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Embodied Energy and CO_2 Emissions of Widely Used Building Materials: The Ethiopian Context

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Abstract: Buildings use a wide range of construction materials, and the manufacturing of each material consumes energy and emits CO_2. Several studies have already been conducted to evaluate the embodied energy and the related CO_2 emissions of building materials, which are mainly based on case studies from developed countries. There is a considerable gap in cases of developing countries regarding assessment of embodied energy and CO_2 emissions of these building materials. This study identified the top five most used construction materials (cement, sand, coarse aggregates, hollow concrete blocks, and reinforcement bars), which are also prime sources of waste generation during construction in the Ethiopian building construction sector. Then, what followed was the evaluation of the embodied energies and CO_2 emissions of these materials by examining five commercial and public buildings within the cradle-to-site lifecycle boundary. The evaluation results demonstrated that cement, hollow concrete blocks (HCB), and reinforcement bars (rebars) are the major consumers of energy and major CO_2 emitters. Cumulatively, they were responsible for 94% of the embodied energy and 98% of the CO_2 emissions. The waste part of the construction materials has inflated the embodied energy and the subsequent CO_2 emissions considerably. The study also recommended several strategies for the reduction of embodied energy and the related CO_2 emissions. The research delivers critical insights into embodied energy and CO_2 emissions of the five most used building materials in the Ethiopian construction industry, as there are no prior studies on this theme. This might be a cause to arouse awareness and interest among the policy makers and the wider public to clearly understand the importance of research on this crucial issue to develop national energy and CO_2 descriptors for construction materials, in order to take care of our naturally endowed, but yet fragile, human habitat.

Keywords: embodied energy; embodied CO_2; building materials; construction waste; Ethiopia

1. Introduction

The construction industry uses more raw materials by weight than any other industrial sector. About 50% of all materials extracted from the Earth's crust are processed into construction materials [1]. In building construction, a wide range of materials are used, and the production of each material consumes energy and emits CO_2. The United Nations Environment Programme (UNEP) reported that buildings and construction are responsible for more than 36% of the global energy consumed, and as much as 40% of energy-related CO_2 emissions [2]. According to the UNEP, the amount of total buildings-related CO_2 emissions (including energy-related emissions from buildings construction) in 2017 alone was more than 11 $GtCO_2$ [2]. Buildings and the construction sector have the largest shares of global energy and emissions compared to other sectors, such as industry and transport. The global energy demand from this sector will rise, mainly due to: (i) Improved access to energy in emerging countries, (ii) substantial usage of energy-consuming devices, and (iii) exponential growth of the building sector.

Energy and CO_2 emissions can be regarded as being 'embodied' within the building materials. Over the past few decades, embodied energy and CO_2 emissions of building materials have been studied in different parts of the globe [3–7]. This has given a holistic comprehension of the energy consumption and CO_2 emissions as part of buildings construction, eventually providing a better understanding regarding the sustainability of buildings over their service life. Analyzing the profiles of embodied energy and CO_2 emissions of building materials is necessary to make appropriate decisions that reduce the overall energy use and environmental impact of buildings.

The exponential growth of the building sector due to rapid urban population increase, especially in developing countries, is likely to cause the embodied energy and CO_2 emissions to rise further in the future. According to the UNEP, the world is expected to construct 230 billion square meters of new buildings in the next 40 years, adding the equivalent of Paris every single week. More than 50% of the buildings expected by 2060 will be constructed in the coming 20 years and two-thirds of them will be built in countries that lack mandatory building energy codes [8].

Ethiopia is one of the developing countries in Sub-Saharan Africa where building energy codes are unavailable. Recently, the country has been undergoing a rapid economic growth which has been attributed mainly to the building construction boom. The building construction is expected to continue to flourish, since the rapid urbanization and capital development is the foremost target for the Ethiopian government to achieve the status of a middle-income country by 2025 [9]. Major cities in Ethiopia and other developing countries, where most of the urbanization will take place in the near future, will consume high amounts of energy and discharge energy-related greenhouse gas (GHG) emissions. This situation is further exacerbated by poor management of building materials and generated wastes in building construction sites. According to [10], wastage of materials in the Ethiopian construction industry is more than 21%. This is a huge amount as compared with the results obtained from building construction sites in developed countries. For instance, wastage of construction materials in the Netherlands is accounted to be 1% to 10% [11]. The generation of more than double the amount of construction materials waste can considerably increase the total embodied energy and CO_2 emissions of Ethiopian building project sites. Studies of embodied energy and CO_2 emissions of building materials have been conducted in some of the Sub-Saharan African countries [12–16]. However, there is nothing so far in the Ethiopian context. Therefore, urgent studies of the embodied energy and the associated CO_2 emissions of the building materials that are used in the Ethiopian building construction sector are exceedingly needed, which will eventually contribute towards the establishment of building energy codes.

The specific objectives of this work are of twofold: (i) To identify the most extensively used construction materials which generate the majority of wastes through critical evaluation of the current situation of materials use on project sites, and (ii) to evaluate the embodied energy and the related CO_2 emissions of the most commonly used materials in the Ethiopian building construction industry.

