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Embodied energy analysis of higher education buildings using an input-output-based hybrid method

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ABSTRACT

During construction and operation, buildings consistently consume nearly half of the global energy supply, indicating a huge potential for reducing annual carbon emissions. This energy use includes operating energy and the three key life-cycle embodied energy components: initial embodied energy (IEE), recurrent embodied energy (REE), and demolition energy (DE). Embodied energy is consumed directly through processes and indirectly through products installed in a building. Unlike operating energy, measuring embodied energy is a complex, unstandardized, and very data-intensive process. Each available embodied energy calculation method differs in its data sources, system boundary coverage, and limitations. An IO-based hybrid (IOH) method could provide more complete, reliable, and study-specific results if appropriate improvements are made to the IOH model. In this study, we developed an IOH model for the United States' economy by integrating human and capital energy and computed the IEE of five higher education buildings. The results suggest that using an aggregated construction cost for calculating IEE may underestimate results in comparison to using disaggregated construction cost components because the calculated values of IEE increased significantly after the cost disaggregation. The relative proportions of different energy sources also changed considerably because of the cost disaggregation.

1. Introduction

The signs of a rapidly changing climate due to the warming of the planet are evident in the increasing frequencies and intensities of extreme weather events, such as storms, flash floods, tornadoes, hurricanes, and droughts [1,2]. The key cause of this global warming is the emission of carbon dioxide into the atmosphere from fossil fuel consumption [3,4]. A huge potential exists in the building sector to radically reduce fossil fuel consumption and the resulting carbon emissions [5–7]. The building sector depletes nearly half of the world's annual energy supply in building construction, operation, and other related processes [3,8]. Over 90% of this energy use comes from fossil fuel-based sources, which adds significantly to annual carbon emissions [4,9]. For instance, in 2016, the United States' residential, commercial, and industrial sectors consumed 91%, 94%, and 90% fossil fuel-based energy sources, respectively [9]. Such heavy dependence on fossil fuels, as well as the resulting carbon emissions, can be reduced considerably by reducing the life cycle energy consumption of buildings [10–12]. A building consumes embodied energy and operating energy over its service life [8,13,14]. The embodied energy is used directly, onsite and offsite, in construction and other related processes and indirectly using materials, products, and pieces of equipment [6,15–17]. It is consumed in a building's initial construction as initial embodied energy (IEE), through its maintenance and replacement as recurrent embodied energy (REE), and during its demolition as demolition energy (DE) [14,18,19]. The life cycle energy, therefore, includes operating energy and the embodied energy components of IEE, REE, and DE [19,20].

The relative proportions of embodied and operating energy in total life cycle energy have been debated extensively in the literature [6,21–23]. These proportions depend on a multitude of factors such as geographic location, building design, and construction type [24–26]. However, a consensus emerges from the literature around the fact that the significance of embodied energy will increase, particularly as the number of energy-efficient buildings grows [26–29]. In fact, studies argue that, in most cases, operating energy efficiency is gained at the cost of increased embodied energy [10,12,30]. Addressing embodied and operating energy collectively, therefore, is crucial for creating buildings with zero-life cycle energy and carbon footprint [10–12]. Measuring and evaluating embodied energy is more challenging than operating energy because of a lack of complete and accurate embodied energy data [6,29,31], and no consensus exists on a standard method to mea-

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sure it [17,28,32]. Three approaches are used commonly to measure embodied energy: process-based, input-output (IO)-based, and hybrid approach [2,31,33,34]. The three approaches cover different system boundaries, utilize different data, and result in differing embodied energy values [2,8,35], and each method has limitations in terms of completeness, reliability, and specificity [6,7,32,36]. A process-based calculation is deemed reliable but highly incomplete because of data unavailability and the resulting system boundary truncation [26,28,34,37]. An IO-based method, on the other hand, is considered complete in terms of system boundary coverage, but its results are regarded as unreliable because it utilizes price data that may be under or over-estimated [7,28,34]. These two methods are combined in a hybrid approach to enhance both reliability of the calculation and system boundary completeness [2,34]. A hybrid approach can have a process-based or IO-based framework and may contain some of the limitations of the two methods [6,20,32]. For instance, a process-based hybrid method still carries some system boundary incompleteness due to its process-based framework [6,38]. Similarly, an IO-based hybrid (IOH) method may still use unreliable price data introducing some unreliability to embodied energy results [6,16]. The issue of system boundary incompleteness of a process-based framework may cause more error in the calculation than the reliability issue of an IO framework [4,38–40]. To provide more complete, specific, and reliable embodied energy results, an IOH calculation may apply techniques of sectoral data disaggregation and human and capital energy integration [6,20,41].

