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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.

Keywords: Life cycle; Operating energy; Embodied energy; Low-energy; Solar house; Passive house

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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].

Table 2
Overview of literature, energy data

Source	Operating energy	Heating only	Embodied energy	Recycling	Other energy	LCA
Adalberth et al. [4]	End-use		*I*, *T* +*f*	X	X	X
Adalberth [13]	End-use		*I*, *T* +*f*		X	
Adalberth [9]	End-use		*I*, *T* +*f*	X	X	
Cole and Kernan [14]	? (Primary)		*I*, *T*		X	
Fay et al. [15]	Primary		*I*, *T*			
Feist [5]	Primary		*I*, *T*			
Hallquist [1]	? (End-use)	X	*I*		X	
Hannon et al. [2]	? (End-use)	X	*I*		X	
Mithraratne and Vale [6]	Primary	X	*I*, *T*			
Scheuer et al. [10]	Primary		*I*, *T* +*f*		X	X
Suzuki and Oka [16]	? (Primary)		*I*, *T*		X	
Thormark [7]	Primary		*T* +*f*	X		
Treolar et al. [11]	Primary		*I*, *T*			
Winther and Hestnes [3]	End-use		*T* +*f*			
Winther [12]	End-use		*I*, *T* +*f*	X		
Zimmermann et al. [8]	Primary		*T*			

I, initial; *T*, total; +*f*, feedstock energy included.

than one case, it means that either more than one building or different versions of the same building were presented in the source itself. In some of the literature data were found in tables and/or text form, while in other only graphs were available (see Table 1, column 7). In the latter case, numerical values have been estimated from the graphs, thus they might be subject to slight imprecision.

Cases differ for climate, country, type of building, type of construction, assumptions on indoor climate and source of data (whether measured or calculated). For this reason, it would be inappropriate to directly compare the cases against each other. Rather, the authors' intention has been to assess the relative importance of operating and embodied energy within each single case, and then to compare these relations amongst the various cases. Cases also differ in size and estimated lifetime. In order to neutralize these differences, energy figures were normalized per unit of area and time (kWh/m^2 year). After a first screening, the authors decided to exclude from the analysis the case presented in reference [1], because it presented the necessary data only in percentages.

Another major difference is whether data were expressed in the form of primary or end-use energy. End-use energy is measured at final use level, and so, it somehow expresses the performance of a building. Primary energy is measured at the natural resource level, including losses from the processes of extraction of the resources, their transformation and distribution, and so it expresses the real load on the environment caused by a building. In other words, the same hypothetical building placed in different countries but with similar climates is likely to have very similar figures about end-use energy. The difference in terms of primary energy, however, can be significant because of the different energy carriers available for thermal purposes (like district heating, natural gas, biomass or electricity only) and/or because of the different ways to produce electricity. For example, Norway, 98% hydropower [3]; Sweden, 49% nuclear and 44% hydropower [4]; OECD mix, 56% fossil fuels and 40% nuclear [4]. Information on energy carriers and relative conversion factors found in the literature was fragmented, so this aspect was not taken into consideration in this study. Therefore, all figures presented in this paper refer to undifferentiated, overall amounts of energy.

Concerning operating energy, some sources expressed it as primary, others as end-use, while few sources did not give clear specification (see Table 2, column 2). The latter are shown with a question mark. The supposed form of energy assumed, as inferred by comparison with the known cases, is given in brackets. Concerning embodied energy, no clear statement about primary/end-use was found in any of the sources. It was here assumed that data were expressed as primary energy, as this is the common praxis in LCA analysis of products and related industrial activity and environmental impact. The analyzed cases were grouped in two categories, according to the expression of their operating energy, primary or end-use.

The total number of cases analyzed amounted to 60. The cases have been assigned a progressive number according to the alphabetical order of their source (see Table 1, column 3) and in the rest of the paper; they are presented in the graphs by their number. Whenever relevant to the discussion, the source is also mentioned. As it is in the purpose of this article to stress the differences between conventional and low-energy buildings, this feature is always highlighted.