The structure of the paper is as follows. In Section 2, an overview of energy consumption in buildings is presented. Literature reviews on embodied energy and CO_2 emissions of building materials are also elaborated in this same section. The significance of the research work is presented in Section 3. In Section 4, the applied methodology to assess the construction waste part of the materials, as well as computation of the embodied energy and CO_2 emissions, is discussed in detail. In addition, an overview of the case buildings is elaborated in here as well. In Section 5, the results and discussions of the findings are presented in a solid manner. Finally, Section 6 presents the concluding remarks.

2. Energy Consumption in the Building Sector

High energy consumption and its associated environmental issues are critical matters of concern all over the world, and buildings are one of the main reasons for these problems. A building's lifecycle energy comprises its embodied and operational energy [17–23]. Embodied energy represents the total energy consumed during the lifecycle stages of buildings. The embodied energy of buildings can be categorized into three components [20,22,23]: (i) Initial embodied energy (IEE): Energy consumed in the production process of a product, from the extraction of raw materials and processing of natural resources to the manufacturing and transport of products to building construction sites. It also includes the energy that is directly associated with the construction activities. IEE is thus all the energy that is consumed in the pre-use phase of the building's lifecycle. (ii) Recurrent embodied energy (REE): Energy required to maintain, repair, and/or refurbish the buildings during their service life. REE is a function of how a building is used by its occupants, the maintenance demands of the occupants, the service life of the building, and the life span and quality of the materials and components. (iii) Demolition embodied energy (DEE): Energy consumed to destroy the building at the end of its lifecycle, recycle and re-use some components, and dispose of others by transporting the debris and waste to landfills or incinerators. DEE is a largely uncertain component of the embodied energy content due to data unavailability issues, and therefore it is difficult to capture. It has the lowest share in the lifecycle energy use of a building [6,23]. The embodied energy can be consumed directly in construction of buildings and other related processes, or indirectly for extracting raw materials, manufacturing the building materials and related products, and transporting. Computation of indirect energy consumption is relatively more complex than that of direct energy use due to lack of relevant input data [20]. On the other hand, operational energy in buildings is the energy consumed mainly for space heating and cooling, lighting, and operating appliances and auxiliary systems. Buildings located in regions experiencing extreme climatic conditions require more operational energy to meet the heating and cooling energy demands [18]. Figure 1 illustrates the energy consumption phases of buildings during their lifecycle. It also shows the different stages of a building's lifecycle, and system boundaries that define the input parameters that are included in embodied energy/CO_2 emission computations. For instance, the impacts of a system boundary, "cradle to gate", are accounted from processes only up to the point in time where the building materials are ready to leave the gate of the manufacturing facilities. It includes extraction of raw materials, transportation, and manufacturing processes [22].

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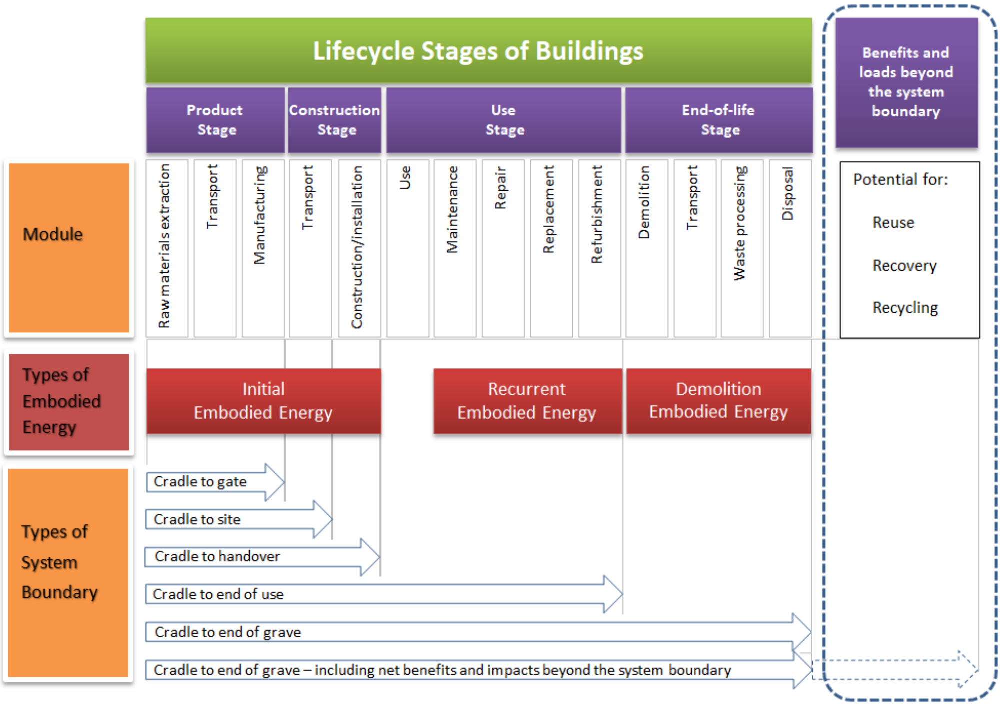

Figure 1. Energy consumption phases of buildings during their lifecycle period, with system boundaries. Adopted from [24].

To efficiently optimize the total energy footprint of the building sector, diminishing both embodied and operational energy is crucial. Standardized methods and tools are presently available to reliably evaluate operational energy. Nonetheless, little attention has been given to minimizing embodied energy use and the associated CO_2 emissions. Computing embodied energy is still complicated and resource intensive. It needs large-scale quality data, which are often unavailable [19].

