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Sustainable housing: Emergy evaluation of an off-grid residence

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ABSTRACT

Sustainable construction aims to utilize environmental-friendly materials and decrease energy and material demands in the construction, operation, and maintenance of a structure. A potential obstacle to building sustainable infrastructure is the initial cost of construction, as environmental-friendly materials are often more expensive. To quantify costs with environmental trade-offs, inputs must be measured taking into account both quality and quantity. Emergy, a method that converts various energies to a common unit, the solar energy joule (sej), offers a more holistic evaluation because it takes into account the quality of inputs. Data on all inputs required to construct and operate a 176 m^2 off-grid house were collected and an emergy evaluation determined it took 8.12 E14 sej/m^2 without service and 4.41E15 sej/m^2 with service to construct the house. Labor and service accounted for 82% of the total. Annual emergy required to operate the house in terms of electricity, propane, water, and services associated with them was 0.05E15 sej/m^2/yr, a value less than those found in previous studies. Results revealed that a higher initial emergy investment into sustainable construction can result in lower annual operational emergy requirements, thus a potential emergy savings over the long term.

1. Introduction

It is estimated that approximately 40% of all global raw resources extracted are for construction purposes [1]. Additionally, in the United States, 41% of total energy consumed was by the building sector [2]. Considering there are such great resource and energy requirements in construction, an emphasis has been placed on determining more sustainable alternatives to traditional buildings. There is extensive literature on the topics of sustainability and sustainable development [3–7]. Sustainable construction aims to use environmental-friendly materials [8] and to lower demands of both materials and energy in the construction and operation phases of the building [9]. Sometimes, there is a tradeoff between structures that are durable and structures that require less energy intensity to build, maintain, and supply energy to [10]. A goal of sustainable construction is to maximize the building's useful life while concurrently minimizing environmental impacts and energy and resource consumption.

A negative to sustainable construction is the initial monetary investment, as green or environmental-friendly materials are typically more expensive than standard construction materials [11]. Also, being off-grid comes at a price, as initial money must be spent on alternative power systems and other specialized infrastructure.

While short-term, sustainable construction may appear to be the less financially viable option to standard construction, the potential long-term operation and maintenance savings in terms of money, materials, and energy can make the initial investment more cost effective. Sustainable construction may reduce annual utility, operation, and maintenance costs, as well as increase a building's overall efficiency [12]. In order to determine if a sustainably constructed house is worth the initial investment, the costs of construction must be compared with the cost of a building's operation over its useful life. *Fifty* years is considered an average useful life and is typically used in many evaluations [13]. It is critical then to evaluate initial construction costs with costs associated with 50 years of building operation to determine if sustainable construction is a worthwhile investment.

1.1. Green building

Integrated environmental accounting methods and global sustainability indicators are required to evaluate the general environmental performances of buildings because the topic of housing is greatly concerned with global environmental problems, such as the use of non-renewable energy, overexploitation of materials, exhaustion of resources, and wasting of energy [14]. Part of the green building initiative is to use local, renewable materials or ones

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are made of biodegradable or recycled materials. These are an ecologically responsible alternative to importing materials that may have substantial fossil fuels and service associated with their transport [15]. Another initiative of the green construction movement is to install alternative energy systems and be less dependent on grid utilities [16]. The house under study was completely off-grid, utilizing solar and hydro electricity and obtaining water from surficial aquifers. In this study it is of interest to see how living off-grid effects annual operation inputs of a household.

1.2. Emergy and sustainable infrastructure

Emergy is a measure of real wealth or environmental support associated with a process [17]. Emergy methodology is capable of measuring both direct and indirect inputs of resources and services that went into making the system under study, all in the same unit, the solar emjoule (sej) [17]. In theory, emergy methodology can be applied to all systems on Earth. Previous studies have applied emergy methodology to a wide variety of systems, from human-dominated systems [18] to ecosystems [19], as well as the interface of human and natural systems [20], demonstrating emergy methodology's versatility as a tool for system analysis.