According to reference [5], a low-energy building can be defined as one having an annual requirement for heating below 70 kWh/m^2 year, expressed in end-use energy. Yet, data reported in the same source (in graphic form) show that such a building has an overall end-use operating energy of about 120 kWh/m^2 year; that can be converted into about 200 kWh/m^2 year of primary energy requirement. Although conversion factors between end-use and primary energy depend on the energy carriers used and the energy system of a specific country, a common definition of low-energy building was necessary also for cases with primary energy figures. Generalizing the definition found in reference [5] to all the cases presented in this paper, and considering a little margin because of the possible imprecision in converting graphical data into numbers, the authors have adopted the following

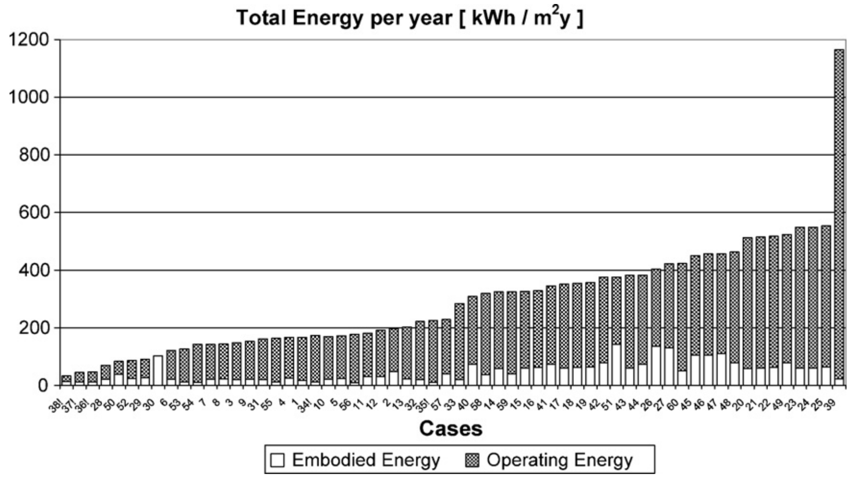

Fig. 1. Normalized total energy for the 60 cases.

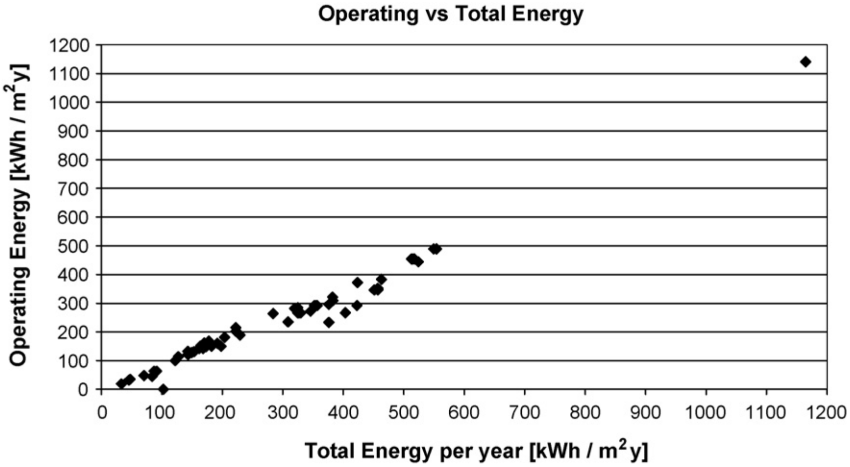

Fig. 2. Relation between operating and total energy for the 60 cases.

definition: a low-energy building is one having an operating energy ≤121 kWh/m^2 year when expressed in end-use energy,[1] or ≤202 kWh/m^2 year when expressed in primary energy.

3. Results

The sum of both operating and embodied energy, which virtually amounts to the total life cycle energy (except for ca. 1% used for erection, demolition and transportation as mentioned above), was calculated and normalized in kWh/m^2 year for each case. The results are shown in Figs. 1 and 2, where the cases have been sorted in ascending order of their normalized total energy. Case numbers followed by an exclamation point mark those cases where operating energy considered only heating. Case #30, which had only embodied energy, is the ‘‘Self-sufficient solar house’’ presented in reference [5] and will be further discussed.