In the past, the operational phase has been reported as being the major consumer of a building's total energy usage, since this phase is longer compared to others during the lifecycle. As a result, advanced energy-efficient space conditioning appliances and auxiliary systems are being installed in buildings that progressively decrease their operating energy in most developed countries. However, those improvements are offset by the usage of non-efficient operating energy systems in developing countries. In these nations, energy-efficient buildings are almost non-existent due to several factors, such as lack of information and awareness, lack of expertise, high transaction costs, and absence of regulation [25]. Operational energy demands of emerging countries will increase further, since access to energy is improving and the building sector is exponentially growing due to rapid urban population growth.

Recent studies have demonstrated that the proportion of embodied energy and CO_2 emissions is increasing compared with operational energy [26–29]. For instance, Sturgis and Roberts [26] estimated that the fraction of embodied CO_2 emissions in the United Kingdom will increase from 30% to 95%. Pacheco-Torgal [27] stated that embodied energy constituted 10–15% of operational energy. Cabeza et al. [28] reported that embodied energy represents 10–20% of a building's lifecycle energy. More recently, Shadram et al. [29] reported that the portion of embodied energy could be up to 60% of the total lifecycle energy consumption of buildings. As can be seen in the findings of the above works, the fraction of embodied energy to the total lifecycle energy varies. This is because embodied energy profiles are influenced by geographical location through unique manufacturing practices, prime energy sources, transportation modes, and distances from the construction site to manufacturers, suppliers, landfills, etc. [23]. Even within the same geographical location, embodied energy can vary at the building level, since it is a function of building materials, systems, and technologies that are employed in the construction of the building. For instance, Huberman and Pearlnutter [30] reported that, with the use of different types of wall systems, the embodied energy of a building ranges from 3.28 to 4.91 GJ/m^2 in total. The study was carried out in a building situated in the Negev desert region of southern Israel. Koezjakov et al. [31] claimed that the embodied energy of Dutch dwelling archetypes varies from 3.0 to 6.4GJ/m^2 in total. The same is true for CO_2 emissions. A comprehensive review of articles revealed that embodied CO_2 emissions can account for between 2% and 80% of the lifecycle CO_2 emissions, depending on the type of materials and employed technologies [32].

In Ethiopia, the fraction of the embodied energy to the total lifecycle energy of buildings is currently higher than the portion of operational energy to the total lifecycle energy. This is due to the fact that the majority of the Ethiopian urban buildings are operating in a tropical climate where energy for space heating and/or cooling as well as for operating appliances and auxiliary systems is needless. Hence, in the context of Ethiopia, investigating the embodied energy of a building is more important than the operational energy.

Embodied energy and CO_2 emissions connected with off-site manufacturing of building materials and components (i.e., "cradle to gate"), and conveying the materials and components to the project site (i.e., "gate to site") accounts for a substantial portion of the total building energy and CO_2 emissions [29]. For example, Ding [33] reported that the off-site manufacturing of building materials and components is responsible for over 75% of the total embodied energy. Another study on a low-energy building demonstrated that off-site production of building materials and components, and transportation of them to the construction site are responsible for 87% of the total embodied energy and GHG emissions [29]. This work has also computed the embodied energy and CO_2 emissions within the "cradle to site" lifecycle boundary, as this covers the majority of the total embodied energy and CO_2 emissions of the building construction projects. The scope of the "cradle to site" lifecycle boundary considered in this study covers the waste of construction materials caused by improper storage, inefficient handling, and inappropriate use as well.

3. Research Significance

The choice of energy-efficient building materials can have a positive impact on environmental conservation. Computing the embodied energy of building materials is thus one of the initial steps towards environmental safeguarding. Numerous studies have been conducted to evaluate the embodied energy and related CO_2 emissions of buildings, which are mainly based on case studies from developed countries. There are also lifecycle assessment (LCA) tools that are used by building design stakeholders to improve operating performance and to minimize the embodied energy and impacts of buildings on the environment. However, there is a considerable gap in cases of developing countries regarding assessment of embodied energy and CO_2 emissions of building materials. In general, the gap is mainly due to a lack of research programs focusing on energy efficiency in the construction sectors of those countries. The number of studies performed on embodied energy and CO_2 emissions of building materials in developing nations is extremely limited, and reliable data are almost non-existent, and are to be borrowed from elsewhere, which in actual fact does very little to serve the purpose, if at all.

The production process of any construction material and transporting it to site consumes energy and emits CO_2. As wastage of construction materials in the Ethiopian construction industry is generally significant, it is worth computing the embodied energy and CO_2 emissions associated with the generated waste materials. Hence, in this work, embodied energy and the related CO_2 emissions of the most commonly used building materials in the Ethiopian construction industry are evaluated based on case buildings. As there are no prior in-depth studies on the most commonly used construction materials which generate the majority of construction wastes, extensive surveys have been conducted, and the top five materials were determined. Based on the assessment, this work recommends appropriate strategies for reducing embodied energy and CO_2 emissions of buildings in the context of the Ethiopian construction industry. Since there were no similar studies found while reviewing the literature, the findings of this research will provide critical insights into embodied energy and CO_2 emissions of building materials in the context of Ethiopia. The scope of this work is limited to the estimation of embodied energy and CO_2 emissions of the most widely used building materials and the subsequent generated waste in the Ethiopian construction industry within the "cradle to site" lifecycle boundary.

