Renewable and Sustainable Energy Reviews 79 (2017) 390–413

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Life cycle embodied energy analysis of residential buildings: A review of literature to investigate embodied energy parameters

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ARTICLE INFO

Keywords:
Embodied energy
Building materials
Data quality
Life cycle analysis
Life cycle energy
Embodied energy uncertainty

ABSTRACT

Approximately half of the annual global energy supply is consumed in constructing, operating, and maintaining buildings. Because most of this energy comes from fossil fuels, it also contributes greatly to annual carbon emissions. When constructing a building, embodied energy is consumed through construction materials, building products, and construction processes along with any transportation, administration, and management involved. Operating energy is used in space conditioning, heating, lighting, and powering building appliances. In order to effectively reduce the carbon footprint of buildings, a comprehensive reduction in both embodied and operating energy is needed. Studies so far have focused on reducing either embodied or operating energy in isolation without realizing the trade-off that exists between them. Also, building energy research has concentrated more on operating energy than embodied energy, and as a result, the operating energy of buildings is gradually decreasing. Due to a variety of issues, however, few efforts have been undertaken to comprehensively minimize embodied energy.

Quantifying embodied energy is more tedious, complex, and resource-consuming than measuring operating energy. Furthermore, the reported values of embodied energy vary significantly within and across geographic regions owing to certain methodological and data quality parameters. The literature has repeatedly pointed out a need to standardize these parameters to bring consistency to embodied energy calculations. This paper presents a rigorous review of literature in order to investigate these parameters and their impact on embodied energy calculations. The reported values of initial and life-cycle embodied energy are also presented to highlight variations due to differing parameters. Finally, we suggest a two-step solution to make the process of embodied energy analysis more streamlined and transparent through a set of guidelines and an uncertainty calculation model.

1. Introduction

Buildings consume approximately 48% of global energy each year in their construction, operation, maintenance and deconstruction [1,2]. Energy is consumed directly in buildings mostly as delivered energy sources such as electricity and natural gas. Buildings also use energy sources indirectly through the use of construction materials. Each construction material installed in a building consume primary energy (e.g. coal) and delivered energy (e.g. gasoline) in its manufacturing and transportation to a construction site [3–5]. The sum of primary energy consumed in constructing a building through the use of construction materials, products, and processes, along with related transportation, administration, and services is collectively known as embodied energy [6–8]. During the use phase, when the building is occupied, primary and delivered energy is used in space heating and cooling, lighting, and operating appliances [9,10]. Although life-cycle operating energy is conventionally found to be greater than a building's total life-cycle embodied energy [5,11,12], recent research has provided evidence of the increasing proportion of embodied energy in total life-cycle energy, particularly with the increasing emergence of more energy efficient buildings [13–15]. For instance, Sartori and Hestnes [16] concluded that embodied energy could account for 2–38% of the total life-cycle energy of a conventional building, whereas this range could be 9–46% in the case of a low-energy building. A low-energy building, according to Sartori and Hestnes [16], is designed to minimize its operating energy usage. Thormark [17] also found that the energy embodied in a low-energy house could account for roughly half of total life-cycle energy. Thormark [17] argued that a low-energy building consumes more material and less operating energy (mostly electricity) than a conventional building. Recently, Shadram et al. [18] found that the share of embodied energy could be up to 60% of total building energy use. However, the literature agrees that the proportions of embodied and operational energy cannot be generalized because they depend on multiple factors, such as location, climate, and fuel source [12,19,20].

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http://dx.doi.org/10.1016/j.rser.2017.05.051
Received 7 October 2016; Received in revised form 12 May 2017; Accepted 12 May 2017
Available online 23 May 2017
1364-0321/

Additionally, a consensus is building to quantify and optimize both embodied and operating energy rather than analyze them separately.

Previous embodied energy studies showed considerable variation in the reported embodied energy values owing to differing parameters [2,21–25]. Studies also clearly emphasized the inaccuracy and incompleteness inherent in current embodied energy data of building materials [15,26–30]. These problems make it difficult to compare embodied energy values across studies [15,29]. Inaccurate, incomplete, and inconsistent data is questionable to use for selecting low embodied energy materials by construction professionals, such as architects, engineers, and facility managers [31–33]. Certain parameters cause variation in embodied energy values, which is discussed in detail elsewhere [29,33]. Some of the parameters are methodological such as the differences of system boundary, embodied energy calculation method, and energy units. Other parameters are mainly data quality issues such as, the incompleteness, inaccuracy, and non-representativeness of data used. [24,29,33].

This paper investigates the current state of embodied energy parameters through a rigorous literature review of embodied energy studies from around the world. The main purpose is to investigate how these methodological and data quality-related parameters vary across the referred studies and cause inconsistencies in the calculated embodied energy values. We then answer two questions: (1) can comparability be achieved across embodied energy studies? and (2) should all embodied energy parameters be standardized to streamline embodied energy calculation? We finally recommend a two-step solution to address these differing parameters. For investigating the embodied energy parameters, we focus on studies of a wide range of building types. For demonstrating the variation in reported embodied energy values due to the embodied energy parameters, we mainly focus on published studies of residential building sector, which is the largest consumer of energy [34].

