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Embodied energy analysis of building materials: An improved IO-based hybrid method using sectoral disaggregation

Manish K. Dixit

Department of Construction Science, Texas A&M University, 3137 TAMU, College Station, TX, 77843, USA

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ABSTRACT

Buildings consume approximately half of the annual energy supply of the United States in their construction and operation. To effectively decrease this extensive energy footprint, both embodied and operating energy must be quantified and optimized. Although validated standard methods are available to compute operating energy, quantifying embodied energy is still complicated and inconsistent. Among the available embodied energy calculation methods, an input-output-based hybrid (IOH) method has the potential to offer a more complete calculation. However, its calculation lacks specificity and reliability, which can be improved using suggestions provided by literature. Studies across the globe have proposed techniques such as sectoral disaggregation to enhance not only the specificity and reliability, but also the completeness, of an IOH method.

This study investigated and improved an IOH method of embodied energy calculation. Using the improved method, the embodied energy of commonly used building materials was calculated and evaluated. The results demonstrate a significant difference after disaggregating the relevant industry sectors. The study concludes that using embodied energy values without industry sectors being disaggregated can cause significant errors in a building's embodied energy calculation.

1. Introduction

The building sector consumes nearly two-fifths of the annual global energy supply in building operation alone, adding significant carbon emissions to the atmosphere [1]. In the United States, approximately 48% of annual energy is consumed in building construction and operation [2]. Most of this energy originates from fossil fuel sources and consequently contributes to over 39% of the nation's annual carbon emissions [1–3]. The total energy use of a building includes embodied and operating energy; this study focuses on embodied energy. During a building's initial construction, embodied energy is used directly in onsite and offsite construction, fabrication, transportation, administration, and related services, and indirectly through the use of building materials, assemblies, and equipment [3–5]. Each product installed in the building consumes energy during its raw material extraction, manufacturing, and delivery to the construction site. The sum of all direct and indirect energy consumed during building construction is called initial embodied energy (IEE) [6,7]. While occupied, a building consumes recurrent embodied energy (REE) directly and indirectly [7–9] throughout the maintenance, repair, replacement, and renovation phases. To effectively optimize the total energy footprint of the building sector, reducing both embodied and operating energy is recommended [10–12]. Due to building energy research targeting mostly operating energy, advanced and energy efficient materials, appliances, and assemblies are being installed in buildings that gradually decrease their operating energy [13–15]. Also, more standardized methods and tools are now available to consistently compute operating energy [6]. Quantifying embodied energy, however, is still complicated and resource-intensive and requires extensive quality data, which usually is not available [16–19]. The lack of a standard method to completely and accurately calculate embodied energy further complicates the embodied energy analysis of buildings [6,17,20].

The available embodied energy calculation methods are promising but also have flaws that must be addressed [8,21–23]. For instance, process-based methods provide material-specific and reliable results but are grossly incomplete due to a system boundary truncation [8,16,24]. The IO-based methods are relatively complete but do not provide material-specific results [1,24]. A method's completeness refers to the extent to which all major and

E-mail address: mandix72@hotmail.com.

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minor energy flows are covered in the calculation [8,22]. A hybrid method combines the reliability of a process-based method with the system boundary completeness of an IO-based method to provide a complete and reliable embodied energy calculation [7,17]. However, if an IO-based hybrid framework is applied, the results still are highly aggregated lacking specificity [8,25,26]. This inability of an IO-based hybrid (IOH) method to provide material-specific results is a major problem that may be addressed through disaggregating an industry sector in an IO framework. Studies (e.g. Refs. [16,25–29]) have demonstrated the process of sectoral disaggregation using similar approaches. Various versions of an IOH method have been proposed by Bullard et al. [30], Carter et al. [31], Treloar [25], Dixit et al. [6], and Crawford [24], showing gradual improvements.

This study builds upon a previous study [6], which quantified and integrated human and capital energy into an IOH model. In this study, some of the industry sectors of the IO model were disaggregated to demonstrate the calculation of building material-specific embodied energy. Using the improved IOH model, the embodied energy of commonly used construction materials was calculated. The results were also compared with the values obtained from other embodied energy calculation methods to highlight and discuss major differences.

2. Literature review

2.1. Embodied energy calculation methods

Among the widely used embodied energy calculation methods are: (1) process-based, (2) IO-based, and (3) hybrid methods [1,4,24,25]. Each method differs in the extent of its system boundary coverage [8]. A system boundary defines the energy inputs included in a study.