4. Methodology

In this section, the followed methodology for assessing the consumed and wasted construction materials as well as their embodied energy and CO_2 emissions are discussed. To quantify the consumed and the wasted construction materials, the following tasks were carried out: (i) A questionnaire-based survey and personal interviews, (ii) site visits and observations, and (iii) desk studies of construction documents, such as building drawings, bills of quantities, and technical specifications. The survey was focused on six distinct groups, who were approached with close-ended questions and face-to-face interviews regarding construction materials and wastage. The groups were identified as focal persons to get the right information on construction materials as related to: Design documents, procurement, materials handling and storage, operation, and site management and practices, including other site conditions and external factors. Indeed, some materials could not be quantified directly from the design documents, e.g., the amount of cement, sand, and aggregate. Beside the design documents, the national standard was applied to compute the quantities of these materials needed to produce the desired quality and amount of concrete. The site visits and observations of situations were also carried out to gather first-hand information and to capture a vivid glance of the bigger picture.

It is well known that there are three widely applied methodologies to compute the embodied energy and CO_2 emissions, which are: The process-based method, the input–output (I–O) analysis-based method, and the hybrid method [6,20]. The process-based method uses process flow to consider different activities associated with a product, and it is the most applied methodology to evaluate the impact of embodied energy and CO_2 emissions at a local level. This research work attempted to assess embodied energy and CO_2 emissions of specific building materials and the generated construction waste using the process-based method.

4.1. Data Acquistion

Though getting quantities of materials delivered to projects and distributed on site is manageable from records, assessing the scale of waste demanded a focused survey based on questionnaires. A common goal of any survey-based research is to obtain representative data of a population, and then generalize the findings obtained from the samples back to the population within the desired margin of error. The representative sample size was estimated using the formula given by Equation (1):

$$n_o = \frac{z^2 p(1-p)}{e^2}, \quad (1)$$

where n_o is the uncorrected sample size, z^2 is the confidence level, p is the population proportion, and e^2 is the level of precision.

Based on Equation (1), a sample size of 245 was required to achieve a 95% confidence interval of width ±5% and 20% population proportion. The estimated sample size value was bigger than the target population (N) to be considered in this study, which was 78 active four storey and above commercial and public projects. Normally, Equation (1) assumes that the population is very large compared to the sampled population proportion. Since n_o > 5% of N, the estimated sample size was then corrected using a finite-population correction (FPC). This method reduces the sample unit size without affecting the confidence level considered during the estimation of the uncorrected sample size. The FPC-corrected sample size can be computed using the formula given by Equation (2):

$$n = \frac{n_o N}{n_o + (N-1)}, \quad (2)$$

where n is the FPC-corrected sample size, n_o is the uncorrected sample size, and N is the target population.

Equation (2) reduced the sample size. The estimated FPC-corrected sample size was 59, by substituting the uncorrected sample size (n_o = 245) and target population (N = 78) into the equation.

Questionnaires were prepared for focal respondents representing contractors, real estate developers, consultants, and owners of the selected projects. The questions raised in the questionnaires were constructed using a Likert scale of 1–5, specific to the factors that cause construction waste on construction sites. Likewise, for each waste minimization measure, the respondents were asked to score the level of contribution to waste minimization on the scale of 1–5. In addition, respondents were required to score each measure according to the level of practice in their organization on a scale of 1–5. Finally, concerning the effects of construction wastage, the respondents were asked to score the levels on a scale of 1–5. The selected target respondents were: 42 contractors, two real estate developers, eight consultants, and seven owners, which amounted to 59 respondents in total. In Ethiopia, the role of contractors and real estate developers in terms of construction work are somewhat one and the same. Consultants are often based on sites and supervise day-to-day activities of the construction works. The property owners considered in this study as focal respondents are also construction experts who are actively participating in their construction projects. This means that all the focal respondents of the involved parties did know and understand all the construction activities well.

Once the questionnaire responses were obtained, their completeness, consistency, and readability were checked. Out of the total, only 49 of the responses were accepted as valid data sources. The overall validity index for these responses was 0.89. Strong levels of reliability were confirmed, with an overall Cronbach's alpha index of 0.93. That being assured, the data were analyzed using Statistical Package for Social Sciences (SPSS) software. Progressing further, the sequential weighted average model was applied to scrutinize the relative levels of significant contribution of the waste causes and waste minimization measures:

$$ASS_i = \frac{\sum_{i=1}^{n} X_j N_{ij}}{N}, \quad (3)$$

where ASS_i is the average significant score of the waste minimization measure i,X_j is the assigned waste minimization score (on a Likert scale of 1–5), N_{ij} is the number of respondents who assigned the score X_j for the measure i, and N is the total number of respondents.

4.2. Overview of Case Buildings

To evaluate the actual quantity of construction materials consumed and the subsequent waste generated, five building projects that had almost similar characteristics were selected amongst the target population. The main characteristics considered included structural systems, wall systems, types of construction materials, construction methods, and number of storeys. They are multi-storey commercial and public buildings located in Bahir Dar, the Capital of the Amhara Region in northern Ethiopia. The buildings were selected as an input for the case study, since they represent the overall characteristics of commercial and public buildings in Ethiopia with regard to structure and main building materials. Being of the typical building construction system in Ethiopia, the case buildings have two main elements. The first element is known as the structural system, which comprises a column–beam–slab frame and pad foundation of reinforced concrete. The construction of this frame system involves four stages: (i) Erection of formwork and scaffolding, (ii) installation of reinforcement bars (rebars), (iii) placement of concrete, and (iv) dismantling of formwork and scaffolding. The formwork is built on site out of timber or steel, while scaffolding is typically made of matured solid eucalyptus post and wattle. The second element is referred to as a wall system, which consists of non-load bearing hollow-concrete blocks (HCBs) to fill the structural façade and all the internal partitions. The main characteristics of the case buildings are presented in Table 1.

