopes set by WRI, in which all possible indirect emissions are also considered. Emissions through the construction, use, and disposal phases were calculated for the benchmark year 2002 by using a comprehensive hybrid economic input–output life cycle analysis. The results indicate that emissions from direct purchases of electricity (Scope 2) with 48% have the highest carbon footprint in the U.S. buildings. Indirect emissions (Scope 3) with 32% are greater than direct emissions (Scope 1) with 20.4%. Commuting is the most influential activity among the Scope 3 emissions with more than 10% of the carbon footprint of the U.S. buildings overall. Construction supply chain is another important contributor to the U.S. building's carbon footprint with 6% share. Use phase emissions are found to be the highest with 91% of the total emissions through all of the life cycle phases of the U.S. buildings.

1. Introduction

Global climate change is a major problem that requires solid actions to be taken toward solving issues related with climate change and establishment of sustainable development. According to the Intergovernmental Panel on Climate Change's (IPCC) report, global climate change is real and most of the impacts result from human activities [1]. The level of carbon dioxide (CO_2) concentrations increased from 280 to 355 mL/L since 1800 as a result of human activities mainly caused by fossil fuel combustion [2]. CO_2 is the most significant greenhouse gas (GHG) among methane (CH_4), nitrous oxide (N_2O) and others [3]. Since the atmosphere, our common treasure, has no boundary, studies addressing climatic issues are conducted across national boundaries. In the 1980s, various group of scientists and international organizations attempted to set goals and prepare agendas to shape governmental policies. However, Kyoto Protocol, the first small step aiming to limit GHG emissions, is a failure, since the world's CO_2 emissions are far from decreasing, in contrast, it is increasing with a rate of 2% in a year [4].

The U.S. is one of the leading countries having adverse effect to the environment with the share of 19% of world's production-based GHG emissions in total, which is the second largest portion after China with 23% of the total emissions [5]. Per capita CO_2 emission of the U.S. is 3.5 times higher than world's per capita average [6]. According to the U.S. Energy Information Administration (EIA), residential and commercial buildings are responsible for approximately 38.9% of total GHGs emitted in the U.S., in which only the emissions from fossil fuel combustion (petroleum, natural gas, coal, and electricity) are accounted [7]. If a wider system boundary is considered, which covers entire life cycle phases and indirect emissions sources, this share would be higher. Considering the fact that the U.S. buildings account for significant portion of GHGs emissions in the U.S., it is necessary to identify and analyze the

* Corresponding author.
E-mail address: tatari@ucf.edu (O. Tatari).

0360-1323/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.buildenv.2013.10.009

sources of CO_2 emissions related with buildings. In this regard, this study aims to reveal carbon footprint hotspots to establish a basis for upcoming studies and policies focusing on developing GHG emission reduction strategies.

The term "carbon footprint" is often described as CO_2 or equivalent GHGs emitted as a result of an activity or process associated with a product, service or region. While carbon footprint is not the only indicator that should be taken into account when assessing the environmental impacts of a product, its appealing recognition in public makes carbon footprint a good entry point to increase the environmental consciousness and demonstrate the usefulness of life cycle thinking [8]. Wiedmann and Minx [9] evaluated various definitions of carbon footprint found in gray literature and proposed that carbon footprint should contain both direct and indirect emissions stemming from all over the life stages of a product. In the view of the abovementioned definition, a life cycle approach is a necessity to conduct meaningful carbon footprint analysis. On the other hand, Kennedy and Sgouridis [10] introduced different urban scale carbon footprint accounting approaches. Despite the fact that the system boundaries they defined are not totally proper for this study due to the differences in goal and scale, there are specific similarities in methodology, emission allocation criteria, and scoping.

