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Article

Sustainable Construction Practices: Integrating Renewable Energy for Carbon Footprint Reduction

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Abstract: The construction sector is a major contributor to resource depletion and greenhouse gas emissions, underscoring the importance of adopting sustainable practices to meet environmental and climate goals. However, current assessments often underestimate impacts because of narrow system boundaries and insufficiently localized material inventory data, creating a critical research gap in accurately evaluating building sustainability. This study therefore applies to a comprehensive Life Cycle Assessment (LCA) framework to evaluate the environmental performance of key construction materials and to investigate strategies for integrating circular design and renewable energy to reduce carbon footprints. The results reveal that medium-term environmental impacts are approximately 20–30% higher than previously reported, while the Global Warming Potential of conventional brick increases by about 23% when additional life-cycle stages are considered. Furthermore, the analysis demonstrates that design-for-disassembly and recycling-oriented approaches can significantly enhance material recovery and reduce waste. These findings imply that developing harmonized, region-specific material databases and promoting circular construction alongside renewable energy integration are essential for improving LCA accuracy and achieving meaningful reductions in the environmental footprint of buildings.

Keywords: Sustainable construction; Renewable energy integration; Carbon footprint reduction; Life cycle assessment; Energy efficiency; Eco-friendly materials.

1. Introduction

Approximately 60% of all raw materials extracted from the Earth's lithosphere are consumed by the construction sector, highlighting its substantial environmental burden. Buildings alone account for about 40% of this demand, representing roughly 24% of total global material extraction [1]. On average, an individual in Africa contributes around 2.3 tonnes of minerals annually for construction purposes equivalent to nearly 64 times their body weight underscoring the urgent need for dematerialization within the industry [2]. This study aims to raise awareness of the considerable carbon footprint associated with the construction, operation, and end-of-life phases of buildings, given that construction remains the most resource-intensive sector worldwide. The scale of this impact is further reflected in resource and energy consumption patterns. In the European Union, construction activities account for about 40% of resource use, 40% of primary energy consumption, and 40% of total waste generation each year [3]. Globally, buildings are responsible for roughly 40% of energy demand and 33% of greenhouse gas emissions, largely driven by material production, transportation, and equipment operation. In 2009 alone, the building sector emitted approximately 5.7 billion tonnes of CO_2, representing around 23% of emissions linked to global economic activity [4]. With the world's urban population projected to surpass six billion by 2045, these trends highlight the pressing need to adopt sustainable construction practices to mitigate future environmental impacts.

In several African countries, the construction of conventional buildings demands an exceptionally high volume of materials. On average, about 2.3 tonnes of materials are required for every usable square metre, drawn from more than 100 material types. Notably, this estimate accounts only for materials directly consumed on the construction site [5]. However, when the assessment is expanded using the Material Intensity per Service Unit (MIPS) framework which evaluates the broader environmental burden associated with resource extraction and processing—the material requirement increases dramatically to approximately 6 tonnes per square metre [6]. This approach captures not only the mass of construction inputs, but also the total weight of resources disturbed during production, including biotic and abiotic materials, air and water inputs, erosion, and other hidden flows. Although materials such as steel, concrete, and glass represent a relatively small share of total construction costs, their production, transport, and installation are highly energy intensive [4]. Furthermore, the extraction and processing of key primary materials particularly iron ore (63%), aluminium (24%), and copper (6%) contribute substantially to the depletion of the planet's natural exergy. This reinforces the urgent need for more sustainable construction strategies that emphasize material efficiency, energy reduction, and optimized resource use [7].

When selecting the most suitable technology for minimizing a building's environmental footprint through design or renovation, it's crucial to adopt a life cycle approach [8]. While highly specialized products may have high upfront costs that never pay off, cheaper alternatives often come with significant long-term maintenance or waste management costs [9]. However, considering the entire life cycle of materials can reveal opportunities for reduction. For instance, concrete, which has high CO_2 emissions, can be repurposed as filler in infrastructure, reducing emissions compared to quarry-sourced materials and even absorbing CO_2 through decarbonation processes [10]-[12]. To determine the most eco-efficient technology, it's essential to consider both environmental and economic consequences throughout the material's life cycle, embracing a holistic view that balances short-term costs with long-term benefits.