Table 1. The main characteristics of the case buildings.

Case Buildings	Level	Number of Storeys	Gross Floor Area (m^2)
Building I	B+G+6	Eight	15,924.00
Building II	G+4	Five	8,758.47
Building III	G+4	Five	5,820.00
Building IV	B+G+6	Eight	14,927.60
Building V	B+G+6	Eight	10,416.00

Level: B—one level below ground floor, G—ground level, 4 and 6—number of storeys above ground level.

4.3. Computation of Embodied Energy and CO_2 Emissions

To evaluate embodied energy and CO_2 emissions of building materials within the "cradle to site" lifecycle boundary, all those associated with direct and indirect processes were taken into consideration. This included energy consumed during material extraction, manufacturing, and transportation to the building construction sites. Vehicles were the mode of transport for conveying all construction materials. The embodied energy of the waste materials was computed separately. The related CO_2 emissions for both the consumed materials and the generated waste materials were also estimated. Relevant research literature was referred to in order to identify suitable embodied energy and carbon coefficient values of building materials. The computation procedure of embodied energy and CO_2 emissions is elaborated in Sections 4.3.1 and 4.3.2.

4.3.1. Embodied Energy

The embodied energy (EE) of the building materials within the "cradle to site" lifecycle boundary was calculated by adding up the material embodied energy (EE_M) and the material transportation energy (EE_T), as given by Equation (4) [21]. EE_M includes energy consumed due to extraction of raw materials, transportation, and manufacturing processes.

$$EE = EE_M + EE_T \tag{4}$$

Material embodied energy was computed by summing up the embodied energies of materials used in the case buildings, as described by Equation (5).

$$EE_M = \sum_{i}^{n} EE_{m_i} \tag{5}$$

Material embodied energy for each individual material (EE_m) was calculated by multiplying the quantity of the material by weight (Q_i) with the embodied energy coefficient (EEC_m), as presented by Equation (6).

$$EE_m = \sum_{i}^{n} Q_i EEC_m \tag{6}$$

Material transportation energy (EE_T) was calculated by adding up the material transportation energies of all the materials used in the project, as described in Equation (7).

$$EE_T = \sum_{i}^{n} EE_{t_i} \tag{7}$$

Material embodied energy for each material (EE_t) was evaluated by linking the hauling distance of the material (D_m), round trips (RT_m), the fuel energy coefficient (EC_f), and lower heating values of fuel (LHV_f). Equation (8) illustrates the computation (EE_t). The fuel type for the vehicles involved in transporting the materials was found to be predominantly diesel. The vehicles' efficiencies were obtained from the manufacturers' databases of the involved vehicles. The transportation energy of each construction material considered in the study differed, since the distance from producers/sources of raw materials to the construction sites varied accordingly.

$$EE_t = D_m RT_m EC_f LHV_f \tag{8}$$

4.3.2. Embodied CO_2 Emissions

The embodied CO_2 emissions of the materials within the "cradle to site" lifecycle boundary were computed by using Equation (9) [7].

$$ECO_2 = \sum_{1}^{i} ECO_{2i} \tag{9}$$

where ECO_{2i} and ECO_2 are the amounts of embodied CO_2 emissions of the i^{th} type of building material and the total (the sum of all the building materials), respectively.

Embodied CO_2 emissions for each individual material (ECO_{2i}) were calculated by multiplying the quantity of the i^{th} type of building material by weight (Q_i) to the CO_2 emission coefficient of the i^{th} type of building material (CO_2EC_m). Equation (10) describes the computation of (ECO_{2i}):

$$ECO_{2i} = \sum_{1}^{i} Q_i CO_2 EC_m \tag{10}$$

To estimate the embodied energy and CO_2 emissions of the building materials, embodied energy and emission coefficients are required. Due to the lack of a unifying document pertinent to Ethiopia, the Senegalese embodied energy and CO_2 emission coefficients were selected for the computation after taking into account various factors. The main factors are geographical location, developmental level, data refinement quality level, and dependence on imported and local construction materials. Table 2 presents the values of the embodied energy and CO_2 emission coefficients of the materials that were adopted for the study.

Table 2. Coefficients of embodied energy and CO_2 emissions of the building materials adopted for the study [16].

Materials	Coefficients	
	Embodied Energy (MJ/Kg)	CO_2 Emissions (Kg/Kg)
Cement	3.32	0.730
Sand	0.06	0.004
Coarse aggregate	0.16	0.010
HCB	7.96	1.550
Rebar	15.97	1.060

5. Results

The step-by-step build-up of the framework to examine the execution, materials management, and generation of waste on construction projects through literary study, surveyed data, and detailed material compilations of five typical buildings has produced a tangible result which led to the determination of construction materials' embodied energy and CO_2 emissions quantification. While analyzing the acquired data, it was learnt that the five most widely used construction materials are cement (in the cases of the selected typical buildings, only locally produced ordinary Portland cement is used. The local cement plants do not yet use industrial waste as partial replacement of clinkers in the production of cement), sand, coarse aggregates, HCBs, and rebars. These materials were also identified as prime sources of waste generation during the construction of the buildings. Quantities of the building materials were evaluated from plans, quantity survey data, and data obtained from material suppliers. Meanwhile, quantities of materials wasted during construction were obtained from surveys collected from respondents encompassing contractors, real estate developers, consultants, and owners, as presented in Section 4.1. The total quantified building materials of the case buildings are summarized in Table 3.

