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Affordable construction towards sustainable buildings: review on embodied energy in building materials

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Affordable construction has identified low embodied energy in materials as key issue. This review paper shows that even though there is a lack of research on this topic, embodied energy and carbon are studied in the context of buildings and construction materials. Moreover, comparison between studies is not possible due to the different assumptions used by the researchers, due to the fact that most studies are focused in a given location, and also due to the great variation between data presented in the embodied energy databases available. This paper shows different studies published in scientific journal papers and carried out around the world on the accounting of embodied energy in building materials. The paper includes the boundary of each of this study, including the location, type of material or building studied, and the conclusions found. Moreover, the paper discusses the definition of embodied energy and the significance of this concept in buildings.

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Introduction

Climate change due to greenhouse gas emissions from anthropogenic and natural activities has been a major concern of all people across the globe [1•]. Fast urbanization, continuous industrialization and improved living standards have boosted up energy consumption in recent years. All human activities essentially need energy as driving force. Since long time fossil fuels have been the basic source of generation of energy, and its combustion results into emission of greenhouse gases predominantly carbon dioxide. With increasing concern to greenhouse gas emission from anthropogenic activity, the concept of energy efficient building has been evolved.

The construction industry requires vast quantities of materials (around 30 billion tonnes in 2005 as was studied by Dr Rincón (**Material Flow Analysis of the building sector in Lleida**, PhD thesis, University of Lleida, 2011) and this, in turn, results in the consumption of energy resources and the release of deleterious pollutant emissions to the biosphere [2••]. Each material has to be extracted, processed and finally transported to its place of use. The energy consumed during these activities not only is critically important for human development, but also puts at risk the quality and longer term viability of the biosphere as a result of unwanted or 'second' order effects [3,4]. Many of these sideeffects of energy production and consumption give rise to resource uncertainties and potential environmental hazards on local, regional or national scales [4]. Energy and pollutant emissions such as carbon dioxide (CO_2) may be regarded as being 'embodied' within materials. Thus, embodied energy of primary production [5] can be viewed as the quantity of energy required to process, and supply to the construction site, the material under consideration.

Construction sector in India accounts for 22% of the direct and indirect total annual emissions of CO_2 resulting from the Indian economy [1•]. Out of the emissions from the construction sector, 80% are resulting mainly from the products/industrial processes of four energy intensive building materials (basic building materials such as concrete and reinforced, compared to masonry materials) [6•]. Moreover, with the rapidly growing population there will be an increasing requirement of these materials, particularly in housing, which accounts for nearly 60% of the materials consumed by the construction sector annually [7].

As the world's largest producer and consumer of building materials, China's building materials industry belongs to high energy consumption trade [8]. In 2009, about 300 million tonnes of coal was used in the manufacturing of building materials, accounting for 10% of domestic coal production [9].

The worldwide demand for affordable housing has grown in recent decades and it is expected to continue growing [10]. Several challenges to affordable housing have been identified, but they can be summarized as: scarcity of resources, shortage of skilled labour, quality control, wastage due to inefficiency, lack of added value creation, and quality and location. From the construction point of view, to overcome scarcity of resources it is necessary to produce good quality construction materials, increasing its efficiency and reducing its embodied energy.

To improve environmental performance of building it is essential to involve all parameters which control its energy efficiency. Vaidehi *et al.* [1•] identify those parameters as regulatory and voluntary policies, rating systems to assess energy efficiency, selection of energy efficient processes and materials through life cycle analysis, and simulation and shifting to low embodied energy materials.

Embodied energy and carbon

Buildings are constructed with a variety of building materials and each material consumes energy throughout its stages of manufacture, use and deconstruction [10]. These stages consist of raw material extraction, transport, manufacture, assembly, installation as well as its disassembly, deconstruction and decomposition. The energy consumed in production (in conversion and flow as proposed by Koskela [11]) is called the 'embodied energy' of the material and is the concern of energy consumption and carbon emissions. Gonzalez and Navarro [12] assert that building materials possessing high-embodied energy could possibly result in more carbon dioxide emissions than would materials with low embodied energy.

Embodied energy (and carbon) is now viewed as being important in the context of buildings [12–17] and construction materials [18].

