

Review

Sustainable Buildings: An Ever Evolving Target

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Abstract: Environmental considerations have called for new developments in building technologies to bridge the gap between this need for lower impacts on the environment and ever increasing comfort. These developments were generally directed at the reduction of the energy consumption during operations. While this was indeed a mandatory first step, complete environmental life cycle analysis raises new questions. For instance, for a typical low thermal energy consumption building, the embodied energy of construction materials now becomes an important component of the environmental footprint. In addition, the usual practice in life cycle analysis now appears to call for some adaptation—due to variable parameters in time—to be implemented successfully in building analysis. These issues bring new challenges to reach the goal of integrated design, construction, commissioning, operation, maintenance, and decommissioning of sustainable buildings.

Keywords: sustainable building; passivhaus; life cycle assessment

1. Introduction

Sustainable development as defined in Brundtland's report [1], is a “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. Today, climate change and resources scarcity, combine with this need to have an ever “growing” economy threaten our ability to reach this goal.

1.1. Reducing Energy Consumption

In response to the need of a sustainable economy, reduction of energy consumption in general and fossil fuel in particular is a global acknowledged priority. To mitigate climate change, the world needs to reduce the CO₂ emission by 50% from the current level by 2050. For developed countries, this translates into a reduction of 80%, a factor five with respect to nowadays emissions [2]. To reach this goal, some authors have proposed to drastically reduce the energy consumption. For example, Kesselring and Winter [3] proposed the concept of a 2,000 W society which aims at consuming no more than what corresponds to an average continuous power of 2,000 W per capita. This concept was later further developed and expanded [4,5]. Since actual rates of energy consumption is about 6,000 W in Europe and even 10,000 W in North America, this would imply a reduction by a factor 3 to 5 of the energy consumption per capita.

The building industry is one of the human activities with the largest environmental impact. As noted by Dixit *et al.* [6], the construction industry depleted two-fifths of global raw stone, gravel, and sand; one-fourth of virgin wood; and it consumes 40 percent of total energy and 16 percent of fresh water annually [7–13]. These figures are more or less similar in any developed country. Indeed, for OECD countries, energy consumption by building varies between 25%–50% of total energy consumption [14], whereas it is closer to 50% in the European Union [15].

To reduce this tremendous demand and consequent impacts, the European Union Directive on Energy Performance of Buildings [16] requires member states to implement energy efficiency legislations for buildings, including existing ones with floor areas over 1,000 m² that undergo significant renovations. In a similar way, the Swedish government promulgated a Bill on Energy Efficiency and Smart Construction, to reduce total energy use per heated building area by 20% by 2020 and 50% by 2050, using year 1995 as the reference [17]. In addition, these energy efficiency measures offer a significant opportunity to reduce CO₂ emissions [2,18].

In conclusion, reducing our global consumption necessarily calls for an improvement in the building industry.

1.2. Zero Energy Buildings

Technologies for energy efficient housing have a long history. One of the first designs of zero energy houses was the 1939 MIT Solar House I, which included a large solar thermal collector area and water storage [19]. This project was followed by the “Bliss House” of 1955 using solar air collectors and rock mass storage [20]. Other projects followed in the 70’s: for instance, the Vagn Korsgaard Zero Energy Home in Denmark in 1977 [21] or the Saskatchewan Conservation House in 1979 [22]. These designs proposed buildings that had a close to zero heating need all over the year. This was achieved mainly and logically by highly insulated envelopes. Approaches that prefigure modern “passivhaus” design, like good air tightness (1.3 air changes at 50 Pa) and consequently an air-to-air heat exchanger, were used some 30 years ago in the Saskatchewan Conservation House. The first passive house in Germany, designed by Dr. Wolfgang Feist, was built in 1991 in Darmstadt-Kranichstein. This type of designs and similar ones tend to result in the use of less material than previously more requiring zero energy designs, and this makes the “so-called” passivhaus more suitable for large scale implementations.

With these achievements in mind, new, more restrictive energy standard were established. Hence, in central Europe countries, including Germany and Austria, the maximum final energy use for space heating required to comply with the passive house standard is nowadays $15 \text{ kWh m}^{-2} \text{ yr}^{-1}$, and the maximum overall operating primary energy use is $120 \text{ kWh m}^{-2} \text{ yr}^{-1}$ [23]. In Sweden, the equivalent requirement is based on purchased energy and is set at 45 and $55 \text{ kWh m}^{-2} \text{ yr}^{-1}$ for the South and North Climate zones, respectively [24,25].

