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# Lime Hemp Concrete with Unfired Binders vs. Conventional Building Materials: A Comparative Assessment of Energy Requirements and $CO_2$ Emissions

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**Abstract:** This work assesses the energy requirements and $CO_2$ emissions of a building made of Lime Hemp Concrete (LHC) with alternative unfired binders as lime replacement, compared to buildings made of standard LHC, and several conventional building materials. The assessment is based on ISO 14040, which deals with Life Cycle Assessment (LCA), and examines two aspects: energy, including pre-use phase Embodied Energy (EE), and use phase Operational Energy (OE); and $CO_2$ emissions, including pre-use phase Embodied Carbon (EC), and use phase Operational Carbon (OC). The EE and EC calculations are based on published databases, while OE and OC were obtained with EnergyPlus simulations. The assessment refers to a specific case study in an arid region, with extreme diurnal and seasonal fluctuations of temperature and relative humidity. Using LHC with 100% unfired binder as lime replacement was shown to save up to 90% of the total energy consumption and $CO_2$ emissions, as compared to conventional building materials. The findings of this research clearly demonstrate the high potential of LHC with unfired binders as lime replacement, which possesses the lowest energy requirements and $CO_2$ emissions, illustrating the potential for a building with significantly low environmental impact over its life cycle, i.e., when calculating both EE and EC, and OE and OC.

**Keywords:** $CO_2$ emissions; energy requirements; LCA; lime; hemp; unfired binder

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## 1. Introduction

A significant portion of the global $CO_2$ emissions, energy consumption, and waste output are related to the building sector. In most industrialized countries, the building sector is responsible for approximately 50% of the $CO_2$ emissions and the energy consumption. This 50% can be divided into two parts: the major part, of about 40%, is derived from the use phase of the building (mainly cooling, heating, and ventilation, alongside lighting and other electric appliances), known as the operational carbon (OC) and operational energy (OE) [1–5]; while the other 10% are related to the pre-use phase, i.e., embodied carbon (EC) and embodied energy (EE), which are involved in the production of the building materials, including the extraction of the raw materials, their transportation and processing, and the construction itself [6,7]. These values of $CO_2$ emissions and energy consumption, and the amount of waste, are constantly rising due to the continuous growth of the world's population, its increasing quality of life, and the intensifying urbanization trend. Thus, minimizing the environmental impact of buildings is a crucial target on the way towards sustainability.

The most commonly used building material in industrialized societies is concrete, with an annual production of 10 billion tons worldwide, and constantly increasing, as more societies are replacing their traditional materials with industrialized ones, such as concrete. Concrete, and a variety of cement-based materials, are used in a wide assortment of applications, both structural and non-structural. However, cement is well-known as a non-sustainable material since its levels of EE and EC are quite high due to the relatively

high kiln temperature of 1450 °C in its production. In addition, cement production emits nearly one ton of $CO_2$ into the atmosphere, for each ton of cement [8,9]. Furthermore, since concrete has a very low thermal insulation ability, in order to obtain low levels of OE and OC, the use of insulating materials is essential, but most of the conventional insulators, such as expanded polystyrene (EPS), extruded polystyrene (XPS), mineral wool, or glass wool, also possess high levels of EC and EE, which are frequently not compensated by the OC and OE they are able to save throughout the building's life cycle [10–12]. Therefore, minimizing the environmental impact of buildings requires a development of sustainable materials. One recent novel development is Lime Hemp Concrete (LHC), which is also known as Hempcrete.

LHC is an innovative sustainable building material based on bio-aggregates made of hemp shives [13], mixed with lime binder. Hemp shives are a major by-product of the hemp fibers industry, accounting for ~70% of the hemp plant's mass. Due to hemp's high porosity shive density and thermal conductivity are extremely low, therefore, the shives possess high thermal insulation properties. Lime is produced from limestone (calcium carbonate), which undergoes a combustion at a temperature of approximately 900 °C, which is lower by nearly 40% as compared to cement (~1450 °C); therefore, its EE levels are also lower. As for the EC levels of lime, these are relatively low since most of the $CO_2$ emitted as a result of the chemical reaction involved in its production process, is absorbed back by the carbonation process which occurs during its hardening. The carbonation reaction transforms the lime (calcium hydroxide), back into limestone, so it can be easily re-used and recycled. Moreover, due to the carbon sequestration of the hemp plant through photosynthesis during its growing period, the EC of LHC is, in fact, negative [14–17].