2. Literature review

The reported embodied energy values of buildings and their materials vary considerably across studies, up to 30–50% [27]. Szaley and Nebel [35] performed a comparative study to evaluate New Zealand embodied energy and carbon dioxide emission data against overseas data. They found the New Zealand values to range from 20% to 350% of the overseas values. Studies such as Dixit et al. [24,29] and Omar et al. [33] have also underscored the problem of embodied energy variations within and across geographic locations. The following sections discuss these parameters that cause wide variations:

2.1. Methodological parameters

Key methodological parameters include system boundary definitions, methods of embodied energy measurement, and type and form of energy included in embodied energy calculations.

2.1.1. System boundary

The system boundary illustrates schematically products and processes used in the manufacturing of a product under study. A system boundary also demarcates energy and material inputs covered in an embodied energy calculation [12,30,36,37]. A building's system boundary may cover distant upstream stages such as raw material extraction to downstream stages such as its deconstruction and material disposal. Among commonly applied system boundary definitions include “cradle to gate,” “cradle to site,” and “cradle to grave.” Cradle to gate system boundary includes all upstream stages of raw material mining, refinement through stages of main manufacturing and finished product packaging [15,22,30,38]. This definition excludes transportation of finished materials to a construction site or retail store, which is covered under cradle to site system boundary. A cradle to site boundary also includes on-site and off-site processes of construction, installation, administration, waste disposal, etc. [15,30,39]. The processes of building operation, maintenance, repair, renovation, retrofit are covered under cradle to grave system boundary, in addition to cradle to site activities. End-of-life processes of demolition, waste sorting and hauling, reuse and recycling, and material disposal are also covered under cradle to grave boundary [30,39,40]. A cradle to grave boundary offers a whole life-cycle-based embodied energy calculation that is critical to creating a true zero-energy or carbon-neutral built environment [13,15,30,40–42].

System boundaries may also differ in terms of direct and indirect embodied energy components [29,30,33,43]. The direct energy embodied in a building includes all energy consumed directly in all onsite and offsite construction, transportation, management, and consulting processes [15,29,30,43]. Studies such as Shrivastava and Chini [43] comprehensively discussed the direct embodied energy component, which is primarily related to construction phase. According to Shrivastava and Chini [43], a majority of direct energy is consumed in onsite management setup, operating construction equipment and tools, and transporting labor, materials, and construction equipment to a job site. The indirect embodied energy is consumed through the use of materials, assemblies, equipment, etc. installed in a building, each of which uses energy during its manufacturing and delivery to a job site [29,30,33,43]. Documenting and quantifying direct construction energy is a challenging task due to unstructured nature of a job site [43]. Worse, the knowledge of quantifying construction energy comprehensively is quite limited [30,43]. Studies [15,40,44–47] have offered numerous regression levels of a system boundary definition, particularly for building and its materials. These regressions cover direct and indirect energy components with varying extents of system boundaries [29,30]. In past, Buchanan and Honey [43] and recently Hammond and Jones [40] and Dixit et al. [30] have offered four regression levels of a system boundary for a building. The first level of regression includes all energy inputs directly consumed in construction, installation, transportation, maintenance, replacement, demolition, and disposal processes. The second level of regression covers all energy directly consumed in main manufacturing process of constituent building materials along with other upstream and downstream processes. In most cases, the second level of regression usually covers over 90% of embodied energy. Covering remaining embodied energy beyond second regression may not be practical looking at the difficulty of gathering energy data [7,39,40]. The energy embodied in manufacturing, supplying, and installing machines for building material production, on-site and off-site construction and transportation is included in the third regression level. Finally, the energy embedded in production machinery used for producing the machines of the third level regression is accounted for in the fourth level of regression. Studies accomplishing embodied energy analysis up to the fourth level of system boundary regression are rare [40,43].

2.1.1.1. Inconsistent system boundary- problem of incompleteness. Edwards et al. [48] claimed that few efforts are made to evaluate a building comprehensively by including all processes and stages related to its life-cycle. Optis and Wild [23] also noted that while it is certain that the building envelope and structure would be accounted for in any embodied energy analysis, the building systems would not. Exclusion of building components, such as furniture, fittings, and building services and processes, including on-site construction and demolition, can cause embodied energy results to vary considerably [29,33,48]. Boundary definition is one of the most critical issues causing some upstream processes to be left out of embodied energy calculations [30,49]. In past embodied energy studies, whenever it is found difficult to gather reliable and accurate information, the system boundary was cut short causing a truncation error in the calculation [14,50,51]. Lenzen [27] found that this truncation error could be up to 50% due to the truncation of upstream processes of a product's life-cycle. The direct energy