Fig. 1 shows that operating energy represented the dominant part in all the cases, while Fig. 2 shows a linear relation between operating and total energy. In other words, despite all the differences between the individual cases, such as materials and construction techniques employed, size and type of building, climate and so on, the general trend turned out to be uniform. This is due to the dominant role of operating energy that trims down the influence of all other differences.

In order to assess possible differences between conventional and low-energy buildings, the results for primary and end-use energy were examined separately. Figs. 3 and 4 mirror the previous graphs for only those cases where operating energy was expressed as primary energy, while Figs. 5 and 6 refer to cases with end-use energy.

Low-energy building cases with data on primary energy were found in these sources: #28–32 in reference [5]; #36–38! (heating only) in reference [6]; #50 in reference [7]; #57 in reference [8]. The cases in references [6,8] resulted in matching the definition of low-energy building adopted in this paper, although they were not presented as such in the original sources. Low-energy cases occupy the left-most positions in the graphs.

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[1] ≤70 kWh/m^2 year when heating only is considered.

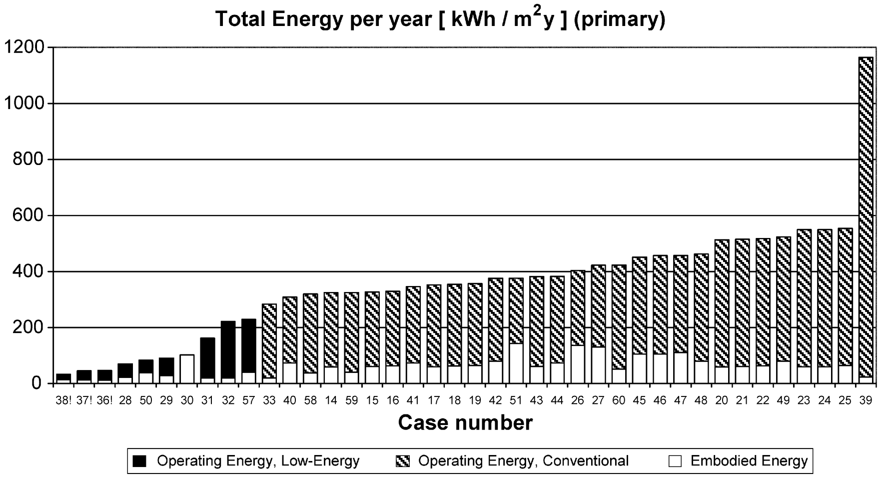

Fig. 3. Normalized total energy for primary energy cases.

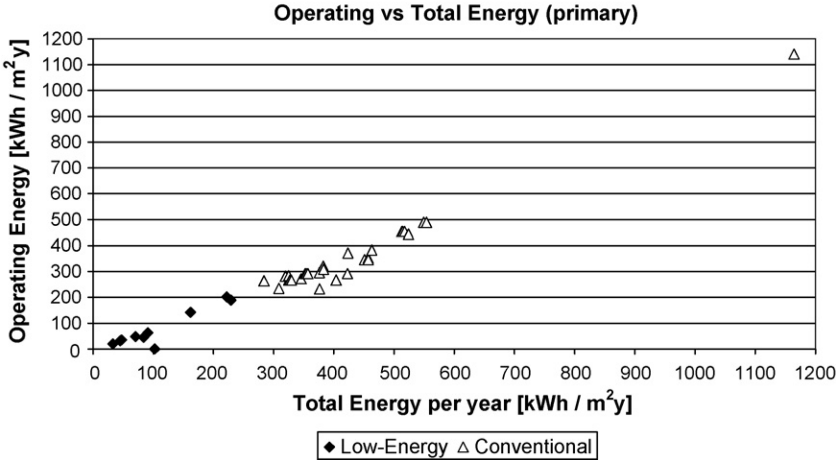

Fig. 4. Relation between operating and total energy for primary energy cases.

Low-energy building cases with data on end-use energy were found in these sources: #6–8 in reference [9]; #52–53 in reference [3]. The cases in reference [9] resulted in matching the definition of low-energy building adopted in this paper, although they were not presented as such in the original sources. The graphs present just one singularity. Case #54 had a slightly lower total energy demand than cases #7–8 even though it had higher requirements for operating energy. It should firstly be noticed that differences in total energy among the three cases were very small. Secondly, they referred to different countries: cases #7–8 Sweden, case #54 Norway. This might explain the higher figures for embodied energy (expressed in primary energy terms) in #7–8.