In addition, due to the high thermal insulation properties of LHC, it enables low levels of OC and OE, as the energy consumed for acclimatizing the building is decreased. Nonetheless, the thermal conductivity of LHC depends on the mixing proportions of its ingredients; the lower content of lime leads to lower conductivity, not least due to the lower density. The current research focused on a ratio of 1:2 (hemp: lime), aiming for a density of 330 kg/m$^3$ [18–21]. This mixture ratio possesses low thermal conductivity and moderate heat capacity (thermal mass), a combination which results in a diminution of the temperature fluctuations within the building, as compared to the outdoor ones. For example, while the outdoor amplitude of a case study was 16 °C, the indoor amplitude was only 4 °C [22]. Furthermore, LHC was proved to moderate the relative humidity fluctuations within the building, as compared to the outdoor fluctuations, with internal amplitude of only 5% RH as compared to an external amplitude of 70% RH [22]. Generally, LHC was found to be very attractive in terms of thermal behavior [23,24], improving the thermal comfort within the building. Though the thermal performance of LHC is its main advantage, its mechanical properties are relatively low, so it can only be used in non-structural elements [20,25–28]. Therefore, its main application is wall infill; it can replace conventional materials such as Autoclaved Aerated Concrete (AAC) and Hollow Concrete Blocks (HCB). It can also be implemented as an insulation layer. Life Cycle Assessment (LCA) revealed that a building made of LHC instead of conventional materials leads to significant savings of $CO_2$ emissions and energy consumption [29,30].

However, due to the kiln involved in lime production, its EC and EE levels are still fairly high. Therefore, replacing the lime with alternative unfired binders, such as clay, either in whole or part, can further reduce the EC and EE levels of LHC [31–34]. Furthermore, clay is a waste by-product of many aggregate quarries, thus its use can offer additional environmental benefits, turning it from waste to a resource. Based on these encouraging findings and environmental advantages of using clay as lime replacement, we conducted a wide-range investigation dealing with the development of sustainable LHC made by a range of unfired binders: clay, limestone, dolomite, and basalt. Our results clearly show the benefits of such LHC, in terms of improved compressive strength, and good thermal performance [35], leading to significant EC and EE savings. Furthermore, the internal temperature and relative humidity of test cells built with those LHC mixtures were

monitored during summer and winter, which also showed benefits during the use phase of the building (OC and OE savings), as the LHC with and without unfired binder presented better thermal performance than HCB and EPS, in terms of indoor temperature and relative humidity [36]. This was also evident by upscaled building simulations performed by EnergyPlus, while LHC presented the best thermal performance, and, consequently, the lowest energy consumption compared to buildings built with conventional materials [37].

The work presented here is part of a comprehensive research program, aiming to take its earlier findings, combine them with existing database sources, and assess the energy requirements and $CO_2$ emissions of an upscaled residential building made of different mixtures of LHC with unfired binders as lime replacement, in terms of the pre-use phase, i.e., EE, EC, and the use phase, i.e., OE and OC of the building. These results are compared to a building made of standard LHC, and several buildings made of conventional materials: AAC, HCB, EPS. While several works already dealt with assessment of energy requirements and $CO_2$ emissions for standard LHC [15,24,30,38,39], the novelty of the research conducted here is its focus in the replacement of the lime in LHC with unfired binders, which is expected to reduce the EE and EC of LHC, therefore, diminishing the environmental impact of the building. Moreover, the uniqueness of this research is that the assessment conducted here refers to a specific case study sited in a desert region characterized by arid climate, with extreme diurnal and seasonal fluctuations of both temperature and relative humidity. Israel's area comprises of 65% deserts, whereas deserts worldwide comprise over 40% of the continents, and are home to approximately 35% of the world population and are constantly expanding in a process defined as desertification, impacted by climate change [40].