In this paper, we developed an IOH model for the United States' economy to compute the embodied energy of five higher education buildings. We used two versions of the IOH method. In the first version, we used the energy intensities of the *Educational and Vocational Structures* commodity to compute embodied energy at the project level. The latest 2007 Benchmark Input-Output Data include highly disaggregated construction sectors and commodities. In the second version, we computed the IOH embodied energy of major materials and services and integrated the remaining inputs using the energy intensities of the *Educational and Vocational Structures* commodity. We then compared the results of the two versions to investigate if the calculations at the material or service level provide different results.

2. Literature review

2.1. Embodied energy

The energy embodied in a building includes all non-renewable energy sources consumed in processes and products used during initial construction, maintenance and replacement, and final demolition [17,42–44]. All renewable energy systems may also contain some non-renewable embodied energy, which must be accounted for [45–47]. For instance, a solar photovoltaic cell may consume non-renewable energy when it is manufactured and delivered to a building site. Embodied energy may be consumed by machines as well as through human labor [2,48–50]. In some countries, the manufacturing and construction sectors are highly labor-intensive and labor energy may account for a considerable portion of the total embodied energy [51–53]. For instance, Dixit et al. [2] found that approximately 1%-9% of the embodied energy of construction materials in the United States could be attributed to human labor. This percentage could be significantly more in labor-intensive countries such as India and China [2]. The energy consumed by both machines and labor should be counted towards embodied energy [2,50,52]. Embodied energy also includes all capital inputs required to construct a building or manufacture any of the materials, assemblies, or pieces of equipment installed in the building [2,54]. For instance, manufacturing of materials requires plant structure and machinery, which must be partially counted towards the materials' embodied energy. Similarly, a construction site utilizes hoisting and heavy equipment, construction vehicles, and tools, each of which uses energy during its manufacture and delivery that must be allocated partially towards a building's embodied energy [2,7,18].

2.1.1. Direct and indirect energy components

The embodied energy of a building is composed of direct and indirect energy components [4,12,55]. Understanding the concept of a main process and its upstream and downstream processes is important to comprehend the idea of direct and indirect energy. When a building is constructed, its construction is the main process, whereas the manufacturing of any materials, assemblies, or pieces of equipment installed in it are upstream inputs [8,15]. Once the building is complete, any inputs required during its life cycle management are its downstream inputs [8,15]. Similarly, when a material is manufactured, its manufacturing is the main process, whereas raw material procurement and delivery is an upstream and packaging and delivery is a downstream process [6,56]. Mostly, a direct energy component is consumed in the main process, whereas an indirect energy component is used primarily in upstream and partially in downstream processes, particularly in the case of a building [6,15,56].

When a building is constructed, any energy sources used directly, onsite and offsite, in the main processes (e.g., construction, fabrication, transportation, administration, consulting) represent the direct energy component [7,28,57]. To comply with environmental regulations, construction sites may also treat their discharge and construction waste, thus consuming some form of energy directly [4]. Note that the energy consumed by both machines and labor are included in this direct energy component. Indirect energy is consumed using non-energy inputs such as, building materials, assemblies, and pieces of equipment installed in a building [4,7,12,55], most of which are consumed in upstream processes. All non-energy inputs contain embodied energy, which is consumed directly and indirectly during initial extraction, processing, transportation, manufacturing, and delivery to construction sites [7,12,18]. If such processes of non-energy inputs' manufacturing and delivery involve environmental remediation, any energy used in remediation must be included in an embodied energy calculation [8,58–60]. When a non-energy input such as a construction material is manufactured, its embodied energy also contains direct and indirect energy components [7,16,17]. All energy sources consumed directly in the main process of manufacturing become the direct energy component, whereas all raw material inputs in the upstream and downstream of its manufacturing are counted as indirect components [6,8].

Accounting for direct energy use is relatively less complicated than for indirect energy because of the lack of energy and non-energy input data [2,15,20,61]. For instance, to compute the indirect energy of cement production, all energy and non-energy inputs of its raw material must be accounted for as stage one inputs [8,15,61]. The production and supply of these energy and non-energy inputs also consume energy and non-energy inputs, which must be included in the indirect energy calculation as stage two inputs. Similarly, there are energy and non-energy inputs for stages three, four, and so on up to stage infinity [2,8,15,61]. Evidently, collecting actual data of all energy and non-energy inputs of all stages is impractical [8,15,61].

2.1.2. Life cycle components

The total energy embodied in a building is composed of Initial Embodied Energy (IEE), Recurrent Embodied Energy (REE), and Demolition Energy (DE) [18,32,57]. The IEE is consumed directly and indirectly in a building's initial construction, whereas REE is used directly and indirectly in a building's maintenance and