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Emergy-based sustainability assessment of different energy options for green buildings

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ABSTRACT

It is necessary to minimize the environmental impact and utilize natural resources in a sustainable and efficient manner in the early design stage of developing an environmentally-conscious design for a heating, ventilating and air-conditioning system. Energy supply options play a significant role in the total environmental load of heating, ventilating and air-conditioning systems. To assess the environmental impact of different energy options, a new method based on Emergy Analysis is proposed. Emergy Accounting, was first developed and widely used in the area of ecological engineering, but this is the first time it has been used in building service engineering. The environmental impacts due to the energy options are divided into four categories under the Emergy Framework: the depletion of natural resources, the greenhouse effect (carbon dioxide equivalents), the chemical rain effect (sulfur dioxide equivalents), and anthropogenic heat release. The depletion of non-renewable natural resources is indicated by the Environmental Load Ratio, and the environmental carrying capacity is developed to represent the environmental service to dilute the pollutants and anthropogenic heat released. This Emergy evaluation method provides a new way to integrate different environmental impacts under the same framework and thus facilitates better system choices. A case study of six different kinds of energy options consisting of renewable and non-renewable energy was performed by using Emergy Theory, and thus their relative environmental impacts were compared. The results show that the method of electricity generation in energy sources, especially for electricity-powered systems, is the most important factor to determine their overall environmental performance. The direct-fired lithium-bromide absorption type consumes more non-renewable energy, and contributes more to the urban heat island effect compared with other options having the same electricity supply. Using Emergy Analysis, designers and clients can make better-informed, environmentally-conscious selections of heating, ventilating and air-conditioning systems.

1. Introduction

Buildings contribute to about 40% of primary energy consumption in developed countries, and the heating, ventilating and air-conditioning (HVAC) system constitutes approximately 50–60% of the annual energy consumption in residential buildings [1]. In China, the proportion of national energy consumption from building sector was around 30% in 2008 [2]. But in some specific cities such as Chongqing and Shanghai, central air-conditioning alone consumes around 23% and 31.1% of their total energy consumption, respectively [3]. With China's rapid urbanization, such proportions are likely to increase [4]. The ever-increasing energy consumption from the buildings inevitably introduces enormous negative environmental consequences such as greenhouse gas (GHG) emissions and the release of various pollutants and wastes. For example, a study in Finland indicated that energy used in the operation process of HVAC systems and in electricity generation contributes to 80–90% of climate change and acidification impacts from buildings [5]. Assessments of the environmental impact of buildings which can support environmental decision-making are therefore the focus of many studies.

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Generally, there are two types of method for assessing the environmental impact of a building [6], one is the application-oriented method, which is based on a multi-item checklist and gives a final score or certificate for a certain type of building. Many such comprehensive building environmental assessment (BEA) tools have been developed in different countries around the world. Examples include Leadership in Energy and Environmental Design (LEED) in the USA, the Building Research Establishment Assessment Method (BREAM) in the UK, the Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) in Japan, BEAM-Plus in Hong Kong, and GB/T in China. The other type is the analysis-oriented approach, which involves quantitatively-based research on specific indicators or aspects, and normally serves as the technical support to the application-oriented method. The analysis-oriented approach includes several elaborative techniques such as life cycle assessment (LCA), embodied energy, and exergy assessment, which have been applied to assess HVAC systems. LCA quantifies the environmental impacts related to the entire life cycle of a product or process in respect of the energy and material flow [7]. Blom et al. [8,9] studied different types of heating and ventilation systems in Dutch dwellings using LCA-based environmental assessment, and found that although heat pumps were considered to be a more sustainable technology, they had more negative environmental impacts compared with gas-fired boilers because they use extra electricity and more material resources. The embodied energy analysis method specifically investigates the energy efficiency of all the gross commercial energy (only including fossil energy such as coal, oil and gas) [10]. Based on the second law of thermodynamics, exergy can identify the imperfection of the system as well as the locations of the exergy losses. Yang et al. [11] compared the environmental impacts of two residential heating systems during the life cycle span using expanded cumulative exergy consumption (ECExC) as the indicator. The most significant environmental impacts were identified during the operating phase, and it was found that the forced-air heating system had a lower life-cycle cost than the hot water heating system.