Despite the need for a carbon-neutral building industry, numerous challenges hinder this transition, according to research. Studies in Singapore and Hong Kong identify high upfront costs, lack of incentives, education gaps, and limited awareness as significant barriers [13],[14]. Another study focusing on commercial buildings in Beijing and Shanghai highlights the absence of regulations, financial incentives, poor oversight, and lack of knowledge about energy conservation as major obstacles [15]. While many studies have explored CO_2 reduction in the construction sector, none have comprehensively addressed carbon reduction across the entire life cycle, from design to management phases, including manufacture, transportation, construction, operation, maintenance, and end-of-life deconstruction [16]. Others review recent methods to reduce the carbon footprint of each phase, including alternative additives in building materials, design improvements, recycling construction waste, alternative water resources, enhanced water technologies, and innovative systems to increase the sustainability of the construction industry.

The construction industry is a significant contributor to greenhouse gas emissions, accounting for approximately 40% of global carbon emissions. Traditional construction practices prioritize cost and efficiency over sustainability, exacerbating the environmental impact. The industry's reliance on non-renewable energy sources and materials perpetuates a cycle of carbon-intensive construction, hindering efforts to mitigate climate change. This research aims to investigate and develop sustainable construction practices that integrate renewable energy sources to reduce the carbon footprint of buildings and infrastructure. The study focuses on identifying and addressing the barriers to adopting renewable energy in construction, exploring innovative materials and techniques, and developing a framework for implementing sustainable construction practices. Therefore, this article highlights the significant carbon footprint associated with the construction industry's entire value chain, spanning from design to operation and management phases. This encompasses production, transportation, construction, operation, maintenance, and eventual deconstruction. By selectively opting for materials, systems, operations, and management strategies that boast a lower carbon footprint, we can substantially reduce greenhouse gas emissions throughout the project's lifecycle, including conceptualization, design, construction, and management phases. This awareness-raising effort seeks to promote environmental stewardship throughout the entire construction process, encouraging more sustainable practices and mitigating climate impact.

The construction industry is a significant contributor to greenhouse gas emissions, primarily due to its reliance on non-renewable energy sources and inefficient practices, leading to a substantial carbon footprint. The aim of this research is to investigate and promote sustainable construction practices that integrate renewable energy sources for reducing carbon footprint in the construction industry while the objectives are to explore and evaluate the potential of integrating renewable energy sources in construction practices. To develop and propose a framework for implementing sustainable construction practices with integrated renewable energy sources. While there is a growing interest in sustainable construction practices, there is a lack of comprehensive research on integrating renewable energy sources into construction practices to reduce carbon footprint. This study aims to fill this knowledge gap by providing a framework for implementing sustainable construction practices with integrated renewable energy sources, addressing the challenges and benefits of adoption, and promoting a more sustainable future for the construction industry.

This paper is organized as follows. Section 2 presents the literature review of this work, review standards, poli-

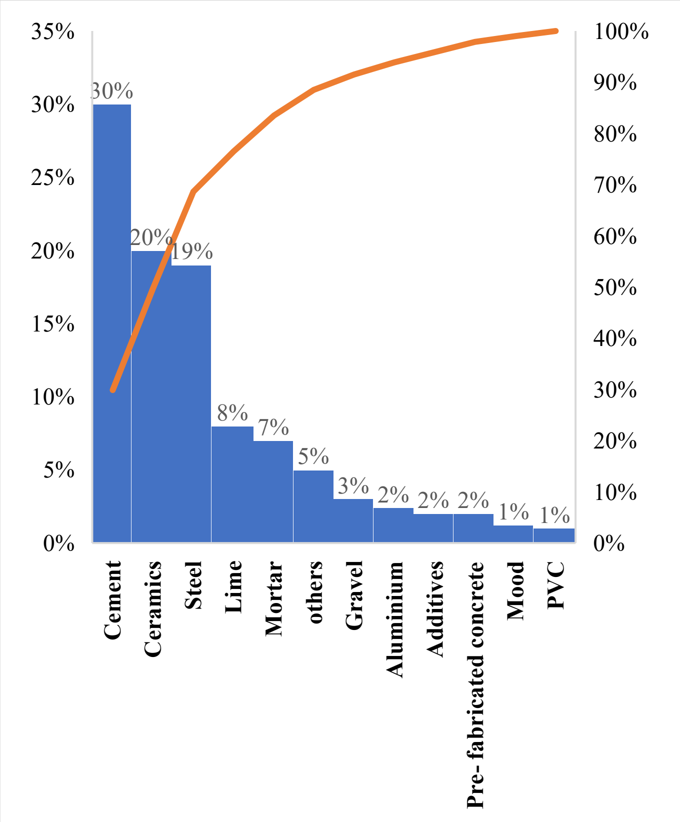

Figure 1. The amount of carbon dioxide emissions resulting from the production of building materials.

cies, technologies Identify research gaps. Section 3 presents the methodology, the schematic framework, LLC Building parameters, Renewable energy system data Emission factors & cost. Section 4 Identify optimal strategies, results and discussed. Section 5 presents the conclusion and future works.

