FAST ESTIMATION OF BUILDINGS' EMBODIED ENERGY USING ECONOMIC INPUT–OUTPUT METHOD FOR AN URBAN MODEL

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Abstract

Research has predicted that the global population shift from rural to urban areas in the 21st century will cause haphazard building and infrastructure development in cities (Reinhart et al., 2016; United Nations, 2014). According to the US Department of Energy, the building sector is responsible for nearly 40% of total US energy consumption (USDOE, 2018). This statistic underlines the role of the building sector in reducing energy consumption and consequential environmental impacts. However, as larger numbers of buildings are becoming more energy efficient during use phase, the share of embodied energy from the total life cycle energy of a building increases. This also highlights the importance of policies and regulations regarding less energy intensive building materials and construction practices to reduce the entire life cycle energy use of buildings.

One objective of this study is to estimate the embodied energy of 197 commercial buildings in the city of Pittsburgh, Pennsylvania, including but not limited to fire stations, police stations, recreation facilities, and campus buildings, as the first step toward completing the entire life cycle energy map of the city. We developed a fast method to estimate a building's embodied energy using publicly available construction cost estimate data and Economic Input-Output Life Cycle Assessment (EIO-LCA) (EIO-LCA, 2018). The construction cost required for EIO-LCA is estimated based on a few parameters: building function, number of stories, floor area, and location. Results show that the total embodied energy of the under study commercial buildings in the city is 7,340 TJ. With this project, an urban life cycle energy map will be created to aid with future infrastructure decision making related to energy production and the built environment.

Introduction

In 80% of countries, at least half of the population are predicted to live in urban areas by the year 2050, compared to 24% in 1950 (United Nations, 2014). This rapid rate of urbanization may lead to arbitrary growth of urban infrastructure and the built environment, potentially creating adverse environmental impacts (Reinhart et al., 2016). Furthermore, urban sprawl and new buildings have increased the energy demand worldwide (Zhao et al., 2017). In the United States, the building sector is responsible for nearly 40% of the total energy consumption, and at least 40% of the annual carbon emissions (USDOE, 2018; USEPA, 2009). The environmental impacts from the building sector are not limited to the operational phase of a building. Manufacturing of construction materials, construction activities, and demolition of a building are also known to be energy intensive with consequential emissions (Ding, 2004). In addition, as more buildings are becoming energy efficient, the percentage of embodied energy from the total life cycle energy of a building increases (Dixit et al., 2010; Nässén et al., 2007; Sartori et al. 2007). Thus, underlining the importance of policies and regulations regarding less energy intensive building materials and construction activities to reduce the total life cycle energy of a building.

The total energy consumed during the lifetime of a building can be divided into two broad categories: operating energy (OE) and embodied energy (EE) (Azari et al., 2018; Dixit et al., 2012). The operating energy is the energy consumed by heating/cooling systems, lighting, hot water systems, appliances, etc. during the operation phase of a building, which is generally from occupancy to demolition. Perez-Lombard et al. (2008) reported that space conditioning has the largest share of energy consumption in the residential building sector in the United States. Also, it is known that the amount of operating energy is highly dependent on climatic conditions, building function, occupant's behavior, and building thermal performance (Ding, 2004). The life cycle embodied energy of a building consists of three stages: First, initial embodied energy (IEE) refers to the energy consumed during extraction of raw materials (e.g., extracting iron ore for steel production), transportation to the manufacturing units, manufacturing processing, and the energy used during construction practices such as installation, assemblies, labor, operation of heavy vehicles, etc. (Azari et al., 2018; Cole et al., 1996; Dixit et al., 2012). The second stage, referred as the recurrent embodied energy, is described as the energy consumed during refurbishment and renovation activities. Finally, the total energy required for demolition of a building and treating the wastes (reuse, recycle, disposal) is known as the demolition energy (Azari et al., 2018; Dixit et al., 2012).

Conducting regional studies for estimating the embodied energy of buildings can aid urban planning since it can be considered as a measure of investment. City planners and utilities managers can align their future investments for developing new infrastructure and prioritizing maintenance of existing ones based on the current embodied energy of different geographic regions in a city. For example, in regions where the total embodied energy of existing buildings is higher, investing in district energy systems or decentralized water systems may be more beneficial.

Estimating the embodied energy of a product or service can be done using life cycle assessment. Life cycle assessment (LCA) is a scientific method of identifying and gathering inventories of inputs and outputs required for producing a product or process, along with assessing associated energy and environmental impacts (ISO, 2014). There are two common approaches to LCA that each have their own advantages and limitations—process-based life cycle assessment (process LCA) and Economic Input-Output Life Cycle Assessment (EIO-LCA). These two approaches can also be combined in a hybrid LCA (Bilec et al., 2006; Bilec, 2007; Treloar et al., 2000).