Table 3. The cumulative quantity of the top five consumed and wasted materials of the case buildings.

Materials	Quantity of Materials (Tonne)	
	Consumed	Wasted
Cement	4184.54	518.46
Sand	8781.47	1585.16
Coarse aggregate	12171.77	1561.62
HCB	1460.45	189.04
Rebar	1023.41	131.65

The percentile quantity of the wasted five materials of the case buildings and the waste limit set by the national Building and Transport Construction Design Authority (BaTCoDA) standard [34] are presented graphically in Figure 2. It can be noticed that, except for sand, about 13% of each of the materials are accounted as wastage. The wastage of sand accounted for 18%. It is also apparently seen from Figure 2 that all the materials, excluding coarse aggregates, do not comply with the limits set by the national standard. Among all of them, cement, HCBs, and rebars exceeded the national limit considerably. For instance, the wasted quantity of HCBs accounted for about 13%, but the limit set by the national standard for this material is only 5%. This means that the wastage of HCBs exceeded the limit by around 160%. The amount of wasted cement and rebars also exceeded the national limit by 148% and 157%, respectively. The amount of wasted sand exceeded the set national limit by about 20%.

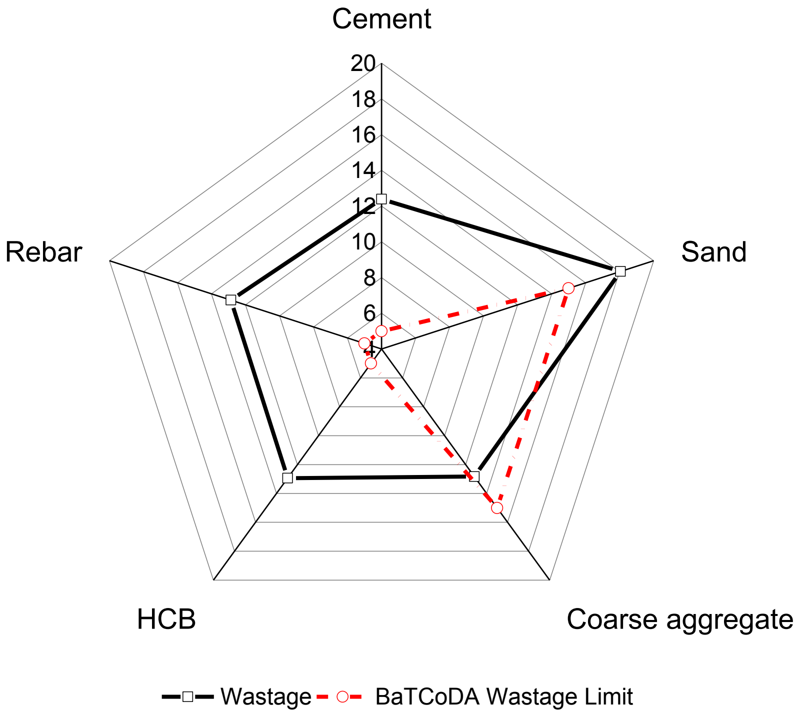

Figure 2. The percentile portions of waste of the five materials along with waste limits set by the national BaTCoDA standard [34].

The amounts of the embodied energy and CO_2 emissions of the individual materials within the "cradle to site" lifecycle boundary are given in Table 4. The consumed embodied energy and CO_2 emissions of the five used building materials of the case buildings are 44,336.08 GJ (0.79 GJ/m^2) and 6560.07 t (117.47 kg/m^2), respectively. This energy value is high, as only a few materials and short lifecycle boundary conditions are considered in this study. Rebars, cement, and HCBs are the major energy-consuming materials, representing 37%, 31%, and 26% of the total embodied energy, respectively. These three materials contributed about 94% of the total consumed embodied energy. In the case of emitted CO_2, cement takes the lead with a relative contribution of 46%, followed by HCBs with a relative contribution of 35%, relegating rebars to the third position, covering 17%. Cumulatively, 98% of the emitted CO_2 is contributed by these three materials. The remaining two percent is contributed by coarse aggregates and sand. Figure 3 graphically represents the percentile portions of the individual building materials to the total weight, embodied energy, and CO_2 emissions. It apparently shows the high contributions of rebars, cement, and HCBs in both embodied energy and the related CO_2 emissions, even if these three materials accounted for the least fraction by weight of the total construction materials used.

Table 4. Quantities of the embodied energy and CO_2 emissions of the individual materials.