The total life cycle energy of a building includes both embodied energy and operating energy [1•,10,19]. This concept was also the topic on Ding PhD thesis who also suggests that the production of building components offsite accounts for 75% of the total energy embodied in buildings (**The development of a multi-criteria approach for the measurement of sustainable performance for built projects and facilities**, PhD thesis, University of Technology, Sydney, Australia, 2004):

(1) *Embodied energy (EE)*: sequestered in building materials during all processes of production, on-site construction, and final demolition and disposal.
(2) *Operating energy (OE)*: expended in maintaining the inside environment through processes such as heating and cooling, lighting and operating appliances.

Until recently, only operating energy was considered, owing to its larger share in the total life cycle energy. However, owing to the advent of energy efficient equipment and appliances, along with more advanced and effective insulation materials, the potential for curbing operating energy has increased and as a result, the current emphasis has shifted to include embodied energy in building materials [19–23]. The share of energy is gradually increasing as a result of the increased use of high energy intensive materials [24•,25,26]. Thus, there is a genuine demand to calibrate the performance of buildings in terms of both embodied and operating energy in order to reduce energy consumption [25–27]. At a macro-level, proper accountability of embodied and operating energies will contribute to data and information needed to create an energy economy that accounts for indirect and direct contributions.

Langston and Langston [26] suggest that, while measuring operating energy is less complicated, determining embodied energy is more complex and time consuming. Furthermore, there is currently no generally accepted method available to compute embodied energy accurately and consistently [28] and as a result, wide variations in measurement figures are inevitable, owing to various factors [19,25,28,29].

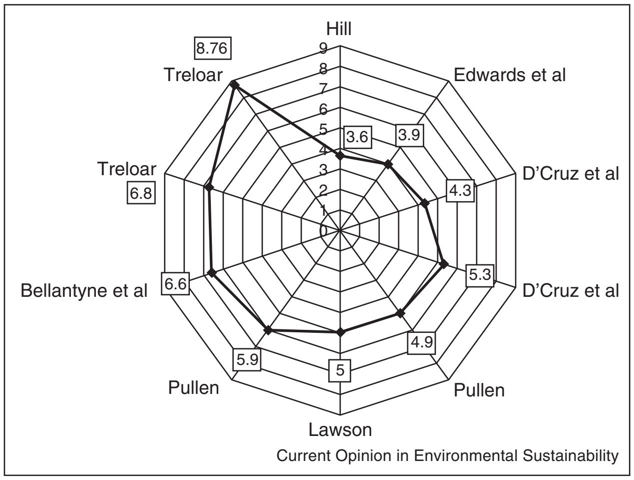
Recent studies have considered the significance of embodied energy inherent in building materials [10]. Current interpretations of embodied energy are quite unclear and vary greatly, and embodied energy databases suffer from problems of variation and incomparability.

Figures 1 and 2 represent graphically the variations in embodied energy results from eight different studies, and point out that residential and commercial units differ in terms of embodied energy [30••]. The mean of residential units' embodied energy is 5.5 GJ/m^2 and standard deviation is found to be 1.5 GJ/m^2, while commercial buildings' embodied energy figures demonstrate a mean of 9.2 GJ/m^2 and a standard deviation of 5.4 GJ/m^2.

As a step forward, Dixit *et al.* [31] proposed an approach to establish an embodied energy measurement protocol, but still this protocol is not presented.

Interesting to mention is that Monkman and Shao [32] studied the feasibility of integrating carbon sequestration into the curing of precast concrete products. Research assessed the CO_2 uptake capacities of carbonation-cured concrete masonry units (CMU), concrete pavers, fibre-glass-mesh reinforced cement board, cellulose-fibre board, and ladle slag fines. Three curing systems were used: firstly an open-inlet system using pressurized recovered CO_2; secondly a closed system using pressurized flue gas with 14% CO_2; and lastly a closed system using dilute CO_2 under atmospheric pressure. The amount of carbon dioxide that could be sequestered in the annual North American output of the various precast concrete products