Employing process-based LCA to calculate embodied energy, as in the case of this paper which is focused on embodied energy, starts by identifying different components or unit processes 'upstream' of the product or process such as raw material extraction and the downstream processes such as maintenance and demolition (Treloar, 1998). Although process-based LCA aims to provide accurate results (Ding, 2004), it usually suffers from the issue of incompleteness because tracking the origin of each component relies on either primary data obtained from data collection, or secondary data obtained from existing datasets. In addition to incompleteness, estimating the embodied energy based on process LCA is labor intensive, time consuming, and has boundary issues (Crawford, 2004).

In order to overcome the limitations of a process-based method, EIO-LCA can be utilized. Input-output, developed by Leontief in 1970s, uses the transactions between different industrial sectors of an economy that are involved in producing a product or providing a service (Leontief, 1970). I-O tables are developed to demonstrate the cost of goods and services that are needed from other industrial sections to produce a particular product. Through inverse matrix operations, the I-O tables are multiplied by an energy and environmental vector, to then estimate the associated energy use and environmental impacts; this can be completed online through the free, publicly available tool, EIO-LCA. Because EIO-LCA accounts for the entire flows of goods and services required for manufacturing a product in an economy, the results encompass the defined system boundary and the issue of incompleteness is largely resolved, but exports are not included. While both approaches have advantages and disadvantages, EIO-LCA was used to calculate the embodied energy of 197 commercial buildings and develop a life cycle energy map of the city for its ease of use and synthesis with the cost estimating approach.

Urban scale energy policies are less effective unless they incorporate various urban elements like transportation, buildings (material, operation), land use, and water use (Mostafavi et al., 2017). In the past 50 years, federal, state, and local policies and legislations regarding energy efficient equipment and buildings have had substantial positive impacts on energy and emissions reduction worldwide. For instance, Geller et al. (2006) reported that implementation of building codes for new construction along with standards for equipment and appliances, reduced the electricity consumption in California by 7% in 2000 compared to the 1970s. Although regulations in a variety of forms like building codes (e.g., International Energy Conservation Code [ICC, 2015]) have resulted in significant reduction of operating energy, there is still a gap in existing policies regarding less energy intensive building materials and construction and refurbishment practices. For effective policies and regulations to be enacted, decision makers should be provided with information regarding how much energy was consumed during construction of a building and where the energy is most concentrated in a city.

This paper aims to propose a fast technique to estimate the initial embodied energy (IEE) of buildings along with developing a life cycle energy map in order to provide city planners with visualization tools. This fast technique makes an estimation of embodied energy of thousands of buildings in urban scale possible, less expensive, and less time consuming. Furthermore, we investigate how the results vary spatially by comparing regional results to national average results.

Methodology

The embodied energy of buildings is estimated using EIO-LCA, which was developed by Carnegie Mellon University (EIO-LCA, 2018). The tool is designed to generally conduct "cradle to gate" life cycle assessment, so it does not account for energy and environmental impacts of a product or service during use phase and end of life (EIO-LCA, 2018). The EIO-LCA model that is used in this study is US 2002 Producer Price which contains 428 sectors derived from North American Industry Classification System (NAICS). Table 1 represents some examples of NAICS's sectors that are used in the background analysis of EIO-LCA (OMB, 2017). The studied buildings that belong to the University of Pittsburgh and the city are located in Pittsburgh, Pennsylvania, and include but are not limited to laboratories, dormitories, office buildings, fire stations, police stations, and recreation facilities.

NAICS Code	NAICS Sector
238110	Poured Concrete Foundation and Structure Contractors
23812	Structural Steel and Precast Concrete Contractors
23813	Framing Contractors
23814	Masonry Contractors
23815	Glass and Glazing Contractors
23816	Roofing Contractors
23817	Siding Contractor
23819	Other Foundation, Structure, and Building Exterior Contractors
23821	Electrical Contractors
23822	Plumbing, Heating, and Air-Conditioning Contractors
23831	Drywall and Insulation Contractors
23832	Painting and Wall Covering Contractors
23833	Flooring Contractors
23834	Tile and Terrazzo Contractor
23835	Finish Carpentry Contractor
23891	Site Preparation Contractors

Table 1: Potential NAICS's sectors used by EIO-LCA for estimating a building's embodied energy and environmental impacts. (Source: OMB, 2017.)

