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Energy use in the life cycle of conventional and low-energy buildings: A review article

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Abstract

A literature survey on buildings' life cycle energy use was performed, resulting in a total of 60 cases from nine countries. The cases included both residential and non-residential units. Despite climate and other background differences, the study revealed a linear relation between operating and total energy valid through all the cases. Case studies on buildings built according to different design criteria, and at parity of all other conditions, showed that design of low-energy buildings induces both a net benefit in total life cycle energy demand and an increase in the embodied energy. A solar house proved to be more energy efficient than an equivalent house built with commitment to use "green" materials. Also, the same solar house decreased life cycle energy demand by a factor of two with respect to an equivalent conventional version, when operating energy was expressed as end-use energy and the lifetime assumed to be 50 years. A passive house proved to be more energy efficient than an equivalent self-sufficient solar house. Also, the same passive house decreased life cycle energy demand by a factor of three – expected to rise to four in a new version – with respect to an equivalent conventional version, when operating energy was expressed as primary energy and the lifetime assumed to be 80 years.
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Keywords: Life cycle; Operating energy; Embodied energy; Low-energy; Solar house; Passive house

Definitions

Conventional building, or simply *Conventional*: Refers to a building built according to the common practice of a specific country in a specific period.
Conversion factor: Multiplicative coefficient that converts values from end-use to primary energy. Conversion factors vary from energy carrier to energy carrier and from country to country.
Embodied energy: The sum of all the energy needed to manufacture a good. It may or may not include the feedstock energy. Generally expressed in term of primary energy.
End-use energy: Energy measured at the final use level.
Feedstock energy: Heat of combustion of raw material inputs, such as wood or plastics, to a system. Generally expressed as gross calorific value.
Initial embodied energy: The sum of the energy embodied in all the material used in the construction phase, including technical installations.
Low-energy building or simply *low-energy*: Refers to a building built according to special design criteria aimed at minimizing the building's operating energy.
Operating energy: Energy used in buildings during their operational phase, as for: heating, cooling, ventilation, hot water, lighting and other electrical appliances. It might be expressed either in terms of end-use or primary energy.
Passive house: A type of low-energy building; design is oriented to make maximum exploitation of passive technologies (eventually adopting also some active solar technology).
Primary energy: Energy measured at the natural resource level. It is the energy used to produce the end-use energy, including extraction, transformation and distribution losses.
Recurring embodied energy: The sum of the energy embodied in the material used in the rehabilitation and maintenance phases.
Solar house: A type of low-energy building; design is oriented to make maximum exploitation of solar energy (with both passive and active technologies).
Total embodied energy: The sum of both initial and recurring embodied energies.

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Total energy: The sum of all the energy used by a building during its life cycle (total embodied energy plus operating energy multiplied by lifetime).

1. Introduction

Buildings demand energy in their life cycle, both directly and indirectly. Directly for their construction, operation (operating energy), rehabilitation and eventually demolition; indirectly through the production of the materials they are made of and the materials technical installations are made of (embodied energy). Case studies that explicitly consider the phases of construction, demolition and relative transportation of materials (see Table 2, column 6), all show that the sum of the energy needed for these phases either is negligible or settled at approximately 1% of the total life cycle energy need. In some of the literature, however, energy for construction and relative transportation is included in the definition of the initial embodied energy, showing that there is no clear agreement on how this should be handled. Only a few studies include the phase of recycling building materials after demolition (see Table 2, column 5). Although these studies offer an interesting point of view, the mass of literature does not consider waste management as part of a building's life cycle.

Therefore, this paper focuses only on operating energy and embodied energy in the life cycle of buildings. The recycling phase has not been taken into account. Until few decades ago it was known that operating energy represented by far the largest share in the life cycle energy bill, ranging to about 90–95% even when accounting only for the heating demand [1,2]. More recently, the increased awareness of environmental problems related to energy processes together with a trend of ever increasing energy demand from the building sector have lead building designers to develop more energy efficient design criteria, and states to implement building codes that are more and more stringent on energy requirements. In addition, increased interest and better methodologies, such as Life Cycle Assessment (LCA), provide better understanding and better estimation of energy (and other environmental) aspects in the life cycle of any sort of good. Hence, the relative importance of operating and embodied energy has changed.

The purpose of this article is to clarify the relative importance of operating and embodied energy in a building's life cycle, especially in low-energy buildings. Design of low-energy buildings directly addresses the target of reducing the operating energy. This is done by means of both passive and active technologies. Passive technologies include, for example, increased insulation, better performing windows, reduction of infiltration losses and heat recovery from ventilation air and/or waste water. Active technologies include, for example, heat pumps coupled with air or ground/water heat sources, solar thermal collectors, solar photovoltaic panels and biomass burners. There has been, and there is, a variety of approaches to designing low-energy building, and it is not in the scope of this paper to analyze their peculiarities. However, a common aspect is that a reduced demand for operating energy is achieved by increased use of materials, and especially of energy intensive materials, both in the building envelope and in the technical installations. It has even been argued for a substitution effect [3], for which the benefit of reducing operating energy is, to a large extent or completely, counterbalanced by similar increases in the embodied energy.

2. Method

For what it is relevant in this paper, Tables 1 and 2 give a comprehensive overview of the main characteristics of cases presented in literature. Where a source is reported to have more

Table 1
Overview of literature, general data

Source	Country	Case numbers	Type of building[a]	Area (m^2)	Lifetime	Data[b]
Adalberth et al. [4][c]	Sweden	1–2	Res m	700–1520	50	G
Adalberth [13]	Sweden	3–5	Res	129–138	50	T
Adalberth [9]	Sweden	6–13	Res m	700–1520	50	T
Cole and Kernan [14]	Canada	14–25	Off	4620	50	T
Fay et al. [15]	Australia	26–27	Res	128	50	T
Feist [5]	Germany	28–33	Res	156	80	G, T
Hallquist [1][d]	Norway	–	Res m	?	40	T
Hannon et al. [2]	USA	34–35	Res	457	Annualized	T
Mithraratne and Vale [6]	New Zeland	36–38	Res	94	100	G, T
Scheuer et al. [10]	USA	39	Oth	7300	75	T
Suzuki and Oka [16]	Japan	40–49	Off	1253–22,982	40	G
Thormark [7]	Sweden	50	Res	120×20	50	T
Treolar et al. [11]	Australia	51	Res	123	30	T
Winther and Hestnes [3]	Norway	52–56	Res	110	50	G, T
Winther [12][e]	Norway	–	Res	110	50	T
Zimmermann et al. [8]	Switzerland	57–60	Oth	National average	Annualized	T

[a] Res, residential one- and two-dwellings; Res m, residential multi-dwellings; Off, office; Oth, other.
[b] G, graph; T, table and/or text.
[c] Two additional versions to Adalberth [13].
[d] Screened out because it presented the necessary data only in percentages.
[e] Additional data on initial embodied energy to Winther and Hestnes [3].

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