1.3. The Need of Other Means to Reduce a Building Environmental Impact

Notwithstanding the relevance and importance of those policies, they all focus on the energy consumption through the usage phase, while the building is in operation. Although this is an important factor in the overall environmental impact, focuses are now shifted to other aspects of building environmental impacts (mainly construction, maintenance, and decommissioning). However, since these points were less important in the past, they are not as much documented and formalized than the strict energy consumption in the operation phase. In addition, classical environmental indicators are not optimized for long lifetime goods like buildings, which brings several new, interdependent, hard to solve problems (see Section 6) All these factors bring new challenges to the development of better practices in sustainable building design.

2. Building Life Cycle Assessment

2.1. Life Cycle Analysis

As mentioned above, beyond the sole energy consumption of a building, other issues have to be considered to account for their global environmental impacts or footprint. This is why a full life cycle analysis (hereafter LCA) is commonly used to assess better design practices. This approach takes into account all of the aforementioned aspects of the building life: construction, commissioning, operation, maintenance, and decommissioning.

Nevertheless, instead of doing a complete LCA, total energy consumption is often used as a proxy. Indeed, the gross energy requirements [26], non-renewable energy, global warming potential—as an indicator of greenhouse emissions with a time horizon of 100 years [2]—are seen as essentially equivalent [27]. This can naturally be justified since energy production is in general a preponderant source of greenhouse gas emission and also because energy consumption reduction by itself represents an objective to achieve sustainability. Notwithstanding this strong correlation between these indicators, there are also other environmental impacts that are taken into account in a LCA (For example: resource depletion). However, Blengini and Di Carlo [28] remarked that there is neither consensus on weighting [29–34], nor on the best weighting method to integrate all the environmental impacts in a global indicator.

2.2. Low Energy Buildings (Operation)

As pointed out by Blengini and Di Carlo [34], low energy buildings should use low quantities of energies regardless of the sources. In addition, Sartori and Hestnes [35] noted that one must differentiate between primary and secondary energy consumption. Quoting Feist [36], they observed

that the definition of a low-energy building as one having an annual requirement for heating below $70 \text{ kWh m}^{-2}\text{yr}^{-1}$ could be misleading. Indeed, an overall end-use consumption, which includes all energy consumption of $120 \text{ kWh m}^{-2}\text{yr}^{-1}$ is typical for those building. This translates in the equivalent of $200 \text{ kWh m}^{-2}\text{yr}^{-1}$ once converted into primary energy. This lead Sartori and Hestnes [35] to refine the definition of a low energy building as one having an operating energy $<120 \text{ kWh m}^{-2}\text{yr}^{-1}$ when expressed in end-use energy, or $<200 \text{ kWh m}^{-2}\text{yr}^{-1}$ when expressed in primary energy.

Far from being semantic, this modification of the definition has many practical consequences. First, it allows for a more direct comparison between the contribution of embodied energy and the consumption of energy over the operational lifetime of the building. Second, this redefinition also means that it takes also account of the nature of the energy used. The largest impact is on the electricity consumption, for which the conversion factor depends on the local production basket. Third, as discussed later, this conversion factor will also change with time as the efficiency of thermal power plant will improve with time and as the fraction of renewable energy source will increase.

2.3. Embodied Energy (Construction)

Historically, the contribution of embodied energy was considered minimal compared to energy consumption trough the operational phase [33,35,37–42]. However, for low energy houses, this is not the case as the lifetime energy consumption is much lower while the embodied energy is higher due to additional—sometimes pretty sophisticated—construction materials, energy production and recovery systems [30,35,43–48]. Nevertheless, embodied energy can also have a significant impact in conventional designs in clement weather conditions as observed by Treloar *et al.* [49], for a two bedroom house located in Australia or for an office building in Greece [50].

Indeed, it has been argued that embodied energy was somehow a substitute to operating energy: therefore the overall gain in efficiency was not as impressive [36]. This situation lead Feist [36] to distinguish between “green” houses for which care is taken to reduce the utilization of synthetic materials, and “low energy” houses that have only for objective the reduction of energy consumption through the operation phase. In this specific case, the embodied energy was somewhat higher than in the conventional design for the “green” house. This is due to the utilization of cellulose fiber as the insulation material, for which the embodied energy was largely increased by the addition of fire retardant materials. For the solar house (the low energy case), the embodied energy requirement was double of that of the classical design while reducing the total energy demand by 50% over a 50 years lifetime. However, as noted by Sartori and Hestnes [35], a much simpler design—the passivhaus—could have achieved a factor three in total energy demand reduction and even a factor four for an improved design.