Because EIO-LCA relies on the cost of a product, the analysis begins with estimating the construction cost of the buildings. In order to calculate the construction cost without having access to architectural and structural drawings, an online tool called "building journal" was utilized (Online Construction Estimating, 2018). This fast estimation of construction cost is based on the following variables: 1) building function, 2) number of stories, 3) floor area, 4) project location, and 5) cost index. The cost index indicates a building's condition (low, median, high), and our analysis considered median for all buildings. Also, the EIO-LCA model applied in this study is based on US 2002 Producer Price model, thus overhead, profit, and bonding costs are not considered in estimating the construction cost. The monetary results obtained from the building journal represent the 2018 US currency rate; therefore, these results are deflated to the 2002 US currency rate to be consistent with the US 2002 Producer Price model for construction of nonresidential commercial and health care structures.

After the embodied energy was calculated, we created an urban embodied energy map, in which the Geographic Information System (GIS) was used. The map contains several layers, such as Pittsburgh's boundary, the city's zip codes, building footprint, etc. These layers were originally obtained from Western Pennsylvania Regional Data Center, which is a publicly available dataset (WPRDC, 2018). The GIS dataset was completed by adding different attributes of buildings such as number of floors, tax parcel ID, floor area, construction cost, and embodied energy to the existing layers. These attributes were gathered from multiple resources (e.g., tax property assessment, Google Earth) and visual observation of case study buildings. The map presents the embodied energy of buildings as embodied energy use intensity (embodied energy per square foot of floor area). The ultimate goal of this study is to motivate the city to employ this methodology to estimate the embodied energy use intensity of all the buildings and present the results at zip code level or smaller geographic boundaries (e.g., census tract) for further planning purposes.

Results

The estimated total construction cost of the 197 commercial buildings in Pittsburgh was $879.52 million based on the 2002 US currency rate. The embodied energy of studied buildings obtained from EIO-LCA was estimated to be 7,340 TJ. The EIO-LCA US 2002 Producer Price model for construction disaggregates IEE of buildings into various construction related categories. Ten categories that have the largest share are presented in Figure 1, with the eleventh category as "other." Results show that commercial and health care structure has the largest share among other categories (41% of total initial embodied energy).

In order to investigate the impact of geographic location on the initial embodied energy, the construction cost was estimated using the national average for further comparison with Pittsburgh's results. The initial embodied energy of case study buildings based on Pittsburgh's construction cost was 2.6% higher compared to that of the national average. This slight difference suggests that the cost of building materials and construction activities in Pittsburgh is almost the same as the national average. Figure 1 also shows the difference between total IEE calculated based on the national average versus Pittsburgh along with disaggregated embodied energy by different categories (e.g., truck transportation, cement manufacturing, oil and gas extraction, etc.) for both scenarios.

The energy map developed for urban planning and infrastructure investment purposes depicts the embodied energy of case study buildings in the form of embodied energy use intensity for each building. It also provides a broad vision of how the map would look like if data for all buildings in Pittsburgh including floor area, building function, etc. were available and their embodied energy were calculated by employing the proposed technique. As is shown in Figure 2, the buildings that are involved in this study are scattered in the city except the ones that belong to the University of Pittsburgh. The part of the map that highlights the university's campus is an example of how the city's complete energy map would look like when all buildings are engaged in this program and how it will aid decision makers with their future investment plans in the city.

Discussion

This research introduces a building's embodied energy as a measure of investment for new infrastructure development and prioritizing refurbishment of existing ones in an urban environment. In addition, the energy map may provide the city and local decision makers with a better vision of where the energy is concentrated and how to invest their budget for developing new roads, bridges, public transportation facilities, etc. to improve sustainability in Pittsburgh. Likewise, decision makers and regulators may utilize embodied energy as a basis for enacting policies and regulations regarding more energy efficient construction and refurbishment activities. Conducting life cycle assessment in large scale for example urban areas is known as expensive, time consuming or even impossible due to lack of available data and tremendous amount of detail. The fast estimation of a building's construction cost is a new approach to use monetary value of buildings along with input-output LCA to conduct urban-scale life cycle assessment. Although one of the shortcomings of input-output LCA is lack of accuracy in comparison with process-based LCA, accessing and processing detail information of thousands of buildings for conducting process-based LCA in urban-scale seems burdensome and inefficient. Thus, we can suggest that input output analysis provides sufficient and reliable information to be utilized in urban planning.