## 2. Materials and Methods

### *2.1. Methodology, Boundaries and Assumptions*

The method employed in this research is based on ISO 14040 2006 [41], the international standard which defines a widely accepted methodology for Life Cycle Assessment (LCA). As part of this method, the system's boundary used in this study for the quantification of EE and EC is defined according to IFIAS Level II [41], which includes all processes involved in the production of the materials (including cultivation of the hemp plant, manufacturing of the hemp shives, the lime binder, and the alternative unfired binders, as compared to several conventional building materials) which are required to produce the envelope materials for the construction of a prototypical single-family one-story building. It is aimed to capture above 90% of the direct energy and carbon involved in the production of the building. The particular sub-forms of assessment examined in this specific work are energy requirements and $CO_2$ emissions, as these are the most significant parameters for assessing the influence of the building on the environment [42], especially when dealing with LHC, which is known as a material that can lead to major savings in these parameters. The assessment takes into account: (i) the building's pre-use phase, in which EC and EE are evaluated for a specified case study building; and (ii) the use phase, which quantifies the OC and OE of a similar unit.

In this study, both pre-use and use phases are evaluated for a prototypical single-family one-story house, each time made with a different uniform envelope (walls and ceiling). For this purpose, one of three different LHC mixtures is considered each time and results are compared with those of three identical prototypical buildings, each with a uniform envelope made of AAC, HCB, and EPS. The pre-use phase analysis (EE and EC) is based primarily on data from existing sources, some of them locus specific, while the use phase analysis (OE and OC) is based on a combination of physical experimentation and computational simulation, conducted in previous work stages undertaken within the framework of this research [37]. The application of LCA may follow either an attributional or consequential approach. The attributional approach is mostly used for tracing a specific product's aspect (for example, energy requirements in a building) back to its contributing processes, and the attribution of these is usually assessed for a single product. The consequential approach is mainly used for large-scale systems, which are more complex [15]. The two approaches

may produce different results since they have different applications and aims. Considering the simplicity of the functional unit (a single-family one-story house), the variable feature (several building materials), and the processes (energy requirements and $CO_2$ emissions) which are considered in this study, the attributional approach was adopted.

LCA results are significantly influenced by the assumptions which are taken, and the system boundaries. Thus, it may vary even when applied to an identical product or process [6]. The boundaries adopted here include energy consuming processes and their equivalent $CO_2$ emissions that are generated during the pre-use phase and the use phase of the building [17]. The pre-use phase includes all processes involved in material production, while the use phase includes only the acclimatization of the building, i.e., heating and cooling. The following assumptions have been taken for the LCA in the current work:

- A 50-year life span is assumed for a building.
- The annual energy required for acclimatization is assumed to be constant over its life span.

The $CO_2$ emissions and energy consumption of the following factors were excluded from this LCA:

- Manufacture of the machines, tools, vehicles, etc., involved in the production.
- Transportation: all materials are assumed to be manufactured locally.
- Lighting and other electric appliances which are not directly involved in the acclimatization of the building.
- Maintenance and repairs of the building.
- The post-use phase was excluded due to the high level of future uncertainty.

### *2.2. EE and EC Values*

The EE and EC values of LHC, with and without alternative unfired binders, were calculated based on the values presented in Table 1, which were taken mainly from the Inventory of Carbon and Energy (ICE) database [33]. This database does not include values for hemp shives, thus these were taken from other sources [13,15,17,30,32,34]. In addition, no values are given for unfired binders, thus the values used are the ones for sand and aggregates, which are the best alternative available. This strategy was also employed in other studies [32,34]. Therefore, all unfired binders that were examined in previous research [35–37] are assumed to possess approximately similar EC and EE values. Furthermore, all LHC mixtures possess similar OC and OE, as they all present similar thermal performance [36,37].

**Table 1.** EE and EC values for the ingredients of LHC with unfired binders [33].

| LHC Ingredient | EE [MJ/kg] | EC [kg $CO_2$/kg] |
|---|---|---|
| Hemp shives | 0.0014 [1] | −1.8 [1] |
| Lime | 5.3 | 0.74 |
| Unfired binder | 0.1 | 0.005 |

[1] taken from other sources [13,15,17,30,32,34].

Based on the values presented in Table 1, the EE and EC of three different mixtures of LHC with density of 330 kg/m$^3$ (hemp: binders ratio of 1:2) were calculated, with and without unfired binders as replacements to lime: (i) LHC_0—standard LHC with 0% unfired binder (only lime); (ii) LHC_50—LHC with 50% unfired binder as lime replacement; and (iii) LHC_100—LHC with 100% unfired binder as lime replacement (no lime). These mixtures were studied previously under the same research framework [35–37]. Based on these calculations, i.e., EE [MJ/kg] and EC [kg$CO_2$/kg], the building's EE [MJ/building] and EC [kg$CO_2$/building] were also calculated and compared to the conventional building materials which were examined in the previous stages of this research program: AAC, HCB, and EPS.