2.4. Total Energy Consumption

Blengini and Di Carlo [28] came to a very similar conclusion when comparing a standard house to its low energy counterpart. The low energy version allowed a reduction of the heating requirement by a factor 10. This ratio was maintained when carrying out a cradle-to-gate perspective. However, when considering the whole building operation phase, therefore adding sanitary water, cooking, lighting and use of appliances, the ratio between the two houses dropped from 10:1 to 3.7:1. Moreover, when

considering the full life cycle, the ratio was reduced to 2.5:1 in terms of energy requirement, 2.4:1 in terms of global warming potential, and 2.3:1 in terms of Ecoindicator 99 [51]. In another work, these authors [34] observed that, while the heating requirement of a low energy house was reduced by a factor 10 compare to a standard design, the life cycle energy was only reduced by 2.1:1 and the carbon footprint by 2.2:1. Moreover, with a global perspective the environmental trace is no longer dominated by a single major point but is spread through several items. As a result, the designer must not only concentrate his effort on the energetic performance but also on the embodied energy in the building material and their eventual disposal at the end of life of the building. These authors also found that transportation of the building components was only a minor contributor to the environmental trace [34], confirming the previous result of Peuportier [52].

This conclusion is shared by Gustavsson and Joelsson [53], who studied primary energy use and CO₂ emission for the production and operation of conventional and low-energy residential buildings in Sweden. They showed that for conventional and low-energy buildings, the primary energy used for production can reach 45% and 60%, respectively. The importance of the production stage favored the use of wood frames to reduce the environmental trace. They also pointed out that the most effective measure was to improve the building envelope. Indeed, the improvement of the attic insulation and the use of energy-efficient windows provide energy savings 10 times larger than the energy needed for their fabrication.

A similar conclusion was obtained by Verbeeck and Hens [54], who carried-out an analysis of the impact of the embodied energy on the LCA. They pointed out that for the four types of dwelling they studied in Belgium, the additional embodied energy added to improve the energetic performance was recovered in very short terms (<2 yr). Only on extremely low energy building (900 MJ/m³ over 30 yr), the impact of embodied energy was larger than the energy consumed. As in previous studies, they noted that the return on energy invested (EROI) of insulation is about 10 for a 30 yr period when applied to a building that complies with the legal energy performance level.

Bribián, Usón and Scarpellini [55] did also take account of the embodied energy in a life cycle assessment for a Spanish building. In their study, the embodied energy represented 30% of the primary energy used over a 50 yr lifetime. They also proposed an optimization process for the insulation level on the life time energy consumption. Their analysis indicates that a broad optimum design exists, which allows to minimize the heating and cooling loads as embodied energy. This robustness in the result provides some leeway for architectural integration.

In a study of a residential building, Utama and Gheewala [56] demonstrated that a double wall was more energy efficient over a 40 years period than a single wall. Nevertheless, the initial embodied energy of typical double wall and single wall envelopes for high-rise residential buildings is 79.5 GJ/m² and 76.3 GJ/m², respectively. This small difference in embodied energy is overwhelmed by the expected energy savings; the energy consumption dropping from 480 GJ/m² to 283 GJ/m². In this study [56], the authors raised an interesting point: in this specific case, not only the thermal conductivity of the wall had to be taken into account but also its thermal inertia. Previously, Radhi [57] made the same observation that some of the extra energy consumed by a cooling load is not merely due to the effect of external heat through the envelope and incident heat; rather it is a result of the heat being stored into the building structure (inertia). This illustrates the need for a refined and accurate simulation of a building to be really able to optimize its design.

2.5. Life Cycle Zero Energy Buildings

Hernandez and Kenny [58] extended the idea of a net-zero energy building to the life cycle zero-energy building (LC-ZEB). As defined by the European Parliament, a net-zero-energy building is “a building where, as a result of the very high level of energy efficiency of the building, the overall annual primary energy consumption is equal to or less than the energy production from renewable energy sources on site” [16]. Two other definitions are often used: ‘net-zero site energy’ and ‘net-zero source energy’. The first definition takes only account of the energy exchange over the year. The second definition is somewhat more precise as it takes account of the primary energy. Hence, energy source substitution might allow for a larger amount of energy consumption of heating if electricity is replaced by natural gas [59]. By extension, a life cycle zero energy building includes embodied energy of the building and its components together with the annual energy use. Overall, these energy expenses must be completely compensated by the energy generated by the building over its lifetime.