Despite the popularity of the above-mentioned indicators, current methodologies to quantitatively assess a building's environmental impact have the following shortcomings:

(1) The above-mentioned indicators ignore the critical role that nature's products and services play in supporting industrial activities. For example, exergy analysis as a thermodynamic approach has been extended for life cycle and sustainability assessment; it takes for granted all goods and services from ecosystems which are required in sustaining all industrial activities [12]. There is no inclusion of the energy being used by ecosystems or ecological goods that indirectly contribute to building life cycle energy use. Environmental services such as the wind and solar energy are thought to be naturally free, but they should have an energy value [13].
(2) There is a lack of holistic evaluation of the overall environmental impact. It is a challenging task to create a unified framework where different environmental impacts can be compared and synthesized. Biophysical/thermodynamic models (exergy, embodied energy, etc.) allow substitution within the same form of natural capital and resource but not between different kinds or qualities [13]. In addition, in a building system, apart from the energy and material flows, there are the flows in relation to economic and social activities which are hard to define using the above-mentioned indicators.
(3) No studies have considered the assessment of anthropogenic heat emission into the atmosphere by the HVAC system, which is regarded as one of the dominating factors for controlling urban heat islands [14].

In order to address these above-mentioned concerns, the concept of '**Emergy**' (spelled with an 'm') is introduced in the present study. Emergy Analysis (EA) is a thermodynamic environmental accounting method based on all forms of energy, materials, human labor, economic services, and information, which was first presented by Odum in the 1980s [15]. All types of resources can be converted into equivalents of one form of energy, i.e. solar energy, which is the common basis of all energy flows circulating within the biosphere. The ecological cost from the environmental service, which is difficult to value using commonly-defined, energy-based indicators, can be assessed by Emergy Accounting to unveil the real sustainability of the whole system. The more work done to produce a product or make a service, the higher the Emergy content of the product or service would be. EA has been widely applied in ecological engineering. Only a handful of research efforts have been made to assess building systems under the emergy framework. Meillaud et al. [16] was the first to apply emergy accounting into building sector, and they evaluated a school building in Switzerland, with the output of scientific information disseminated via publications, courses, students, and services. Pulselli et al. [17] evaluated the environmental resource use of three wall systems for building envelops relative to different geographical locations and climates using emergy evaluation. Pulselli et al. [18] applied emergy analysis to assess the specific emergy of cement and concrete for building materials. The results identified a high dependence of cement and concrete production on external resource flows. Li et al. [19] presented an eco-efficiency evaluation of building manufacturing for six residential buildings in China using emergy analysis. The evaluation results revealed that construction materials were the dominating source of the total emergy amount for building manufacturing. Surprisingly, no studies of HVAC systems have been found, especially energy supply options. In this paper, the efforts are devoted to evaluating the environmental performance of the different energy options adopted in the HVAC system. In order to take into account the anthropogenic heat emissions from the HVAC system, the concept of a support area to absorb anthropogenic heat emission based on emergy analysis was developed. The emergy evaluation considers the environmental impact of natural resources depletion, GHG emission and anthropogenic heat within the same framework. Therefore, the environmentally favorable design solutions can be optimized. This emergy-based framework can aid decision-making in the selection of the best available technologies to minimize the environmental impact of different energy options for HVAC systems.

2. Environmental impact assessment indicators based on Emergy

2.1. Emergy concept

By definition, emergy uses the thermodynamic basis of all forms of energy and materials (measured by their heat content, mass or energy, i.e. the available energy of each flow relative to the environment), but converts them into equivalents of one form of energy, usually sunlight. The units of emergy are *emjoules*, to distinguish them from joules, referring to the available energy of one kind consumed in transformations. For example, sunlight, fuel, electricity, and human services can be put on a common basis by expressing them all as the emjoules of solar energy required to produce each one. Therefore, solar emergy is often used with unit solar emjoules (abbreviation: *sej*). As a whole, the emergy analysis accounts for quality differences among distinct forms of energy and allows for the inclusion of information and monetary flows with energy and materials [20].