Materials	Embodied Energy (GJ)			Embodied CO_2 Emissions (Tonne)		
	Consumed	**Wasted**	**Total**	**Consumed**	**Wasted**	**Total**
Cement	13,892.67	1721.29	15,613.96	3054.71	378.48	3433.19
Sand	526.89	95.11	621.40	35.13	6.34	41.47
Coarse aggregate	1947.48	249.86	2197.34	121.72	15.62	137.34
HCB	11,625.18	1504.76	13,129.94	2263.70	293.01	2556.71
Rebar	16,343.86	2102.45	18,446.31	1084.81	139.55	1224.36

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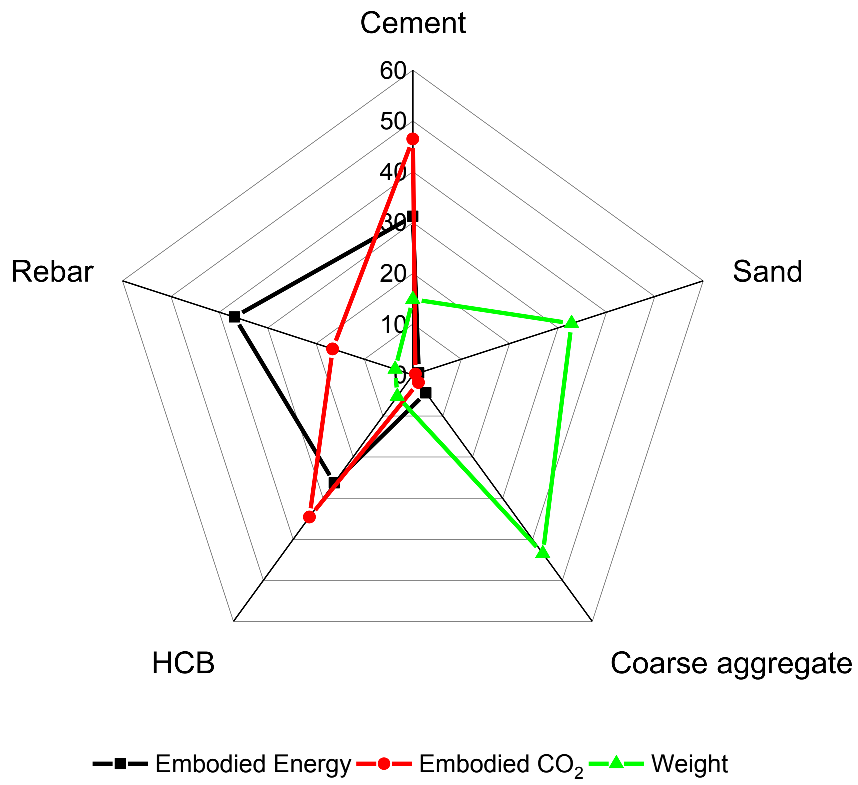

Figure 3. The percentile portions of the individual building materials to the total weight, embodied energy, and CO_2 emissions.

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The embodied energy and CO_2 emissions of the five wasted materials of the case buildings within the "cradle to site" lifecycle boundary are also given in Table 4. The total embodied energy of all the wasted construction materials is 5,673.47 GJ (0.10 GJ/m^2), whereas the associated CO_2 emission is 833 t (14.92 kg/m^2). In both cases, the waste part of the construction materials is accountable for about 11% of the total energy consumption and CO_2 emissions. The percentile contributions of each wasted material to their own total bases for both the embodied energy and CO_2 emissions are identical with the equivalent portions for the consumed materials. This is due to the fact that all the considered parameters for the computation of embodied energy and CO_2 emissions for the consumed and wasted construction materials within the "cradle to site" lifecycle boundary were the same.

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Table 4. Quantities of the embodied energy and CO_2 emissions of the individual materials.

Materials	Embodied energy (GJ)			Embodied CO_2 emissions (Tonne)		
	Consumed	**Wasted**	**Total**	**Consumed**	**Wasted**	**Total**
Cement	13,892.67	1721.29	15,613.96	3054.71	378.48	3433.19
Sand	526.89	95.11	621.40	35.13	6.34	41.47
Coarse aggregate	1947.48	249.86	2197.34	121.72	15.62	137.34
HCB	11,625.18	1504.76	13,129.94	2263.70	293.01	2556.71
Rebar	16,343.86	2102.45	18,446.31	1084.81	139.55	1224.36

6. Discussion

Though building construction itself is a huge consumer of embodied energy and a generator of CO_2 emissions, the waste given off in the process is a cause for their inflation, quantitatively. The computation in this study falls short of the whole lifecycle of the buildings. However, the findings show that the embodied energy of the consumed construction materials and the accompanying CO_2 emissions are a debt burden of the coming generation, since it will be released into the environment at the ends of the buildings' lifecycles. On the other hand, the construction waste part of the embodied energy and CO_2 emissions are the realities of today. The waste is destined to landfill or recycling. If its fate is a landfill, it can be an environmental burden to the whole eco-system as a source of pollution. The situation we are in today tells us that, since there is no recycling facilitation, the waste surely ends up at landfill. This, coupled with the excess generation of construction waste as compared to the limits set by the national BaTCoDA standard, calls for swift action to normalize the unaccounted for cumulative effect on the dearly contested habitat and the fragile environment. Moreover, according to [35], the generated waste from the five construction projects have incurred an average of 11% extra costs, which in actual fact, are losses in profits for the contractor. This is due to the fact that, like many

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other developing countries, contractors in Ethiopia are responsible for transporting all the necessary construction materials to the site as well as producing some materials such as concrete and HCBs.