To reach the goal of a life cycle zero energy building, embodied energy, energy consumption, and production over the lifetime of the house must be analyzed. As we have noted previously, this was not a standard practice for low energy house until recently. Consequently, many components of very-low energy buildings are probably over designed. Using this methodology, Hernandez and Kenny [60,61] argued that solar collectors and high levels of insulation were often not the most efficient way to reduce the life cycle energy of some buildings.

As the awareness of the importance of embodied energy in low energy buildings is growing, critics of the actual evaluations methods follow the same trajectory. Indeed, Dixit *et al.* [6] also emphasize on the importance of embodied energy in the overall life cycle of housing. However, they noted the problem of the absence of reliable templates, standards or protocols regarding embodied energy computations. Especially, they observed that while the geographic location is commonly stated, the nature of feedstock energy is rarely provided. In addition, the aging of the LCA data is problematic as it creates inconsistencies between studies. Similar concerns were formulated by Papadopoulos and Giama [62] who noted that a detailed statement on the origins of the basic data used for the evaluation of the building components should be provided with any environmental study.

In addition, it is difficult to estimate the lifetime of most components. Hernandez and Kenny [60,61], like Kellenberger and Althaus [29], deplored the lack of reliable data on life span of building components, which becomes an important issue of LCA in low energy houses and buildings. Similar problem arise, with the lifetime of the building itself. To handle this problem, they suggest to refer to the norm ISO 15686 “Buildings and constructed assets—service-life planning” [63] or using a 50 years time frame as a reference for major renovations, since it is acknowledged and used in many studies [35].

Habert *et al.* [64] also criticized the methodology used for life cycle assessments of bulk materials used in buildings. Their concern is concentrated on state-pressure environmental indicators [65]. This type of environment indicator is calculated by comparing a flow of matter to a reference stock. They pointed out that one key weakness of this approach is the inappropriate account of the local and temporal variations of the stock. Using a methodology they have developed previously [66], they analyzed the depletion of aggregates, which are not normally considered to have a depletion potential. For example, while the depletion of bulk resources is negligible at global level [67,68] and hard to put

in evidence at the scale of a country like France, depletion becomes clear in a relatively small region like Île de France, where depletion time scale is the same order of magnitude than quarries or buildings lifetime.

In addition, to take account of the impact of power hungry industrial processes, which might be difficult to operate with a power mix dominated by renewable and distributed production, they developed an indicator of “power intensity” of materials. Instead of using the usual total energy consumption as an indicator of sustainability, they used the average of the power needed to produce materials pondered by their energy content [66]. This indicator does not have a true physical meaning but from an environmental point of view, it can be used when comparing two solutions to select the one who is the less dependent to high power processes.

To illustrate their idea, they compared the production and operation phases of three houses made respectively in stone masonry, in rammed earth, and in concrete. The details of the construction have been published by Morel *et al.* [69] and the energy needed during the use of the houses is estimated at 4,600 kWh/yr for a service life of 50 years. In these cases, while average energy consumption is rather uniform and dominated by the operation phase, the power indicator for the concrete house was ~3.5 larger than the same house build in stone masonry and mortar. They also pointed out that energy consumption should also be considered on a territory-based approach as it was already proposed by Pulsili *et al.* [70].

2.6. Post-occupancy Evaluation

While some researchers critic the analysis of materials used, others raise doubts on the projection of those models. Meir *et al.* [71] reviewed the importance of post-occupancy evaluation in the optimization of the actual environmental trace of a building. Indeed, they noted that there is an ever increasing demand on comfort in buildings, while there is pressure to improve the energy efficiency [72]. A way to better fulfill these contradictory requirements is to have a better knowledge of the interaction of the user with the building itself. Indeed, occupant behaviors vary widely and can impact energy consumption by as much as 100% for a given dwelling [73].

For instance, they summarized three post-occupancy evaluation studies conducted in Germany on green buildings relative to thermal comfort and occupant satisfaction [74-76]. The results of these studies indicate that under specific conditions involving a high level of activity, occupants of those buildings could tolerate temperature settings outside the normal ones for an air-conditioned building. Such an increase in comfort range compared to air-conditioned buildings could be an easy energy efficiency application. However, this knowledge is not yet included in the green building design evaluation, which might lead to under optimized design. A similar phenomenon was observed for buildings with opening windows that increase the satisfaction of users [77-79]. However, windows optimization is tricky since large window can save on lighting and improve visual comfort [80], but not always since occupant can also suffer from glare and excessive heat [80,81].