Figure 1



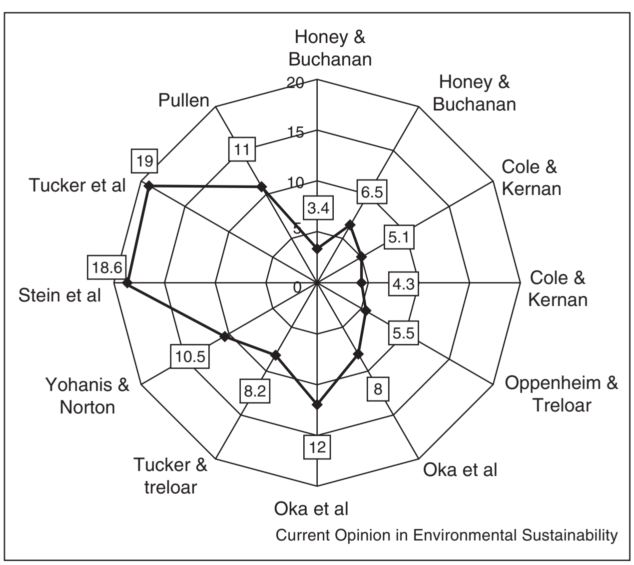
Differing embodied energy values in residential buildings, in GJ/m^2 [30••].

was estimated. The net efficiency was calculated accounting for CO_2 emissions penalty resulting from the capture, compression, and potential transport of the curing gases. Carbonation curing of the considered products could result in a net annual CO_2 sequestration in US and Canada of approximately 1.8 million tonnes if recovered CO_2 is used and one million tonnes if flue gas is used.

Significance of embodied energy

As mentioned earlier, until recently, major endeavours for energy conservation assumed the operating energy of a

Figure 2



Differing embodied energy values in commercial buildings, in GJ/m^2 [30••].

building to be much higher than the embodied energy of a building [10]. However, current research has disproved this assumption and found that embodied energy accounts for a significant proportion of total life cycle energy [33,34]. Embodied energy is expended once in the initial construction stage of a building, while operational energy accrues over the effective life of the building. Operational energy conservation could be accomplished more optimally with energy efficient appliances and advanced insulating materials, which are available more readily [20,20,23].

According to Dixit *et al.* [30••] embodied energy data depend on 10 parameters, which are system boundaries, methods of embodied energy analysis, geographic location of study area, primary and delivered energy, age of data sources, source of data, completeness of data, technology of manufacturing processes, feedstock energy consideration, and temporal representativeness. Embodied energy of different construction materials is dependent on its production process [6].

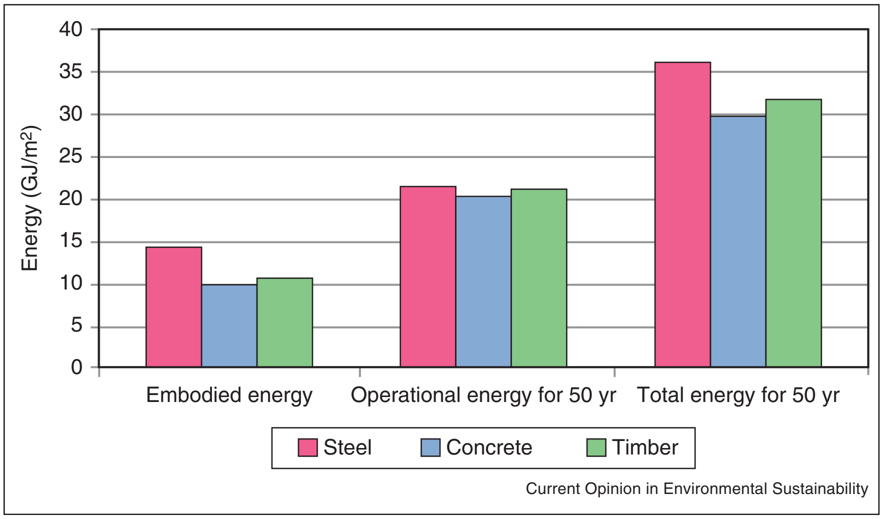
Embodied energy content varies greatly with different construction types. As an example, Figure 3 shows the embodied energy and the life cycle energy of three forms of construction for multi-residential buildings in Melbourne (an eight-storey, 3943 m^2 multi-residential building): conventional concrete construction, modular prefabricated steel, and modular prefabricated timber [35].