2.1.1. Process-based analysis

While process-based analysis provides material-specific energy values, its calculations are significantly incomplete [16,21,22]. It is a bottom-up approach that starts with gathering data of actual energy use from manufacturers and works backward covering most of the direct and some indirect energy inputs. Beyond a certain point in the upstream, gathering energy use becomes difficult and in some cases impractical due to data unavailability. Consequently, some processes for which data is unavailable remain excluded from the calculation causing a truncation of the system boundary [32,33]. Lenzen [33] quantified the incompleteness and truncation error due to boundary truncation as 50% and 10%, respectively. To calculate the embodied energy of a building, all material quantities are calculated and multiplied with respective process-based embodied energy intensities [1,24]. Although such calculations provide energy values specific to the building, the energy embodied in building construction, administration, and related services (e.g. banking) remains excluded from the calculation [24–26]. The activities of construction management, financing, code compliance, etc., often involve energy consumption through added labor, equipment and vehicle use, and other non-energy material usage such as office supplies, which may be quite difficult to quantify if a conventional process-based approach is used [23–25]. Other energy inputs, such as the energy used in remediating the adverse environmental impacts of building material production and construction, are also excluded from process-based calculations [8,25]. For instance, if a material manufacturing plant treats its emission, discharge, or waste before releasing it to the environment, such processes also consume energy, which must be allocated to building material production. Construction sites are also required to treat and divert any construction discharge from the sites, which may involve energy use through equipment and vehicles [8,23].

2.1.2. Input-output (IO)-based analysis

An IO-based embodied energy calculation is a top-down approach in which direct requirement coefficients are derived from an economic input-output model [34]. A direct requirement coefficient represents inputs (in $) required by an industry sector from other sectors to produce a unit dollar output [35]. Using direct requirement coefficients, direct energy inputs from energy providing sectors can be quantified [6,25]. Since each industry sector has a chain of suppliers, all direct requirements also cause indirect requirements. For instance, when the cement industry sector increases its production of cement by $1, all other industry sectors supplying inputs, such as coke, limestone, gypsum etc., also increase their production in order to meet the increased demand. Such increased requirements are termed stage one indirect requirements [6,35]. Each supply sector also has a chain of other sectors supplying inputs, which also increase their output as stage 2 indirect requirements. Likewise, there are indirect requirements associated with stages 3, 4, 5, and so on up to infinity. The increased output of the cement sector actually causes an economy-wide indirect impact [8,23–26]. The total indirect requirement is the sum of all indirect requirements spread over stage 1 to stage ∞ [6,8]. These stages of indirect requirements are known as indirect stages. Fig. 1 illustrates the direct and indirect inputs associated with various stages. To calculate indirect requirements, direct requirements are subtracted from the total requirements. The total requirements are calculated using either Leontief's inverse matrix or power series approximation (PSA) method [6,24–26]. More details on these methods can be found in Miller and Blair [35]. Using appropriate energy tariffs, the direct and indirect energy requirements can be translated from monetary to energy units [24–26,36].

An IO-based analysis covers a comprehensive system boundary, as it accounts for the economy-wide inflows and outflows [31,36–38]. However, its results may be highly aggregated and not product-specific [39–41]. For instance, in an IO analysis, the embodied energy of structural steel is calculated by quantifying the energy intensity of the manufacturing sector producing structural steel as well as a wide range of other steel products. This approach assumes that all of the sector's products have the same embodied energy, which may be inaccurate [6,8,23–26]. Also, since the input and output of energy sources is tabulated in monetary units, energy tariffs are used to convert them to energy units [6,8]. If energy tariffs are miscalculated, the quantified values of embodied energy may contain significant errors [6,8,26]. The energy intensity of a manufacturing sector is calculated in energy units per unit of monetary output. To convert energy intensity into energy units per mass or volume, product prices are used. Like energy prices, any fluctuation in product prices grossly affects the embodied energy calculation [6,8,26]. IO tables are also prepared based on the assumptions of homogeneity and proportionality [24,25]. According to the homogeneity assumption, each product produced by a sector has a homogeneous mix of inputs that may not be correct. In the proportionality assumption, the cost of a product is directly proportional to its input requirements, which may be inaccurate [24,37]. According to Treloar [25], an IO-based embodied energy calculation entails counting energy inputs multiple times. For instance, if the electricity sector purchases large amounts of coal, natural gas, and petroleum, the total energy embodied in electricity, according to the IO model, would include all energy purchased, as well as the energy content of generated electricity [38].

2.1.3. Hybrid analysis

Hybrid analyses combine the benefits of process-based and IO-