### *2.3. OE and OC Values*

The OE values used for the assessment were taken from previous work undertaken within the framework of this research [37]. During the previous work stages, we calculated the energy required for acclimatization (heating and cooling) of a prototypical building made of different LHC mixtures (with and without unfired binders as lime replacement) as compared to similar buildings made of conventional materials: AAC, HCB, and EPS. This calculation was based on a simulation conducted by EnergyPlus (based on and validated by monitored data of test cells made of the specific tested LHC mixtures) [37]. The simulated building (Figure 1) is a typical single-family one-story building located on the Sde Boker Campus of the Ben-Gurion University in the Negev, in an arid highland area in the south of Israel, characterized by extreme diurnal and seasonal temperatures, and humidity fluctuations. The external dimensions of the building are 10 m × 10 m × 2.9 m, and the thickness of the walls and the ceiling is 0.2 m. These dimensions give a material's volume of 36.8 $m^3$ (without considering structural elements, such as columns and beams made of reinforced concrete, wood, or steel). The OE values were converted from [kWh/year] to [GJ/year] by 1 [kWh] = 0.0036 [GJ]. These values were multiplied by 50 to represent a cumulative figure for the building's estimated 50 year life span. Then, the OE was converted to OC using a conversion factor of 220 [$kgCO_2/GJ$], representing the Israel Electric Company's current fuel mix [30].

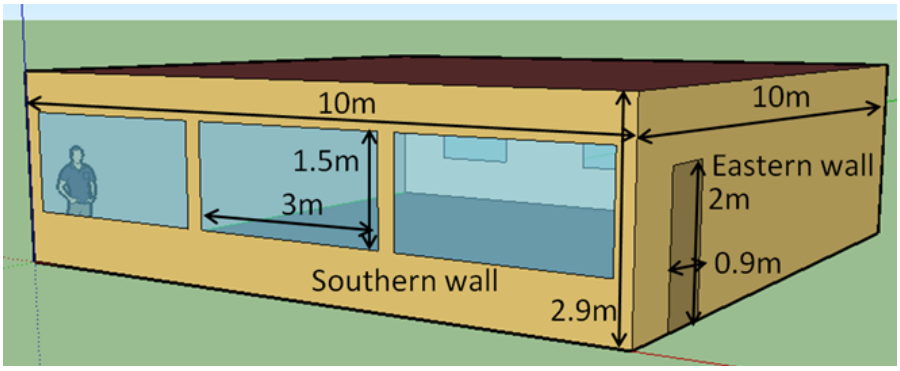



**Figure 1.** Schematic drawing of the tested prototypical single-family one-story building [37].

Finally, the building's total energy requirements were calculated by summing the EE of the building with its OE over the assumed life span of 50 years. A similar procedure was followed for the assessment of the building's total $CO_2$ emissions, summing the EC with its OC for 50 years.

## 3. Results and Discussion

### *3.1. Pre-Use Phase: EE and EC Values*

The calculation of the EE and EC of the buildings made by the different materials include several steps. The first step calculated the EE and EC of each LHC mixture by weight: [MJ/kg] and [$kgCO_2/kg$] respectively. Then, the EE of the entire building [MJ/building] and its EC [$kgCO_2$/building] were calculated based on the material's weight required for the building, which varied and depended on the density of each investigated material. The volume of material required for constructing the envelope of the prototypical building is 36.8 $m^3$. The material's weight values of each building [kg/building] are presented in Table 2 (these were calculated by multiplying the building material's volume, 36.8 $m^3$, by the material's density) [35], and the EE [MJ/kg] and EC [$kgCO_2/kg$] results of all LHC mixtures, and the conventional building materials. The values for the conventional materials were taken from two different databases: (i) Inventory of Carbon and Energy (ICE) [33]; and (ii) The Embodied Energy of Building Materials in Israel [42], which is the first Israeli database compiled from local companies, producers, and utilities. The latter