The results presented until here show that buildings with low energy requirement for their operation also result in being the best energy performing in absolute terms. Nevertheless, it might be argued that although a relation between operating and total energy needs exist, it is not a cause–effect relation. It might be argued that it is somewhat the indirect consequence of external variables, as for example the climate, that influence the demand for operating energy but does not affect the embodied energy. Thus, a favorable climate would produce the case of a building that requires little energy for operation, and consequently a low total energy regardless of the role of embodied energy and the building's design. Even though that seems not to be case here (considering that 7 of the 15 low-energy buildings were found in countries like Norway, Sweden and Switzerland; countries that can hardly be said to have favorable climates[2]), it is worth sharpening the investigation on this point. For those cases that matched the definition of low-energy the embodied energy's share of the total ranged between 9 and 46%. The minimum was found in reference [5] and the maximum in reference [7]. Conventional buildings had shares ranging between 2 and 38%, the minimum found in reference [10] and the maximum in reference [11]. These wide ranges are in good part related to the different backgrounds of each case. Estimation of embodied energy values can vary greatly from country to country, according to which energy carriers are predominantly available, the transformation processes that generated those carriers from the natural energy sources and the efficiency of the industrial and economic systems that produced the materials. The differences from case to case are, indeed, simply too great to allow any further general conclusion.

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[2] The other cases were found in Germany and New Zealand.

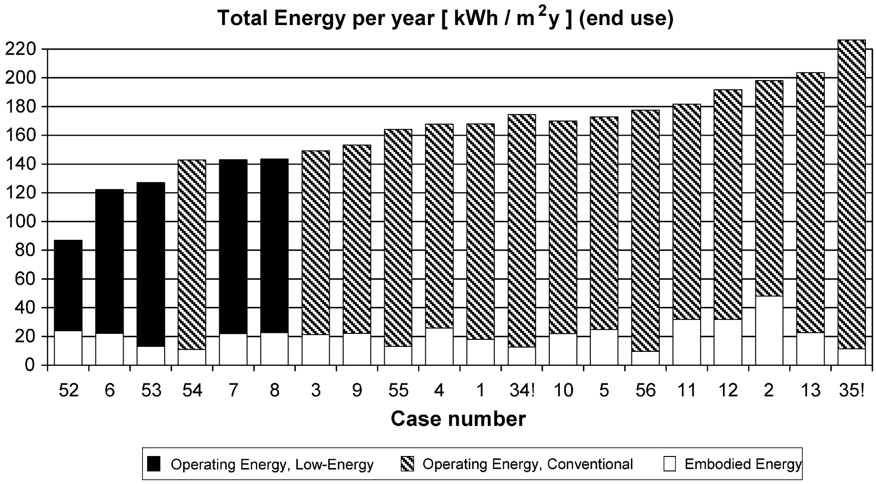

Fig. 5. Normalized total energy for end-use energy cases.

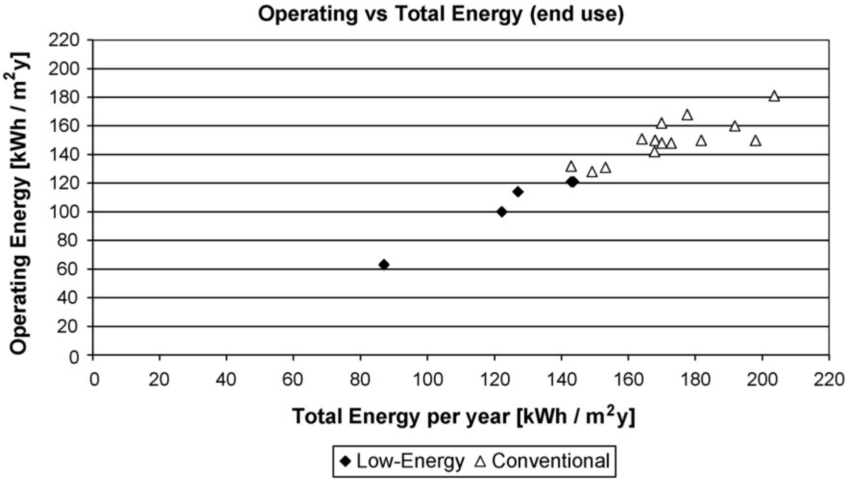

Fig. 6. Relation between operating and total energy for end-use energy cases.