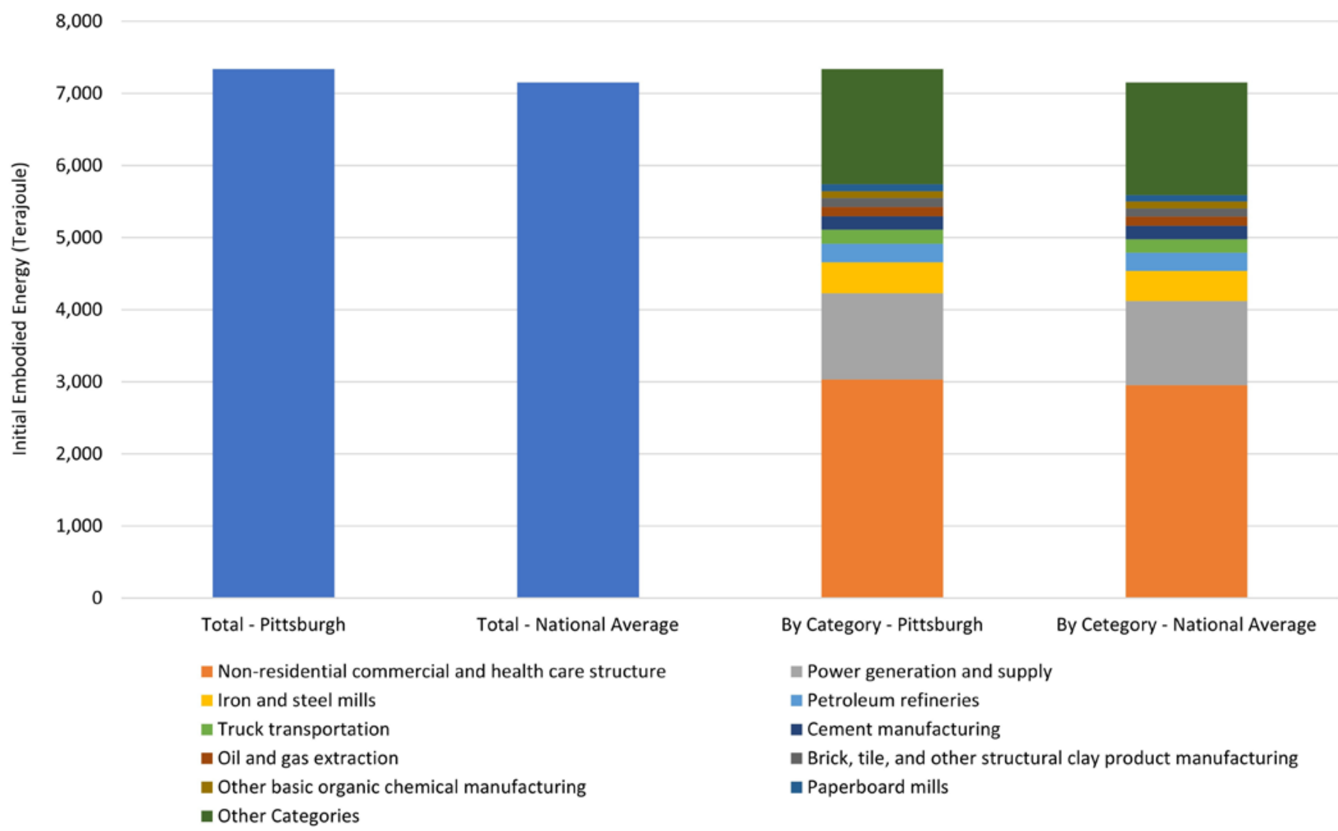

Figure 1: Initial Embodied Energy (IEE) of case study buildings obtained from EIO-LCA. The construction cost is based on Pittsburgh and the national average.