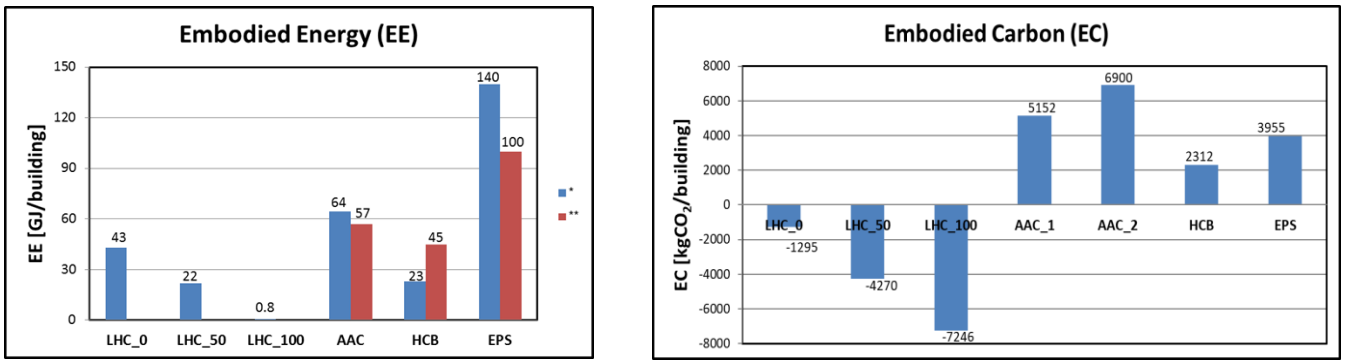
includes only EE values (not EC) which are given as volumetric EE [MJ/m$^3$], while the ICE database is based on weight rather than volume.

**Table 2.** EE and EC values of the tested LHC mixtures (based on Table 1), as compared to conventional materials.

| Material | Density [kg/m$^3$] | Weight [kg/Building] | EE [MJ/kg] | EE [MJ/m$^3$] | EC [kgCO$_2$/kg] |
|---|---|---|---|---|---|
| LHC_0 | 330 | 12,144 | 3.53 | 1166 | −0.11 |
| LHC_50 | 330 | 12,144 | 1.8 | 594 | −0.35 |
| LHC_100 | 330 | 12,144 | 0.067 | 22 | −0.60 |
| AAC | 500 | 18,400 | 3.5 [1] | 1536 [2] | 0.3–0.288 [1] |
| HCB | 1030 | 37,904 | 0.6 [1] | 1216 [2] | 0.06 [1] |
| EPS | 43 | 1582 | 88.6 [1] | 2710 [2] | 2.5 [1] |

[1] based on [33]. [2] based on [42].

Figure 2 presents the calculated EE and EC values of the buildings made of the three different LHC mixtures (calculated based on the values from Table 2), as compared to similar buildings made with conventional materials. Generally, the building made with LHC exhibits relatively low EE as compared to buildings made with conventional materials, mainly of EPS and AAC, while using LHC_100 (no lime) provides the lowest EE value (Figure 2a). Using LHC_100 or the other LHC mixtures instead of conventional materials allows savings in the EE values of up to 99% and as high as 96%, respectively, relative to the other tested materials, as presented in Table 3. Additionally, the EE savings in LHC buildings is approximately similar to the percentage of the lime replacement, i.e., 100% replacement of the lime by unfired binders is equivalent to a 98% reduction in EE (Table 3).




(**a**) (**b**)

**Figure 2.** EE and EC values of all LHC buildings (based on Table 2), compared to conventional materials buildings. (**a**) EE; (**b**) EC. * is based on [33], and ** is based [42].

**Table 3.** The savings in EE and EC relative to a building made of LHC_100 (e.g., LHC_0/LHC_100).

| Material | EE Savings [%] | EC Savings [%] |
|---|---|---|
| LHC_0 | 98 | 82 |
| LHC_50 | 96 | 41 |
| AAC | 99 | 171–195 |
| HCB | 96 [1]–98 [2] | 132 |
| EPS | 99 | 154 |

[1] based on [33]. [2] based on [42].

Comparison between the EE values calculated with data from the different databases reveals a major difference for the HCB building, ~23 [GJ/building], based on [33], and ~45 [GJ/building], based on [42], the latter being approximately double the former (Figure 2a). Another significant difference of 40% is shown for the EPS building, ~140 [GJ/building]

based on [33], and ~100 [GJ/building] based on [42], whereas, for the AAC, the difference is smaller ~64 [GJ/building], based on [33], and ~57 [GJ/building], based on [42]. These differences should not come as a surprise, considering the specificities, local essence and nature of the EE assessment, which are dependent on very specific national and even local constraints and considerations, among them energy sources, resources availability, processes efficiency, and transportation distances [6].