2. Environmental Impact Assessment of Building Materials

Research has highlighted the importance of using natural and recycled construction materials [17] when possible, due to their low embodied energy. Studies conducted on a diverse range of Nigerian buildings have shown that the embodied energy in materials used and life cycle assessments account for a significant proportion of the total energy consumption over the building's lifetime. Specifically, the findings reveal that for low-energy consumption buildings, which typically feature adequate insulation and passive conditioning, the embodied energy ranges from 7% to 43% of the total energy used. In contrast, conventional buildings exhibit a slightly lower range of 3% to 40%. These results highlight the importance of considering embodied energy in building design and material selection to reduce overall energy consumption and environmental impact [18]. However, the studies varied in their consideration of building lifetime, with only one assuming a 30-year lifetime and eight others assuming longer lifetimes (65-80 years) [19]. Other research has found that in typical buildings in Northern and Central Europe, embodied energy in materials accounts for around 10-20%, while energy used during the utilization stage accounts for 80-90% and less than 1% [20]. These studies demonstrate significant regional variations in lifetime and building characteristics. A Life Cycle Assessment (LCA) for building materials can be conducted using various methods and simplifications [21].

In Nigeria, the energy required to produce a square meter of certain materials is equivalent to burning over 150 liters of gasoline [22], [23]. The environmental impact of buildings varies depending on their architectural design, with an average carbon dioxide emission of 0.6 tonnes and energy consumption of 6043 MJ per square meter, considering only material-related consequences. A case study of an apartment building designed by international standards as shown in Figure 1 reveals the significant contributions of various building materials to primary energy consumption and CO_2 emissions per square meter. However, steel, cement, and ceramics are identified as commonplace materials with a substantial impact on the environmental footprint of buildings, highlighting the need for sustainable material selection and optimization in building design.

A comprehensive review of existing literature reveals that Life Cycle Assessment (LCA) has been extensively employed to evaluate the environmental implications of various building materials and solutions. Specifically, LCA studies have consistently shown that kenaf fiber boards exhibit a significantly lower environmental impact compared to thermal insulation materials composed solely of synthetic materials. This finding underscores the potential of kenaf fiber boards as a sustainable alternative for thermal insulation, highlighting their reduced environmental footprint throughout their entire life cycle, from raw material extraction to end-of-life disposal or recycling. In a similar vein, External Thermal Insulation Composite Systems have been shown to offer advantages through LCA, considering energy, emissions, and economic factors [24]. These systems can reduce energy consumption, CO_2 equivalent emissions, and life cycle costs by up to 20% compared to conventional insulation.

Additionally, LCAs have been conducted on various wood flooring coverings, identifying areas for improvement in installation methods, surface treatment, maintenance, and the types of adhesives and varnishes used. Experimental investigations have evaluated the environmental implications of incorporating phase change materials (PCMs) in Mediterranean building applications [6]. The findings indicate that while PCMs can reduce operational energy demand, they do not lead to a substantial decrease in the overall life-cycle environmental impact of the building. Nevertheless, after approximately 25 years of service, the cumulative energy savings achieved during the use phase outweigh the energy costs associated with PCM manufacturing.