In order to achieve a better understanding of the interplay between embodied and operating energy and its repercussions on the total energy needs, different versions of the same building have to be analyzed at parity of all other conditions. Two studies were found in literature that coped with this aspect [3] and [5], and they are discussed here. Reference [5] analyzed six versions of a residential unit in Germany and presented life cycle results in primary energy, while [3] analyzed five versions of a residential unit in Norway and presented life cycle results in end-use energy (see Figs. 7 and 8). Both studies analyzed both conventional and low-energy buildings. The conventional cases were named, in reference [5], "Ordinance 1984"; in reference [3], "Code 1987", "Code 1997" and "Green". All the others were low-energy buildings. The percentages reported in the graphs refer to the embodied energy (initial plus recurring). It is worth reporting that the cases named: "Self-sufficient solar" and "Passive, as built" in one article, and "Solar IEA", "Solar case 2" and "Code 1997" in the other, respectively, referred to buildings actually built. The other cases referred to hypothetical versions of the same buildings.

The results from the two studies show that low-energy buildings are not those buildings that just happen to demand little energy for whatever external cause. Low-energy buildings are the result of specific design criteria, and at parity of all other conditions, they demand less operating energy and less total energy than if built according to conventional criteria.

Both studies showed that the amount of embodied energy used in any sort of low-energy version was higher than in the conventional ones, both in percentage and absolute. Both studies also showed that the trend of increasing embodied energy was accompanied by a trend of decreasing total energy, with the only exception being the "Self-sufficient solar" house in reference [5]. This house requires no energy delivery for its operation – neither fuels nor electricity – as all the energy it needs is locally produced (exploiting solar and wind sources) and stored. So, total and embodied energy are coincident. However, the high embodied energy needed to install and maintain all the additional technical equipment exceeded the requirements generated by the two versions representing the passive house standard.

The passive houses could achieve a great decrease in total energy use over the life cycle with just a little increase in the

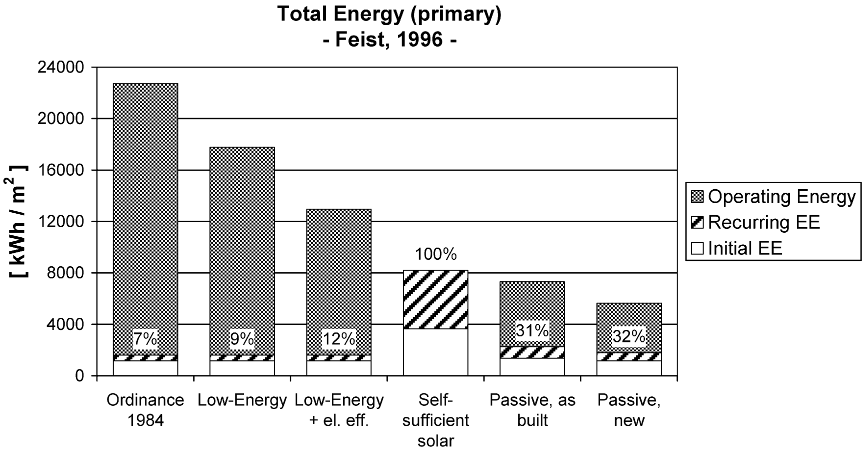

Fig. 7. Life cycle energy of the six versions in Feist [5]. "Ordinance 1984" is a conventional building, all the others are low-energy.

embodied energy. In the original source, the author explained that the relatively small increase in embodied energy, in spite of using additional materials to make the house highly insulated and air-tight, is explainable by the fact that no conventional heating system was needed. The heating demand (very little after all the passive measures were applied) was met through the supply air. The reported initial embodied energy was 1171 kWh/m^2 for the "Ordinance 1984" version and 1391 kWh/m^2 for the "Passive, as built" version. In other words, with an increment in initial embodied energy of just 220 kWh/m^2 (about the equivalent of 1 year of operation for the "Ordinance 1984" house) the "Passive, as built" house could achieve a three-fold decrease in the total energy, with an assumed lifetime of 80 years. The new version, "Passive, new", was expected to achieve a four-fold decrease (operating energy in primary energy terms).