Comparison of the EC values displays an even more favorable trend for the LHC buildings, with negative values for all buildings made with LHC mixtures as opposed to the positive EC values of the AAC, EPS and HCB buildings (Figure 2b). The EC values are significantly lower (negative) as the percentage of lime replacement is higher, i.e., LHC_100 possesses the lowest EC, as expected. Comparing the EC of the LHC buildings to those made with conventional materials shows the significant advantage of using LHC. Compared to HCB and AAC, the standard LHC (LHC_0) saves 3607 and 8195 $kgCO_2$, respectively, for a building (Figure 2b); while replacing all the lime with unfired binder, i.e., LHC_100 mixture, saves more $CO_2$ emissions, up to 14,146 $kgCO_2$ for a building as compared to AAC_2 (Figure 2b), i.e., savings of 195% (Table 3). These significant savings of above 100% are due to the negative EC values of the LHC mixtures compared to the positive EC values of the conventional materials.

### *3.2. Use-Phase: OE and OC Values*

The OE values of the building, based on our previous work [37], are presented in Table 4. These were converted from [kWh/year] to [GJ/year] by a factor of 0.0036. Then, the values were multiplied by 50 to represent a cumulative figure for the building's estimated 50 year life span. Finally, the OE was converted to OC using a conversion factor of 220 [$kgCO_2$/GJ], representing the Israel Electric Company's current fuel mix [30]. Note that all LHC mixtures (with or without alternative unfired binders as lime replacements) present similar thermal performance, therefore, they all possess similar OE and OC values [36]. The results show the significant advantage of using LHC instead of conventional materials, in terms of OE and OC savings, as the building made of LHC saves ~40% of the OE and OC as compared to the buildings made of AAC and EPS, and ~90% as compared to the building made of HCB, since the thermal conductivity of LHC is significantly lower than HCB (0.06–0.07 (based on laboratory measurements [35]) and 0.32, respectively). These savings of energy and $CO_2$ emissions are related to the use phase only. Adding the pre-use phase savings yields even greater savings in favor of LHC as compared to conventional building materials, as will be shown below (Section 3.3).

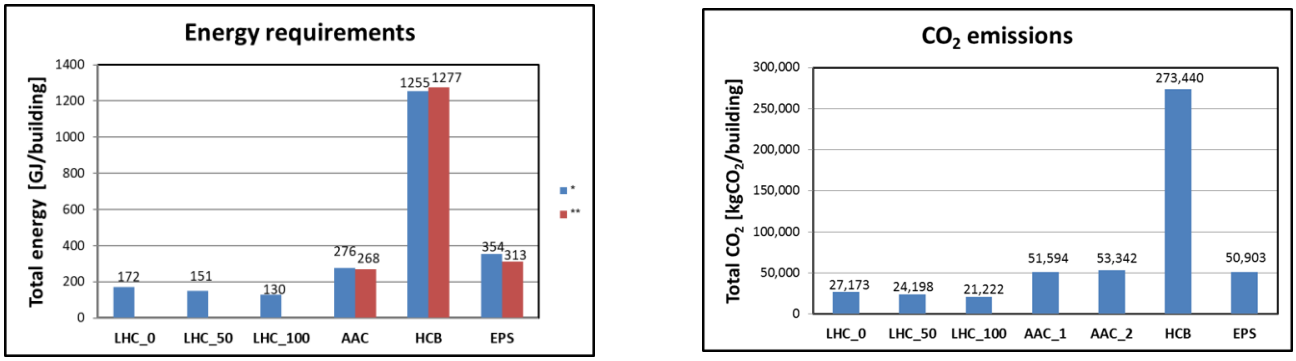
**Table 4.** Calculations of the building's OE and OC, based on [37].

| | **Operational Energy (OE)** | | | **Operational Carbon (OC)** |
|---|---|---|---|---|
| | [kWh/Year] | [GJ/Year] | [GJ/50 Years] | [$kgCO_2$/50 Years] |
| LHC | 719 | 2.59 | 129 | 28,468 |
| AAC | 1173 | 4.22 | 211 | 46,442 |
| HCB | 6847 | 24.65 | 1232 | 271,128 |
| EPS | 1185 | 4.27 | 213 | 46,948 |