Extensive research has investigated the environmental benefits of green roofs using Life Cycle Assessment (LCA). Similarly, A comprehensive review of life cycle assessment (LCA) studies on ceramic goods has highlighted the significant energy intensity associated with their production processes, particularly the firing step. These studies have identified key areas for improvement, including the optimization of energy consumption and the reduction of environmental impacts. The findings of these LCA studies have important implications for the ceramic industry, underscoring the need for sustainable production practices and the potential for environmental savings through targeted improvements in the production process. In comparison, using alternative materials like Adobe can reduce embodied energy in a building's life cycle by 1.5 to 2 times, although it may increase maintenance-related embodied energy [25]. Notably, over 50% of a building's embodied energy is typically attributed to construction materials. Consequently, a life cycle assessment spanning 50 years reveals that substituting materials with high embodied energy, such as reinforced concrete, with alternative materials like hollow concrete blocks, stabilized soil blocks, or fly ash, can potentially yield a 20% reduction in total energy consumption. This finding suggests that strategic material selection can significantly mitigate energy intensity over the lifespan of a building, underscoring the importance of considering embodied energy in building design and material choices. Moreover, reusing construction materials is crucial for reducing embodied energy. For instance, using recycled aluminum and steel can achieve embodied energy savings of over 50% [26].

The structural system of building exerts a profound impact on its environmental performance. A comparative life cycle assessment (LCA) study was conducted on steel and concrete construction systems employed in office buildings, revealing distinct disparities in their environmental footprints as shown in Figure 2 [27]. Notably, the steel construction system demonstrated higher primary energy consumption and greenhouse gas emissions throughout its entire life cycle, despite requiring 25% less energy per square meter for production. This counterintuitive finding can be attributed to the poorer thermal transfer coefficient of concrete, which necessitates additional energy expenditures during the building's operational phase, ultimately offsetting the initial energy savings [28]. Research from various countries shows that buildings with wooden structures use less energy and produce less CO_2 over their lifetime compared to other construction types [29]. For example, a Canadian office building's steel structure has 1.61 times higher embodied energy than a concrete structure, which is 1.27 times higher than a wooden structure. Numerous life cycle studies in northern European countries highlight the benefits of timber construction.

In Norway and Sweden, replacing steel with wood in buildings avoids 0.06-0.88 kg CO_2-Eq per kg input of timber, while replacing concrete with wood avoids 0.16-1.77 kg CO2-Eq/kg [30]. Nevertheless, it is important to acknowledge that wood treatments can have detrimental toxicological effects on both ecosystems and human health. On the other hand, a significant advantage of wooden structures in residential buildings, particularly when combined with biomass cogeneration systems, is their potential to achieve net carbon sequestration throughout their entire life cycle. This beneficial outcome is contingent upon various influencing factors, highlighting the need for careful consideration and optimization of these parameters to maximize the environmental benefits of wooden structures and biomass systems [31].

3. Methodology

This work follows the methodological guidelines set out in the ISO 14040:2006 and ISO 14044:2006 standards, incorporating specific assumptions and simplifications. This study's main goal is to assess the energy and environmental performance of different construction materials, finding areas for development and offering suggestions for material selection. In alignment with the 20-20-20 targets and current European energy and environmental challenges, this study focuses on three key effect categories: water demand (measured in liters), Global Warming Potential (GWP, expressed in kg CO_2-Eq, primary energy demand (expressed in MJ-Eq, based on the Cumulative Energy Demand (CED) approach).

Since the 1970s, the Cumulative Energy Demand (CED) technique has been employed as an indicator of energy systems [31]. This approach assesses the direct energy consumption associated with the entire lifecycle of economic goods and services, encompassing the stages of production, consumption, and disposal. Additionally, it considers the indirect energy demand embodied in these activities, providing a comprehensive evaluation of the total energy footprint. The CED methodology differentiates between primary energy sources, categorizing them as either renewable (including hydraulic, biomass, wind, solar, and geothermal) or non-renewable (encompassing nuclear and fossil fuels). The Global Warming Potential (GWP) in CO_2-equivalents is a metric used to express the anthropogenic greenhouse effect resulting from human activity emissions [4], [25]. Currently, there is no established method for incorporating desiccation as a potential impact in Life Cycle Assessment (LCA). Despite this limitation, water consumption remains a significant concern in the building industry. Owing to the absence of a desiccation characterization factor, the indicator selected for this study adopts a comprehensive approach, aggregating all forms of freshwater extractions, encompassing withdrawals from rivers, lakes, oceans, soil, and wells. This includes water utilized