3. Construction Materials Environmental Trace

Following the previous discussion, the reduction of embodied energy in construction materials is now as important as ever. To quote Bainbridge [82]: “An ideal building would be inexpensive to build,

last forever with modest maintenance, but return completely to the earth when abandoned”. In a recent review, Joseph and Tretsiakova-McNally [83] explored the alternate materials that could be used to reduce the environmental trace of a building.

3.1. Concrete

In the aforementioned perspective, concrete is regarded as one of the most energy intensive material. It is also a large source of CO₂ emission, its production generating up to 7% of the world total emissions [84]. These emissions are not only produced by the energy used, but also CO₂ is a byproduct of the necessary de-carbonation of limestone itself [85]. Consequently, concrete represents a large fraction of the environmental trace of the buildings. For instance, Asif *et al.* [14] calculated that 99% of the total emitted CO₂ resulting from a semi detached three bedrooms house in Scotland was originating from concrete and mortar.

Blenghini [37] noted that concrete recycling was permitting the recovery of only 19% of its embodied energy. This result complies with the observations of Gustavsson and Sathre [86], who also noted that, while the extraction of aggregate to be incorporated in concrete needed 20 kJ/kg of oil and 9 kJ/kg of electricity, crushing the same amount of concrete requires 120 kJ of oil and 50 kJ of electricity. In a later work [87], they noted that a small benefit of concrete recycling may occur when it is used to replace crushed stone. Another approach to reduce the environmental trace of concrete is to replace the natural aggregate with recycled products: recycled concrete aggregate, crushed blast furnace slag, sand, brick, glass, granulated plastics, waste fiberglass, mineralized wood shavings, *etc.* [83]. However, the integration of these materials is not straightforward as mechanical and chemical properties are different than those of the natural aggregates. In consequence, some adaptations of the concrete mixtures must be done to maintain the desired properties. Notwithstanding these problems, this type of concrete can be used in many applications. Examples include the renewal of Denver’s Stapleton Airport in the US which reused and recycled 6.5 million tons of concrete [88].

An alternate strategy to improve the environmental behavior of concrete is to increase its mechanical strength which allows a reduction of the volume used for the same application [89]. With this objective in mind, an ultra high performance concrete Ductal[®] was developed in France. This concrete uses only 65% of raw materials, 51% of the primary energy, and 47% of the overall CO₂ emissions of the traditional concrete. Its mechanical properties are also largely improved. Its compressive strength is 6–8 times higher, the flexural strength is 10 times higher, while the durability is from 10 to 100 times better [85].

Also, some authors explored the possibility of using alternate materials instead of concrete. For example, Huberman and Pearlmutter [30] calculated that the embodied energy of a house in the Negev desert could be reduced by 20% by substituting reinforced concrete by alternate materials such as hollow concrete blocks, stabilized soil blocks or fly-ashes. In a similar way, unfired bricks can be used instead of fired ones. The energy needed to produce unfired brick (657.1 MJ/t) is much lower than the one needed for the fired brick (4,186.8 MJ/t); a factor 6.4 in reduction [90]. This traditional building material is inexpensive and also involves good thermal and acoustic properties. Moreover, at the end of its useful life, it can be reused by grinding, wetting or can be simply returned to the ground.

However, the unfired bricks lack of durability when exposed to water. Water damage limits their application but this problem can be alleviated by the addition of lime.

In some applications, stone can be used as a substitute for concrete or ceramic. If extracted locally and processed efficiently, stones can reduce the environmental impact of a construction. There is now a renewed interest in dry stone masonry. As many walls build in the 19th and at the beginning of the 20th century are aging, modern engineering tools are needed to assess their mechanical performances [91,92]. The environmental impact of natural stones and aggregates is extensively discussed by Calkins [84]. Stones can also be used as a replacement for ceramic. Nicoletti *et al.* [93] did a comparative LCA between marble and ceramic as a flooring material. Their analysis indicated that marble had an environmental trace 2.2 times less than ceramic in their specific environment.