### *3.3. Total Energy Requirements and $CO_2$ Emissions*

The assessment of the LHC buildings took into consideration both the pre-use and the use phases, i.e., summing the total energy requirements: EE + OE, and the total $CO_2$ emissions: EC + OC of a building, compared to HCB, AAC, and EPS buildings, throughout their entire life cycle of 50 years. Figure 3 presents those results. It should be noted that the EE has a smaller contribution to the total energy requirements values, as compared to the OE values, which are relatively higher. This trend is also similar for the $CO_2$ emissions values, as the EC values are much smaller than the OC. Therefore, the OE is definitely the major contributor to the energy consumption of the building, especially in the case of HCB, which shows a very high OE value. As a result, the differences between the EE values

that were based on [33], and the ones based on [42] (Figure 2a), which was discussed in Section 3.1, become much less significant as the OE values are much more significant than the EE values. It is obvious from Figure 3 that both the energy requirements and the $CO_2$ emissions values are the best for the LHC buildings, i.e., buildings produced from LHC have a much smaller environmental impact.




(**a**) (**b**)

**Figure 3.** The buildings' total energy consumption and $CO_2$ emissions throughout its life cycle, for all LHC mixtures, as compared to conventional materials. (**a**) Energy requirements; (**b**) $CO_2$ emissions. * is based on [33], and ** is based [42].

The above discussed trend is highly notable when the energy and carbon savings (in percentage) are investigated. The calculated saving values presented in Table 5 are relative to a building made with LHC_100, throughout the buildings' life cycle. It can be clearly seen that a building produced from LHC_100 (no lime) can save as much as 90% of the energy requirements compared to a building made of HCB, but, when also compared to AAC and EPS buildings, a building made by LHC_100 offers high savings in energy requirements, of above 50% (Table 3). Furthermore, when the entire lime of the LHC is replaced by unfired binders (LHC_100) it saves 24% of the energy required for material production and building operation as compared to standard LHC (LHC_0, with lime). Half of that saving is obtained when the building is built with LHC_50 mixture (50:50 lime: unfired binder), as expected. In terms of $CO_2$ emissions, a building made of LHC_100 saves 92% of the $CO_2$ emissions values as compared to the HCB building, and ~60% savings when compared to the AAC and EPS buildings, showing the advantage of LHC in significantly reducing building carbon footprint.

**Table 5.** The energy and $CO_2$ savings which can be obtained throughout the buildings' life cycle if the building is made of LHC_100 instead of other materials (e.g., LHC_0/LHC_100). * is based on [33], and ** is based [42].

| | **Energy Savings [%]** | | **$CO_2$ Savings [%]** |
|---|---|---|---|
| LHC_0 | 24 | | 22 |
| LHC_50 | 14 | | 12 |
| AAC | 53 * | 51 ** | 59–60 |
| HCB | 90 * | 90 ** | 92 |
| EPS | 63 * | 58 ** | 58 |

## 4. Conclusions

This study calculated the total life cycle's energy requirements and $CO_2$ emissions of a building's envelope made of LHC with alternative unfired binders as replacement for lime, in comparison to standard LHC and several other conventional building materials: AAC, HCB, and EPS. The assessment includes the pre-use and the use phases of the building.

Our findings clearly show the environmental benefits of using LHC with alternative unfired binders:

- Replacing the lime in LHC with unfired binders significantly reduces the environmental impact compared to standard LHC mainly of the pre-use phase, i.e., reduction in the EE and EC values, as the OE and OC of all LHC mixtures are similar (due to similar thermal performance).
- Using LHC with unfired binders is beneficial both in the pre-use (lower EE and EC values) and the use phases (lower OE and OC values) as compared to conventional building materials. Therefore, it can lead to significant savings in energy consumption, and in $CO_2$ emissions.

It can be concluded that the findings of this research clearly demonstrate the high potential of replacing the lime in LHC with alternative unfired binders, as the LHC mixtures with the unfired binders possess the lowest EE and EC values of all the examined materials. Moreover, since LHC with unfired binders proved to have the lowest levels of OE and OC among the examined materials, the overall energy requirements and $CO_2$ emissions along the life cycle of the building are significantly low.

A more thorough LCA should include a comprehensive assessment of all environmental impacts (resources depletion, water consumption, global warming potential, etc.). Since this research dealt with a significant portion of waste materials, the assumption is that such a comprehensive LCA would probably enhance the environmental advantages of the proposed admixture and this research findings.

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