One concept that also would need to be considered is the expected life of the buildings. The literature on embodied energy in materials does not consider it, but all studies in LCA mention this as one very important input data for all evaluations [36]. Two methods presented to estimate the service life of buildings show that even though it is an essential point to determine the period of the operational phase of the LCA it is still not been systematically evaluated. These recent studies present the service life of the dwelling stock in Spain [36] together with the concept of life table, and a specific case study for estimating the service life of public buildings in the harsh of weather of Kuwait using the factor method [37]. Service life can be applied to building materials, urban and territory planners, or even to the building stock economic analyses and its future evolution for dwelling policies. Service life is an important parameter for the dwelling stock design and management. Minimizing obsolescence and extending longevity are fundamental issues to maintain the physical, economic, and societal investments involved [36].

Embodied energy in building materials

Materials used in buildings are mainly concrete, wood, bricks, and sandstone. In the past few years, research has

Figure 3



Life cycle energy requirements of the three Australian form of construction for multi-residential buildings over 50 years [35].

focused in evaluating the impact of using wastes in materials such as concrete and bricks, or in more natural materials such as rammed earth and bamboo.

Talukdar *et al.* [38] examined the use of waste materials such as crushed glass, ground tire rubber, and recycled aggregate in concrete. Jiao *et al.* [8,39] used solid wastes to launch the experimental work on low carbon building materials and studied the carbon emissions of autoclaved fly ash bricks. They estimated the carbon emissions and the percentage of each part to the total carbon emissions. In these two studies only the material point of view is given and both aim to use industrial wastes in building materials. Nevertheless, the first study comes from Canada and the second from China.

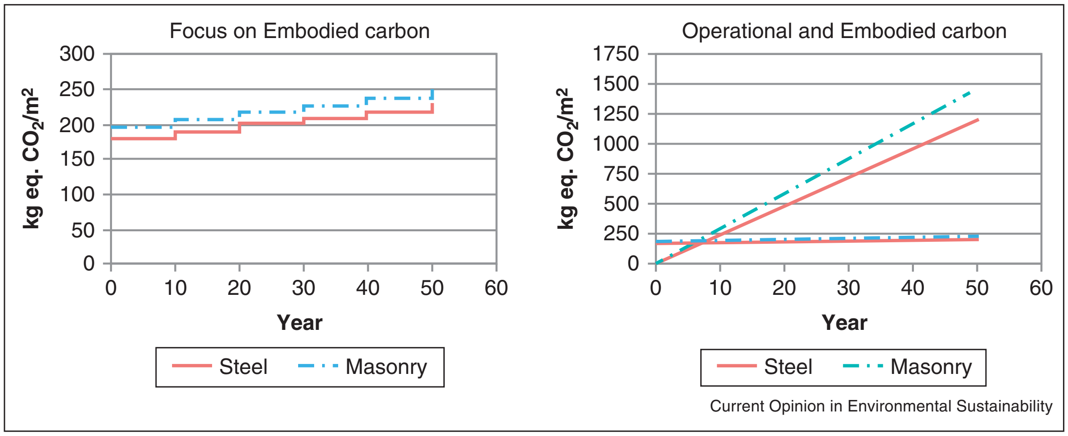
Reddy and Kumar [40] studied the influence of soil grading, density and cement content on energy input during rammed earth compaction. A comparison between energy content of cement and energy in transportation of materials, with that of the actual energy input during rammed earth compaction in the actual field conditions and the laboratory was made. Furthermore, Reddy and Jagadish [6] studied embodied energy of cement stabilized rammed earth walls. They proved that even though the addition of cement in rammed earth walls needs more compaction, therefore more energy in the construction process, this energy expenditure is negligible when compared to the energy content of the cement added. Both studies focussed on low rise buildings in India, but the second one compared buildings with different and finally used, such as residential buildings (with two stories) and schools (with three stories). The main conclusion of this study is that energy expenditure in the compaction process is a negligible quantity when compared to energy content of the cement, without differences between the two types of building compared.

Crishna *et al.* [41] carried out a survey based on LCA where eight production operations on a cradle-to-site base for UK destination, and the carbon footprint of sandstone were calculated. They showed the high impact of transportation on the carbon footprint, and therefore suggested the use of local sandstone. Similar conclusions can be carried out for any other building material.