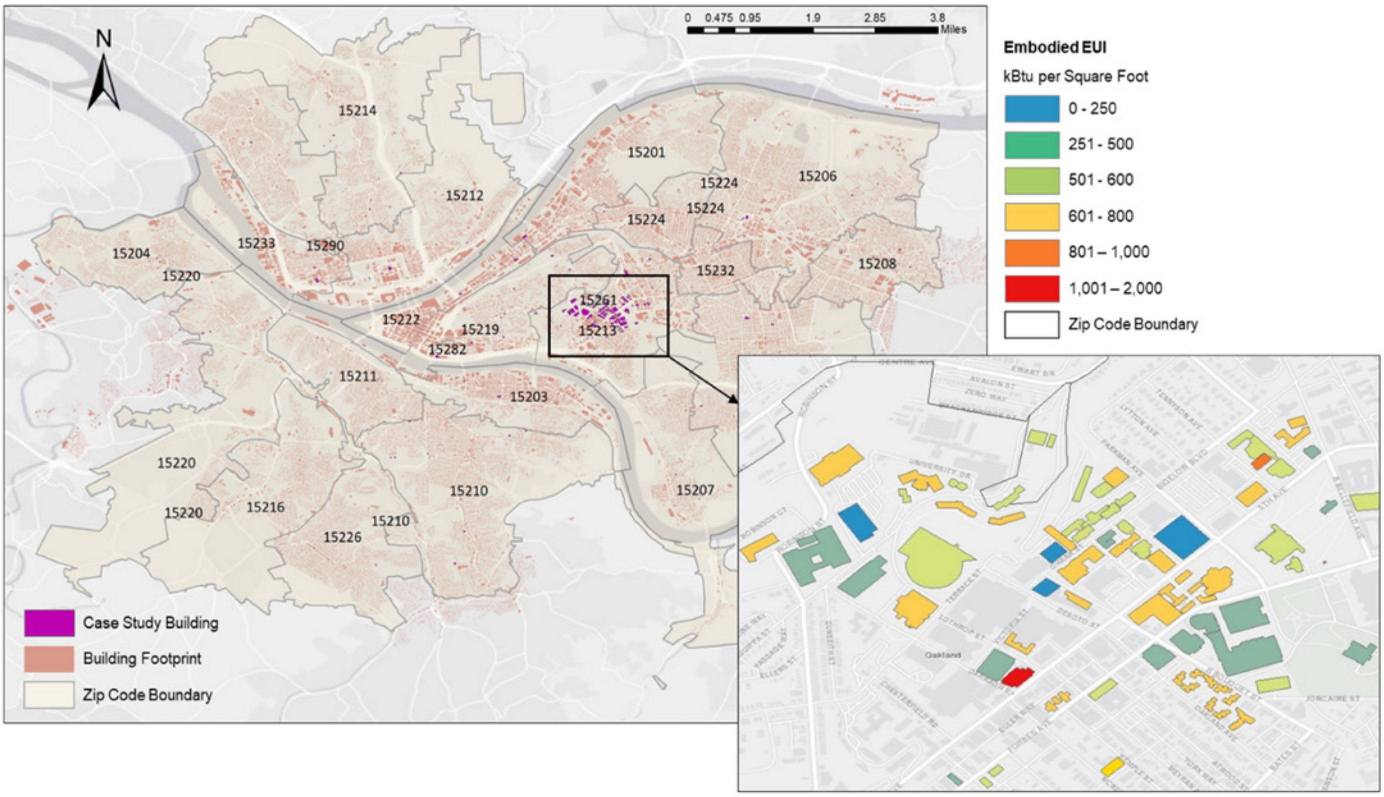

Figure 2: Embodied energy intensity map for case study buildings in Pittsburgh. Energy use intensity is presented in kBtu per square foot.

Existing literature has drawn attention to the limitations regarding the EIO-LCA tool. Uncertainty due to aggregating smaller industrial sectors to form a bigger sector inhibits an LCA practitioner from discovering energy and environmental impacts of smaller sectors (EIO-LCA, 2018). Future studies are required to address this model uncertainty in addition to uncertainty caused by input variables of our proposed approach, such as building function, number of stories, floor area, etc. According to Chouquet et al. (2003), there are different means of accounting for uncertainty in building LCA like scenario analysis, probabilistic approaches, etc. For example, Monte Carlo simulation, a probabilistic approach, can be employed to first form the probability distribution functions of input variables, then estimating embodied energy based on selected values from the distributions for each input. Iteration of this process for numerous times will result in probability distribution function of embodied energy. Moreover, comparing Pittsburgh scenario with national average scenario, which was conducted in this study, can be recognized as a scenario-based uncertainty analysis accounting for geographic location.

As building stocks are aging, the significance of energy required for refurbishments including construction materials, renovation activities, and processing wastes is becoming undeniable. Future studies can focus on employing the proposed approach as a foundation for estimating the energy embedded in refurbishment activities. Niko et al. (2018) developed a scenario-based model to compute the required energy and environmental impacts of refurbishments for Swiss building stock. They projected six refurbishment scenarios for building stock based on different percentages of the initial embodied energy (Niko et al,. 2018). The recommended methodology by Niko and colleagues along with the results of this study can be used by the city of Pittsburgh to compute the embodied energy and the environmental impacts of refurbishing Pittsburgh's building stock.

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