In reference [3], the version named "Green" referred to a building designed with careful attention to the materials used. Here, the use of synthetic materials was reduced to a minimum by substitution with natural, or "green", materials that could perform the same functions, while no special attention was devoted to minimize operating energy requirements. The results for the "Green" version were worse than those for low-energy buildings. The embodied energy was somewhat higher than in the conventional versions, and this is attributable, according to the original source, to the cellulose fiber used for insulation. The authors reported that cellulose fiber has higher energy intensity than conventional insulation materials, because its feedstock potential is lost when it is impregnated against fire. The "Solar IEA" house, when compared with the conventional cases, was shown to require about double the embodied energy while at the same time bringing about a factor two in net benefit over a life cycle of 50 years (operating energy in end-use terms).

Another way to look at the same cases is to project their energy demand on a temporal diagram. Fig. 9 refers to reference [5] and Fig. 10 to reference [3]. For simplicity, the recurring embodied energy was first annualized and then assumed to occur regularly on a yearly basis regardless of the actual maintenance periods. That is the reason why the lines presented in the graphs here do not show a stepwise behavior, as they do in reference [5].

The graphs show how the higher initial embodied energy in low-energy buildings is largely paid back during the lifetime. It is worth noting that at no point in time is the energy of the "Self-sufficient solar" house lower than that of

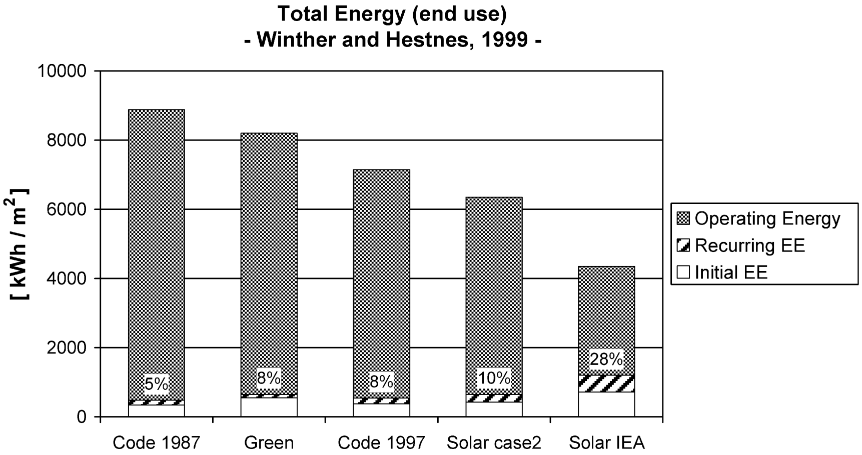

Fig. 8. Life cycle energy of the five versions in Winther and Hestnes [3]. "Solar case 2" and "Solar IEA" are low-energy buildings, all the others are conventional.

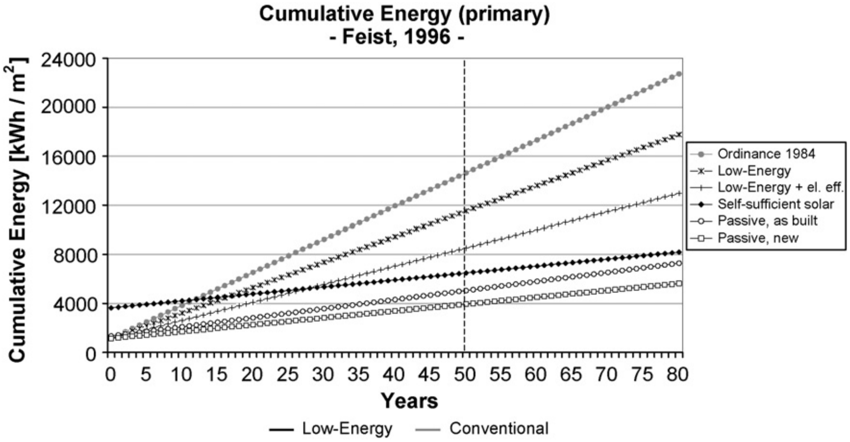

Fig. 9. Cumulative total energy in Feist [5]. "Ordinance 1984" is a conventional building, all the others are low-energy.