The literature is abundant with various carbon footprint studies encompassing cities [11], corporates [12], federal buildings [13], households [14]. For more information covering current methods of estimation carbon footprint, please see Pandey et al. [15]. While carbon footprint calculations differ in boundaries, scopes, GHGs and methodology selected, the increasing number of carbon footprint reporting in response to legal and business demand paved the way for worldwide acceptance and adoption of the Greenhouse Gas Protocol (GHG Protocol) set by the World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD) [15]. Huang et al. [16] studied the categorization of indirect supply chain emissions (Scope 3) for enterprise carbon footprint accounting. Matthews et al. [17] discussed the importance of system boundaries and stressed the importance of Scope 3 emissions. Peters and Hertwich [18] studied carbon footprint of nations and indicated how consumption and production decisions drive global emissions. Especially in household consumptions, indirect impacts are found to be greater than the direct impacts [18]. Ramaswami et al. [19] point out the importance of demand centered life cycle approach for city-scale carbon footprint accounting. Heinonen and Junnila [20] utilized a consumption-based carbon footprint accounting model which stresses how the climate impacts of city-level development indirectly effect the global production of emissions. Kucukvar and Tatari [21] analyzed triple bottom line effects of seven different construction sectors in the U.S. and calculated carbon footprint of the U.S. construction sectors based on scopes set by WRI. Various studies stressing importance of indirect emissions can be found in literature. GHG Protocol is the most widely accepted and used international carbon footprint accounting framework in the world in which all possible indirect emissions are considered [22]. In this regard, this study is the first attempt employing WRI's carbon footprint accounting standard to the U.S. buildings holistically. Also, results of building LCA studies mostly vary due to differences in building type, climate, local regulations, scope, life time, functional unit considered, and system boundaries [23]. Thus, it is also important to standardize the scope of carbon footprint accounting framework for building studies, since most of the building LCA studies are not easy to compare due to the differences in the defined scopes and system boundaries [23,24].

In this study, GHG emission hotspots are identified through the construction, use, and disposal phases of the U.S. residential and commercial buildings in accordance with the WRI carbon footprint accounting standard. Residential buildings include single and multifamily structures. Office buildings, including financial buildings, special care buildings, medical buildings, multi-merchandise shopping, food and beverage establishments, warehouses, other commercial structures are categorized as commercial buildings according to the U.S. Department of Commerce's detailed output accounts [25].

The following section explains the organization of the research. First, the hybrid economic input–output model is introduced. Second, system boundary of the assessment is defined. Next, inventory analysis is conducted to elucidate corresponding data sources. Then, calculation methods of direct emissions and the Economic Input–Output Life Cycle Assessment (EIO-LCA) model are presented including some of the previous EIO-LCA studies and the mathematical framework of the EIO model. In Section 3, carbon emissions are quantified based on the Scopes and life cycle phases. After quantifying the total scope-based carbon emissions of the U.S. buildings, major carbon footprint contributors are presented with details and the results are evaluated with supportive information found in literature. Finally, the results are summarized and the future work is pointed out. Fig. 1 summarizes the analysis workflow.

2. Methodology

2.1. Hybrid economic input–output LCA approach

Life cycle assessment (LCA) is a widely accepted approach to quantify the environmental impacts of products or processes [26]. There are two main approaches to conduct LCA: process based (P-LCA) and input–output based (IO-LCA) [16]. P-LCA approaches use the materials and energy data for each process involved in an activity such as processes of manufacturing of a product. In P-LCA, every process took role in the supply chain of the product needs to be properly inventoried and analyzed. Advantage of this approach is its ability to achieve level of detail desired [27]. Yet, as the system boundary or scope becomes broader, analyzing each process in the supply chain can be challenging and time consuming. On the other hand, IO-LCA approach can easily capture emissions from entire supply chain and eliminates cutoff error. However, IO-LCA approach also introduces uncertainties due to the level of aggregation of the sectors representing the product or activity analyzed [16]. Also, IO-LCA approach can provide information for only typical processes which are well represented by I–O categories. Hence, the rest of the processes can be modeled by process analysis [28]. This approach is a combination of the P-LCA and IO-LCA, which is known as hybrid economic input–output based (EIO) approach. Various hybrid-EIO models have been mostly used for carbon footprint calculation at national and city scale, smaller scales such as carbon footprint of a product or a building were mostly conducted with P-LCA approaches [29]. For more information about different kinds of hybrid-EIO models and their applications, please see referred studies [28,29].

In this research, the Economic Input–Output Life Cycle Assessment (EIO-LCA), an IO-LCA model developed in Carnegie Mellon University, is utilized to calculate supply chain emissions and some of the on-site emissions in accordance with the WRI's system boundary definition [30]. Calculation of process and supply chain emissions are explained with more details in the following sections.

2.2. System boundaries

According to the WRI's carbon footprint accounting standard, GHG emissions are divided into three different scopes. Scope 1 refers to on-site emissions related to combustion of fossil fuels.