3.2. Metals

Metals (steel, aluminum, copper, *etc.*) possess a very large embodied energy compared to concrete (aluminum 191 MJ/kg, steel 32 MJ/kg, concrete 1.30 MJ/kg). In consequence, even if they represent a small fraction of the building mass, they largely contribute to its total embodied energy. As an example, Chen *et al.* [46] studied two high rise residential buildings in Hong Kong. In these cases, steel and aluminum together accounted for ~75% of the overall embodied energy. However, relatively little concrete was used in the structure. Nevertheless, they noted that the embodied energy of the metal could be largely reduced by recycling. They pointed out that the energy intensity is about 10 MJ/kg for recycled steel and 8 MJ/kg for recycled aluminum, which is only 31% of energy intensity of the virgin steel and only 4% of that of the virgin aluminum. Blengini [37] and Gustavsson and Sathre [86] came to a similar conclusion, with slightly different numbers. In consequence, using recycled steel and aluminum can reduce the overall embodied energy by as much as 50%.

Additional gains also arise at the end of life of the building by recycling those materials. However, as noted by Dadoo *et al.* [87], as the recycled fraction of metal in the feedstock is increased, the overall energy gain by end-of-life recycling is reduced. The potential energy recovery from recycling metals led Chen *et al.* [46] to recommend their usage as an alternative to concrete for non-structural elements of the building.

3.3. Wood and Straw Bale

While concrete is considered as an environmental burden, wood has a much better reputation. In that aspect, the literature is essentially unanimous to proclaim that the wood-based constructions have the lowest energy needs and CO₂ emissions [94-105]. They are two main factors which explain the wood small environmental trace. Wood acts as a carbon storage material as long as the lifetime of the building is larger than the lifetime that the trees would have had if they were not cut [97,98,102]. In addition, wood can be used as a biofuel, which can replace fossil fuels. As noted by Gustavsson and Sathre [86], and Dadoo *et al.* [87] not only wood from a building could be recovered, but also all the wood residues from the extraction, manufacturing, and construction processes. However, this gain is real only if the forest exploitation protects its regeneration potential.

Nevertheless, while wood has low embodied energy, it needs often more energy in the construction process than steel. This is largely caused by the transportation of construction workers, which is a

large contribution to the embodied energy. As a result, for some buildings, steel can have an even lower embodied energy than wood. While this might also be true for CO₂ emissions, wood performs generally much better than steel for this environmental indicator due to its sequestration potential. This counter-intuitive result stresses the importance to consider steel as alternate option to wood [102,106].

Another alternate construction material, that is the object of considerable interest, is the straw bale. It has been used as construction material around the world for centuries in place where wood was rare and grass abundant. Straw has many useful properties as a construction material [107]. It has excellent thermal and sound insulation properties. In addition, its production and processing requires little energy compared to other construction materials. While concerns have been raised about its long term reliability, careful construction processes can insure that its lifetime is not an issue in building application. As pointed out by Pierquet *et al.* [108], straw bale wall systems provide the best combination of higher insulating value and lower embodied energy. Still, more research is needed on the most effective way to integrate it in more classical building design.

3.3. Windows and Radiative Thermal Control

While traditional material might have some appeal to reduce the total environmental burden, advanced material and technique can also have a large impact of energy efficiency at a very low initial environmental cost. For example, Hannon [109] reported that a double glazing window can return 136 times the added embodied energy of a single window through its life time. Addition of low-emissivity coatings and utilization of argon or krypton in high performance windows reduces even more the heat and cooling loads with a minimum additional embodied energy [77,110,111]. For example, Blom *et al.* [112] noted that replacing existing single and regular double glazing with high efficiency double glazing provided a gain of a factor 40 in environmental impact compare to the additional resources requirement.

High solar reflectance coating is also an example of technology with a very high environmental return for a minimal investment. The adequate use of high reflectance paints can lower roof surfaces temperature by up to 10 °C, which provides both gains in energy efficiency and improvements of the material life time [113]. Indeed, these coatings can largely (18–93%) reduce the cooling load in air-conditioned buildings [114–116]. Overall, building energy consumption reduction is less impressive [117], but this technique also provides environmental gain not related to energy, like reduction of air pollution by reduction of the heat island effect [116].

4. Building Retrofitting

While most life cycle analyses of buildings have been done on new buildings, only 1% of the building stock is renewed annually [118]. Consequently, the short and medium terms environmental benefits must come from building retrofitting. In many case, this retrofitting would have to be done even without consideration for the energy efficiency since acceptable living conditions standards were much lower in the past or because some element of the building degraded over time [119]. These circumstances provide an opportunity to largely improve the energy efficiency of a building with a minimal addition of embodied energy.