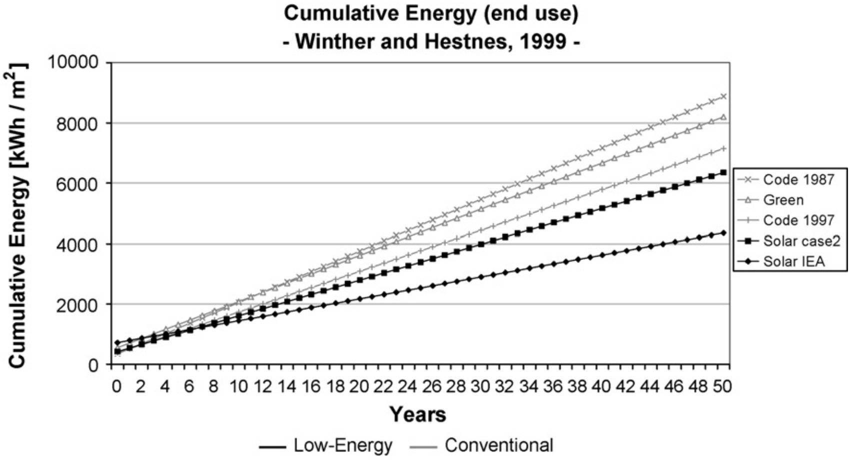

Fig. 10. Cumulative total energy in Winther and Hestnes [3]. "Solar case 2" and "Solar IEA" are low-energy buildings, all the others are conventional.

the passive house versions. Also, the divergence between the cases is more accentuated in Fig. 9 (see values after 50 years—dashed vertical line) than in Fig. 10. Of course the two graphs refer to different cases, but the higher divergence is also due to the fact that the energy was expressed in primary energy terms in Fig. 9.

4. Conclusions

The analysis of 60 cases found in literature showed that operating energy represents by far the largest part of energy demand in a building during its life cycle. It has also been shown that there is a linear relation between operating and total energy, valid through all the cases despite climate and other contextual differences. Hence, low-energy buildings result in being more energy efficient than conventional ones, even though their embodied energy is somewhat higher. Differences in contexts could however not allow for assessments of general validity regarding embodied energy.

Analysis of case studies of buildings built according to different design criteria, and at parity of all other conditions, showed that design of low-energy buildings induce both a net benefit in total life cycle energy demand and an increase in embodied energy.

A solar house, a type of low-energy building, was shown to be more efficient than an equivalent building designed with careful attention to the use of "green" materials but with no special energy measures. The same solar house, when compared to an equivalent conventional building, required about the double of embodied energy while at the same time reduced the total energy need by a factor two, when operating energy was expressed as end-use energy and the lifetime assumed to be 50 years.

A passive house, another type of low-energy building, was shown to be even more efficient than an equivalent self-sufficient house. When compared with an equivalent conventional building instead, the passive house demanded only slightly more embodied energy while it reduced the total energy need by a factor of three, when operating energy was expressed as primary energy and the lifetime assumed to be 80 years. A new version of the passive house was expected to achieve an overall factor of four.

In conclusion, reducing the demand for operating energy appears to be the most important aspect for the design of buildings that are energy efficient throughout their life cycle. Embodied energy should then be addressed in second instance. As regards to this subject, part of the literature surveyed suggests that there is a potential for reducing embodied energy requirements through recycling [4,7,9,12]. Even though in this paper, as in the major part of literature, buildings' life cycle was defined from construction to demolition, to widen the boundaries of analysis in order to include the recycling phase would offer a means to include that potential. Finally, it is also possible to broaden the scope of analysis beyond pure energy accounting, in order to directly address a set of specific environmental loads caused by buildings and their operation. References [4,10] have applied a full Life Cycle Assessment analysis in their studies. They showed that buildings' life cycle phases had different effects on various impact categories; they also concluded that the demand for energy in the operating phase was the single most important factor.

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