Bamboo is a material used in developing countries as building structure material. Here, only low rise buildings are considered. Yu *et al.* [42] analyzed the material-based energy use and carbon emission over the life cycle of a bamboo-structure residential building prototype with innovative insulation technologies. They stated that in comparison with a typical brick-concrete building, the bamboo-structure building requires less energy and emits less carbon dioxide to meet the identical functional requirements, that is, envelope insulation and structure supporting. Moreover, Nath and Das [43] evaluated the role of village bamboo management in the rural landscape of North East India in global climate change mitigation. They showed that the brief periodicity of culm growth in a single growth period.

On the other hand, a few researchers compare the use of different materials for the same application in the building. According to Buchanan and Levine [44], an analysis of typical forms of building construction shows that wood buildings require much lower process energy and result in lower carbon emissions than buildings of other materials such as brick, aluminium, steel and concrete. This study investigates the global impact of wood as a building

Figure 4



Manual calculations — operational and embodied carbon versus lifespan for steel and masonry houses [47].

material by considering emissions of carbon dioxide to the atmosphere. Wood is compared with other materials in terms of stored carbon and emissions of carbon dioxide from fossil fuel energy used in manufacturing. Authors conclude that if a shift is made towards greater use of wood in buildings, the low fossil fuel requirement for manufacturing wood compared with other materials is much more significant in the long term than the carbon stored in the wood building products. The types of buildings considered in this study are two industrial recently constructed single storey portal-frame buildings, two five-storey reinforced concrete office buildings, a six-storey reinforced concrete hostel, and four typical types of house construction in New Zealand and Sweden.

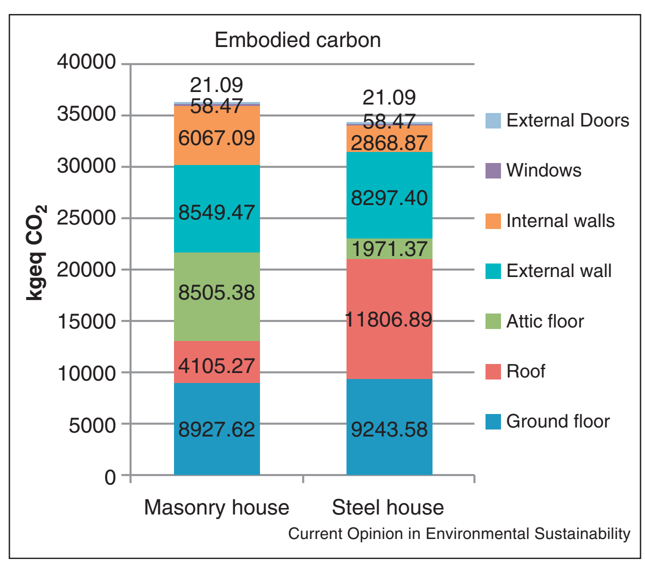
Nässén *et al.* [45] compare buildings with concrete frames and wooden frames concerning their life-time carbon dioxide emissions as well as their total material, energy and carbon dioxide costs. According to these authors, wooden frames cause lower carbon dioxide emissions given the prevailing energy system, but concrete frames obtain about the same emissions as the wood frame in a system where carbon capture and storage is not used for wood incineration in the demolishing phase. It is interesting to highlight that this study takes into consideration systematically the primary energy used by the industry to do this comparison, even presenting scenarios for prices of electricity, fossil fuels, biomass and carbon dioxide emissions we use a global energy systems model, GET, which minimizes the discounted energy system cost for the period 2000–2150.

Tiwari and Parikh [46] showed that the use of technologies with less amounts of cement, steel and burnt bricks in the construction of new buildings in India could reduce carbon dioxide emissions by 61%. This is because the consumption of cement reduces by 47% in low carbon case than in common practices; consumption of burnt bricks reduces by 82% in low carbon case compared to common practices; and steel consumption too can be reduced substantially.

Effect of the material substitution in the embodied carbon of a building

Several studies were made regarding the effects of material substitution in the embodied energy of a building studying the embodied carbon which is directly proportional. Recently, Rossi *et al.* [47] compare the embodied carbon of two structural systems for a Belgian house: steel frame and traditional masonry (Figures 4 and 5).

Figure 5



Share of each building part in the embodied carbon — Masonry house versus steel house [47].