The accounted for embodied energy and CO_2 emissions in here are only for the five selected building projects among the 49 projects which were successfully covered by the study survey. If this finding is to encompass all the assessed projects, the embodied energy would have been 490,049 GJ, and the CO_2 emission would have amounted to 72,452 tonnes, under the assumption that all the 49 buildings adopted similar construction techniques and have almost identical physical and material characteristics. This is a huge environmental burden and a wakeup call to resolutely act as early as possible.

The need to reduce energy consumption and CO_2 emissions requires systematic development of strategies. During the survey and interviews of the study, important issues that are considered to be catapults to sustain the effort towards the reduction of embodied energy and CO_2 emissions in the Ethiopian construction industry context were highlighted. These matters are presented in here as recommendations.

- Energy-efficient cement production: As demonstrated in this study, among the five investigated materials, cement is responsible for a significant proportion of energy consumption and CO_2 emissions. According to [36], there are several natural pozzolans in Ethiopia that can be used as partial substitutes for Portland clinkers, which can lead to energy and CO_2 reductions. Hence, the local cement industries should respond to the high demand for mitigation of energy and CO_2 emissions of cement by producing blended Portland cements with natural pozzolans.
- Adoption of alternative materials: The use of building materials with low-embodied energy and CO_2 emissions is another key strategy for mitigating the embodied energy and the associated CO_2 emissions of commercial and public buildings. For instance, HCBs can be substituted by other eco-friendly alternative building materials. Indeed, due to the scarcity and high cost of cement, HCBs have been replaced by low-cost and eco-friendly building materials (produced from raw materials of agricultural/industrial wastes and natural minerals) in government housing projects over the last decade [37]. Such kinds of low-energy and eco-friendly building materials should be adopted in commercial and public buildings. The use of precast concrete is a better alternative to insitu concrete to mitigate the embodied energy and CO_2 emissions of buildings, since it effectively uses materials and minimizes the construction waste.
- Utilizing prefabrication materials: An effective strategy for prevention or minimization of construction wastes is shifting from the conventional construction practices to prefabrication of building components. This approach can significantly lower the embodied energy and CO_2 emissions of buildings compared to the traditional insitu concrete [38,39]. Hence, utilization of prefabrication materials is one of the highly recommended strategies to mitigate the embodied energy and the associated CO_2 emissions.
- Creating a training platform on applicable building codes and standards: The introduction of a building code that imposes responsibilities on designers to standardize dimensions in the planning phase is an advised strategy in order to minimize the waste of construction materials. In addition, proper training and education should be provided to all responsible stockholders to adopt a more proactive approach in dealing with construction material use and waste generation.
- Materials database and labelling: The lack of information on the embodied energy and CO_2 emissions of different types of building materials is a big challenge for architects to design buildings with low-environmental impact. Hence, creating an embodied energy and CO_2 emissions database for locally produced building materials would be one of the potential strategies to reduce energy consumption and CO_2 emissions of buildings in Ethiopia. In the future, the country should also establish sustainability labelling systems to promote low-energy and low-CO_2 building materials in the Ethiopian construction sector.

- Use of recyclable materials: The utilization of building materials with high recycling potential can be another key strategy to minimize the energy and CO_2 emissions of buildings over an extended period of time. There are several studies demonstrating the use of recycled and reused building materials for significantly mitigating the energy consumptions and CO_2 emissions in buildings [40–42]. Even if recycling of building materials is not yet practiced in Ethiopia, this strategy will play a significant role in mitigating building energy use and CO_2 emissions, assuming that recycling facilities will be available in the future.

7. Conclusions

Investigations on the embodied energy of construction materials that are widely used in the Ethiopian building construction sector and the associated CO_2 emissions are immensely needed to optimize the total energy and carbon footprint of the sector. This study has identified five widely used construction materials which are also prime sources of construction waste in the Ethiopian building construction sector by collecting extensive survey data from contractors, real estate developers, consultants, and owners. The identified materials are: Cement, sand, coarse aggregates, HCBs, and rebars. The consumed and wasted quantities of these construction materials and their embodied energy and CO_2 emissions within the lifecycle boundary of "cradle to site" were analyzed by examining five multi-storey commercial and public buildings situated in Bahir Dar, Ethiopia. The evaluation of the results demonstrated that cement, HCBs, and rebars are the major consumers of energy and the major CO_2 emitters. Cumulatively, they were responsible for 94% of the embodied energy and 98% of the CO_2 emissions. Cement, HCBs, and rebars have also exceeded the national waste limits by 148%, 159%, and 157%, respectively. Although these three construction materials accounted for the least fraction of the overall weight, the findings of this study confirmed that they are the prime consumers of energy and biggest producers CO_2 emissions.

To reduce embodied energy and the related CO_2 emissions of buildings, several strategies were suggested in the context of Ethiopia. More importantly, the country must initiate sustained research on construction materials to evaluate the potential for further mitigation of the embodied energy and the subsequent CO_2 emissions. In this study, some factors were obtained from other literature sources due to the lack of a unifying international document pertinent to a developing country like Ethiopia, which was the primary challenge in performing this research work. Future researches should attempt to establish such data for Ethiopia, based on the type of building function. This will facilitate the stakeholders of the whole industry to conduct energy- and CO_2 emission-related assessments more precisely, leading towards sustainable construction in Ethiopia. This research delivers critical insights into embodied energy and CO_2 emissions of the five widely used building materials and their related wastes in the Ethiopian construction industry, since there were no similar studies found in the literature reviewed focusing on Ethiopia.

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