Nevertheless, there is not that many studies on the optimal approach to energy demand reduction when retrofitting a building [120]. The most effective way to reduce the energy consumption of a residential unit (house) is to improve the building envelope targeting passivhaus standard if feasible. From our own building retrofits experience, in commercial, institutional, and large residential buildings, the reduction in conflicts of operation between the building energy systems, namely heating and air conditioning, was found to be the most effective way to reduce energy consumption with a minimal investment.

Dodoo *et al.* [87] studied the impact of retrofitting a wood-frame house to passivhaus standard. They noted that the primary energy use during the operation phase still dominates after the retrofit. However, the relative importance of other phases of the life cycle was increased. Overall, the retrofit was positive since the primary energy payback period was less than four years. This is aligned with the results of Feist [44]. However, the importance of the gain (energy reduction) was strongly related to the source of energy used. In that case, they compared resistance heating and district heating. Since the source of electricity was not renewable, unlike the district heating, it had a larger environmental trace from the start. In consequence, environmental gains were found to be lower for district heating. This result is coherent with that of Gustavsson and Joelsson [53].

5. Local Energy Production

Some approaches used to reduce the environmental trace of buildings are based on the local production of energy. Nevertheless, the environmental trace of this local production must be compared to the environmental trace of the external energy production it replaces. This is a somewhat difficult task to carry-out but as a proxy, we can use the ratio between energy returned on energy invested (EROI). If the EROI is not available, the ratio between energy return payback period to the expected installation life time can be used in a similar way.

The higher this ratio, the lower the environmental impact per unit of energy is expected. It is likely to be also a better economic investment. In consequence, local production should be preferred if its EROI is higher than the average EROI of the external energy source, if we compare between two renewable energy sources [121,122]. Calculating the average EROI of an energy basket is somewhat tricky. Nevertheless, there is some indication that the average EROI of the US energy basket is close to 10 and that lower EROI have negative economic impacts [123]. In addition, this is the same ratio that has been observed for insulation by several researchers [42,52,54,87,124]. From both arguments, we can estimate that a local energy production from renewable sources that involves an EROI lower than 10 is not environmentally and economically effective, compare to a non local renewable energy source with an higher EROI or simply improving the insulation.

This is similar to the results obtained by Lu and Yang [125] that observed an energy payback time of 7.3 yr for a rooftop integrated photovoltaic system. They also noted than this value varied with the orientation from 7.1 to 20 years. Laleman, Albrecht, and Dewulf [126] did a review of the environmental impact of residential photovoltaic systems in regions with a low solar irradiation: the EROI was 5 in Belgium/UK and 12 in Spain. Battisti and Corrado [127] also obtained similar results for a building integrated PV system, retrofitted on a tilted roof, located in Rome (Italy). In that case, environmental impacts avoided were 5 to 10 times larger than the environmental trace of the PV

system. Radhi [128] estimated that the EROI of building integrated photovoltaic panels was 1.3–1.4 for a site in the United Arab Emirates. However, this ratio improved to 5.2–5.7 when including the reduction of building energy consumption due to an improved thermal envelope. It should be noted that variations in the technology used, the climatic conditions, and the basic assumptions make it difficult to compare results from different studies.

Since they have a smaller initial embodied energy solar, thermal collectors tend to have a shorter energy payback time and consequently a better EROI. Ardente *et al.* [129,130] estimated that the energy payback time was between 1.2 and 2.3 yr for a solar domestic water heater installed in Palermo, Italy. For a domestic hot water system, in UK, Menzies and Roderick [131] report an energy payback time of 2.6 and 6.1 years. These values are a strong function of the latitude and exposure of the collector. This is consistent with the result of Crawford *et al.* [132] who found an energy payback period of 2.5 yr in Brisbane, Australia.

The analysis of Leckner and Zmeureanu [124] reports than EROI of a combined thermal-PV solar panel system is 3.8, when the system is installed in Montreal, Canada. Hence, the utilization of the solar panel is likely to produce more pollution than using directly the energy from another more efficient renewable energy source. This is especially true in this case since, in Montreal, the solar irradiation is not very high and the electricity comes essentially from hydro-power. These results were in line with those of Gustavsson and Joelsson [53], who noted that the use of solar panels for water heating was always less efficient than using the heat pump or district heating. They noted that this was in contrast with previous results that recommended the utilization of electric heating for passivhaus [133–135].

We can conclude from the above investigations that even in the sunniest climates, distributed local energy production can make little environmental sense compared to investing a similar amount of resources in a large scale energy production facility. Care should therefore be taken before selecting such an approach.