Building regulations and low energy materials

Nordby [48] studied the case of Norway's wood-fired mountain cabins to explore whether strict energy-efficiency requirements in building regulations are appropriate and effective. A self-service (holiday) cabin was analyzed in three different scenarios. The carbon emissions from the extra material required to meet the new regulations were calculated and compared with the emissions saved by the expected decrease in operational energy demand over a 50-year life cycle. The results showed that in all three scenarios the carbon emissions from the extra material used and their transport outweighed the savings from reduced heating. The frequency of use (occupancy rate) was shown to be an important variable to determine the usefulness of technical upgrading. Alternative solutions for long-term reductions in carbon emissions for wood-fired mountain cabins were suggested, solutions such as the area efficiency (reduced floor area), low-carbon materials, and the reuse of components instead of improved *U*-values. The authors claim that regulatory measures that create universal standards for all buildings fail to account for particular circumstances and create revenge effects.

Accounting for the carbon footprint of products and buildings has become a well-developed approach to quantifying the success of climate change mitigation initiatives [49]. In the built environment, the focus is either on the emissions during the operational life of the asset or on the embodied emissions defined as 'the total carbon dioxide equivalent that is emitted during the different stages of extraction, processing, use and disposal of the material' [50]. The embodied energy contributes 10–20% of the life-cycle energy consumption of 'green' buildings [51] and is increasing this proportion with contributions reported up to 40% and 45% [16] over a 50-year period. By definition an embodied carbon analysis originates from a life cycle assessment (LCA). A recent development in life cycle carbon accounting is the PAS 2050 standard [52,53].

Green building rating (GBR) systems are developed to provide independent assessment standards that evaluate in a few categories about the performance and sustainability of buildings. However, same category might weigh differently in each of the GBR systems. A particular system might favour certain strategies over others due to difference in weighing. This is particularly the case for industrial halls since current GBR systems are catered more for commercial buildings than for industrial halls, which pose a significantly different geometry. Lee *et al.* [54] explored the impact of different building materials (concrete versus steel) on the embodied energy of the building structure, and compared that to the GBR score earned under the material category for the same structure. Through a sensitivity analysis in the calculation of embodied energy, the major source of uncertainty was identified and its effect on GBR score was discussed. This study demonstrated the potential deficiency of GBR systems, particularly for industrial halls, which might lead to misleading scores that do not accurately represent the actual performance of the structures.

As new buildings become more energy-efficient and building codes and regulations moves towards more efficiency standards, the relative importance of embodied carbon in buildings increases [55].

Conclusions

Even though affordable construction is seen as very important and necessary, and even though sustainable materials with low embodied energy has been identified as a key issue to achieve the aim of affordable construction, there is very little research in the topic.

Nevertheless, embodied energy (and carbon) is studied in the context of buildings and construction materials. In the literature it has also been shown that when considering the life cycle of a building, both embodied energy and operating energy need to be considered. Operating energy is usually considered in many studies, but embodied energy in materials is considered as more complex and more time consuming to evaluate, even though it accounts for a significant proportion of the total life cycle energy. Moreover, embodied energy databases are seen as incomparable due to the great variation between data presented.

When considering construction types, literature shows that embodied energy varies greatly. When considering building materials, research has focused in evaluating the impact of using wastes in materials such as concrete and bricks, or in more natural materials such as rammed earth and bamboo. But there are no studies comparing both construction types or building materials; therefore it is up to the reader to approach such comparison.

Most material research is found in concrete. Ideas such as including wastes, evaluating the CO_2 uptake of it during the curing process and during its lifetime, and the evaluation of its carbon footprint are examples of what is found in the literature. It is not easy to carry out any comparison, because each study has its own assumptions, and many of them are focused in a given location as well (usually a country).

Some studies cited the use of bamboo in housing, always with the idea of increasing the affordability of the new buildings, but the comparison between using wood and bamboo is not found in the literature.

On the other hand, several studies about the effect of materials substitution in the embodied energy of a building can be found. For example, a comparison between as masonry house and a steel house gives nearly the same total embodied energy in the house, but the distribution of such embodied energy between the different house parts (floor, roof and walls) is very different.

Finally, a few local studies about the embodied energy in the buildings and the building regulations being developed can be found. In general it can be said that building regulations do not take into account the embodied energy in the construction materials, but on the other hand, as new buildings become more energy-efficient, the relative importance of embodied carbon in them becomes more and more important.

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