In emergy methodology, unit emergy values (UEVs) are the conversion factor from grams, joules, and dollars to emergy (sej). UEVs measure the quality of a product or process by determining how much emergy when into a single unit of grams, joules, or dollars. The more emergy per m^2, the higher the quality or the more emergy that went into the production of a product or process. The inputs, storages, flows, and outputs of a building may be quantitatively evaluated using emergy. Areal empower intensity (sej/m^2) is emergy intensity per area. As it relates to construction, areal empower intensity is a measurement of development, with a positive correlation between areal empower intensity and intensity of development [21]. This study was designed to evaluate an off-grid home to determine how emergy intense its construction and operation was to provide a more accurate picture of sustainable construction's environmental impact and costs.

1.3. Literature review

Previous studies have assessed the environmental impacts of construction in terms of associated greenhouse gas emissions [22,23]. Others have evaluated the building sector with Life Cycle Assessment [24–26] and building certifications and standards, such as Leadership in Energy and Environmental Design (LEED) [27,28]. Several emergy-based analyses have applied such various techniques as ecological footprint [29] and life cycle assessment [30–32] to determine the associated environmental support of building materials.

There have been several thorough emergy evaluations of buildings. Pulselli et al. [33] evaluated a 10,000 m^3 Italian building combining residential and commercial use. This study found that the most emergy intense phase of a building (construction, maintenance, operation) on an annual basis was the construction phase. Meillaud et al. [31] conducted an emergy evaluation of a 756 m^2 experimental Swiss academic building. Initial materials and energy required to construct this building was not evaluated with emergy, but annual operation inputs were and it was found the greatest annual emergy flow was attributed to electricity consumption. In his 1998 dissertation [34], Buranakarn did extensive work evaluating the built environment using emergy methodology. Two highlights of his work that relate to this study are the following: (1) an extensive list of UEVs was calculated for construction materials, both with and without service and (2) evaluation of a 981 m^2 University of Florida building using emergy and calculating building areal empower intensity (sej/m^2).

1.4. Infrastructure at ecovillage

The off-grid house under study is situated within an ecovillage that is located in a mountainous region just outside Asheville, North Carolina, USA. The property is 130 hectares with 32 residences that annually house a total of 66 people. The village is completely off the grid, with electricity supplied by either solar or hydro power. There is only one flush toilet in the community; all other waste is composted. Community bylaws require that all new houses be built south facing to increase solar gain. Most dwellings catch rainwater and are built so they do not disrupt environmental processes, such as groundwater recharge and soil attenuation.

2. Methods

The research approach of this emergy analysis was to visit with the builder for several months, collecting data that would become inputs into two emergy evaluations, one of the construction of the building and one of the annual operating requirements of the building. Using that data, the next step was to calculate all inputs necessary to construct an off-grid, residential house and convert masses and joules of inputs into solar energy equivalents (sej). Once in the same unit, these inputs were summed to find the total emergy required for construction. It is necessary to clarify that these are not annual material, energy, and labor flows, but rather total emergy inputs required to construct the house. Total emergy needed to construct the house was divided by the area of the house to obtain an areal empower intensity, the emergy intensity of the building (sej/m^2), both with and without service. Next, a separate emergy evaluation determined the emergy required for annual operation of the building. Finally, a long-term cost-benefit analysis of construction and operation costs was done.

The residential house under study was constructed over a time period of 18 months in 2006 and 2007. Known as "Pokeberry Hill" and hereafter referred to as "Pokeberry," the building is a 176 m^2, two-story house with two apartments within the structure, one on each level. Two people live in each for a total of four residents.

Pokeberry is a wood frame house, with 2″ × 6″ exterior walls enveloped by a weather resistant vapor barrier and metal lathe, which allows for stronger adherence of two coats of earth-based plaster. Interior walls were constructed with 2 × 4′s, followed by plaster over sheetrock. The foundation is concrete slab, as are the majority of the interior floors, left exposed to increase passive solar gain. A layer of ethylene propylene diene monomer (EPDM) or heavy-duty rubber provides a water barrier between the structure of the house and the 29 gauge metal roof.

Unique features of this sustainably built house include:

(1) Advanced passive solar design: this house was built facing south.
(2) Photovoltaic panels: their lifetime was taken as the industry-standard of 30 years, according to the recommendations provided by the IEA PVPS experts [35].
(3) Specialized appliances and fixtures (Sundanzer® refrigerator/freezer, Energy Star® Staber® washing machine, 12 V DC coffee maker, compact florescent light bulbs (CFLs), 12 V DC ceiling fans) suitable to run off solar power and which are extremely energy efficient.
(4) Radiant hydronic floor heating.