6. Unsteady Environment Indicators

One of the key problems in building life cycle analysis arises from the long life of the buildings (30–100 yr). Over such a long period of time, the energy basket and even the climate are expected to change. This fact alone raises some concerns about the applicability of the standard LCA method for buildings [136–140]. The same observation was done by Pehnt [141] for renewable energy technologies. In parallel, Dixit *et al.* [6] noted the problematic nature of the aging of the LCA data, which creates inconsistencies between studies. In consequence, LCA in the construction sector cannot be applied without assumptions or additional refinements.

The change of the energy basket introduces far reaching consequences when the environmental trace is dominated by the energy consumption. Gustavsson and Joelsson [52], Dodoo *et al.* [87] and, Ortiz *et al.* [142] noted that the positive impact of a retrofit is highly dependent on the energy input. If we expect (or hope) that the environmental trace of the energy production will improve with time, predicted environmental trace gain for the introduction of a technology are to be lower than predicted from a static LCA perspective. This can have unexpected consequences for climate change mitigation policies. Kannan and Strachan [143] using the UK MARKAL and MARKAL-Macro energy-economic

model, explored a range of scenario for reaching 60% CO₂ reduction for the whole country [144]. They noted that their model showed a huge variation in energy demand projection as a consequence of the uncertainty in model assumptions. Nevertheless, they noted that the most effective way to reduce CO₂ emissions was to concentrate the effort on energy production [145,146] and not necessarily on energy efficiency.

An additional complexity comes from the climate changes themselves that will bring a reduction in heating loads and an augmentation of the cooling loads over the building life time. In a cold climate, this will bring an overall energy consumption reduction, while it will increase it in a hot climate [147].

7. Conclusions

This paper was intended to review the current investigations devoted to the guidelines for the design of new sustainable buildings as well as the retrofit of actual ones. It first states that historically, researchers mainly, if not solely, focused their attention on the reduction of the energy consumption of buildings during their operation phase, leading to the initial concept of zero energy buildings (ZEB). Then, the paper stresses this need to broaden the analysis to complementary ways to ensure sustainability over the life cycle of buildings namely through the phases of construction, commissioning, operation, maintenance, and decommissioning. From these considerations, the initial concept of ZEB evolved to include primary consumption energy first, then embodied energy, total energy, and, finally, to become a life-cycle ZEB or LCZEB. The paper shows that nowadays this concept still has to be refined, standardized, and acknowledged by the building community.

The proposed review also mentions that the occupants may play a preponderant role on the energy consumption requirements as the concept of comfort may strongly influence the actual temperature and humidity levels required in a typical building.

Then, the review attempts to discuss mainly the issue of materials used in the construction phase of a building lifecycle, while recycling impact is mentioned. The review discusses the high impact of concrete on the embodied energy and explores ways to either improve its trace or replace it by other materials such as unfired bricks and stone. The review stresses this need to avoid concrete as much as possible as it may, in some particular applications, account for 99% of the total energy embodied in a building. Windows are also briefly investigated as double-pane windows are found to be better than their single-pane counterparts over the life cycle of a building.

The conclusion about retrofitting is that for residential units the work on a better thermal envelope seems to be the best way to improve sustainability whereas for commercial, institutional and larger residential buildings, the appropriate control of the energy systems—to avoid antagonisms—is the first issue to consider.

When local energy production is concerned, the review points out that an EROI of 10 appears to be the minimum required to justify a local production when compared to large scale production (of renewable energy). Otherwise, the local production could be nonsense in terms of sustainability. Solar thermal heat recovery seems to be more sustainable than other systems.

Finally, the paper ends with warnings when it comes to the life cycle analysis (LCA) of long lasting products such as buildings. Over a long period of time (up to 100 years), LCA could be somewhat difficult to carry out as the climate, the regulations, the energy basket, and the comfort standards vary,

introducing a temporal drift of the parameters used to define acceptable thresholds. The environmental footprint then varies temporally as well as geographically due to buildings extended lifetimes.

The temporal drift of fundamental parameters required in LCA was not much an issue with classical design as the instantaneous energy consumption dominates the total energy need. But, in low energy buildings—that is buildings of the future—where the operation phase characterized by energy consumption is lower, the unsteadiness of the parameters over a long period of time may play a much more important role. As a result, these parameters and their variation with time must be accounted for appropriately if we want to reduce the environmental trace of buildings further than it is now possible.

This is a necessary step to reach the goal of reduction by a factor three (Europe) to five (North America) of the buildings environmental footprint: a mandatory requirement to ensure a sustainable future.

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