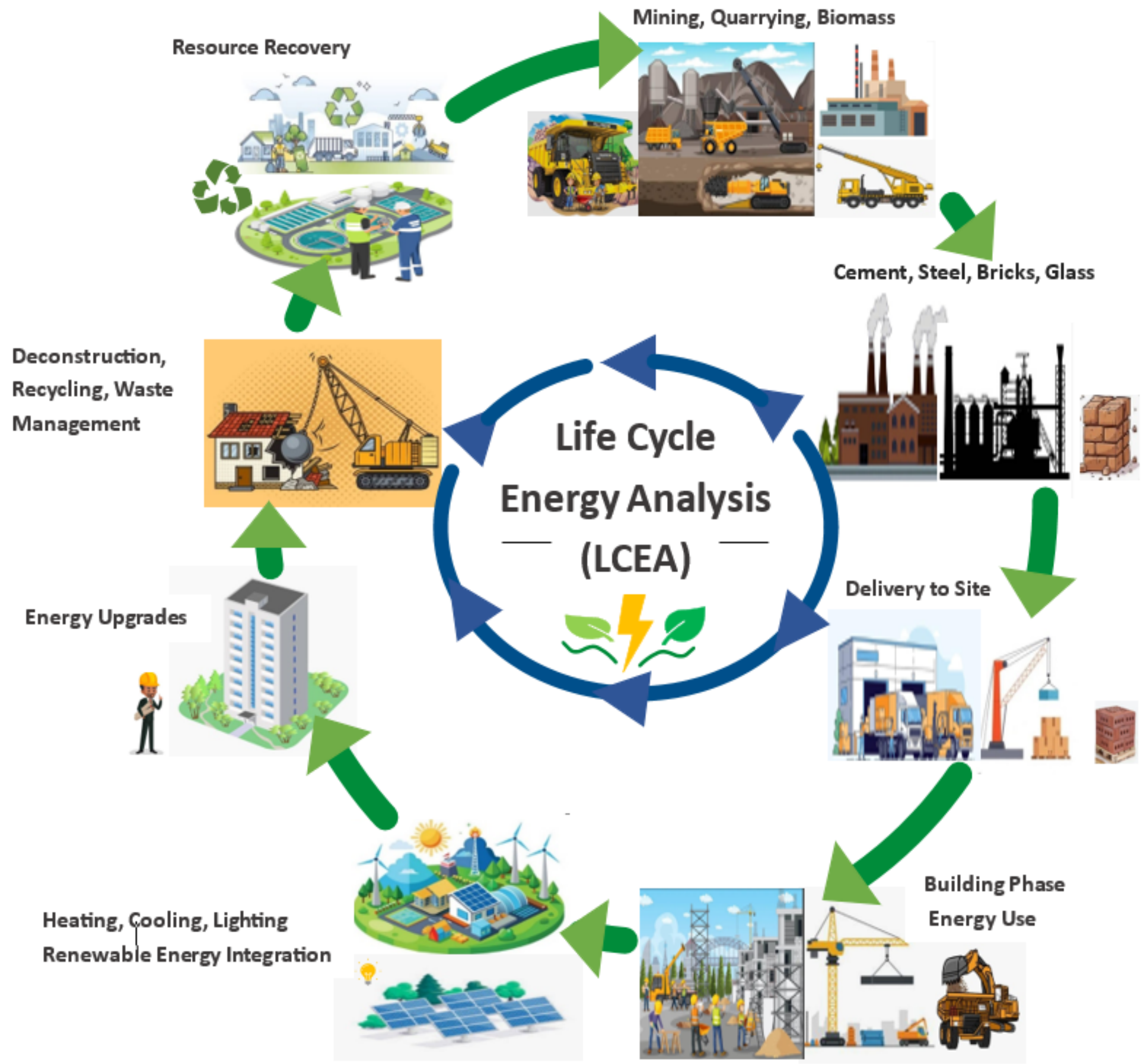

Figure 2. The engineering life cycle [26].

Table 1. Coefficients of impact calculation for the 1-ton stage of transit from the manufacturing facility to the building site [13].

Impact category	**Lorry, road** m_1	**Freight rail** m_2	**Transoceanic freight ship** m_3
Primary energy demand (MJ−Eq/km)	4.312	0.812	0.201
Global Warming Potential (kg CO_2−Eq/km)	0.204	0.410	0.011
Water demand (l/km)	2.003	1.230	0.104

for cooling processes but excludes water employed in turbines for hydraulic power generation. This aggregation enables a broader understanding of freshwater usage patterns while acknowledging the limitation of not accounting for water used in hydroelectric power production [32].

The life cycle stages considered in this study include material manufacturing, transportation from the production plant to the building site, building construction and deconstruction, and final product disposal. The functional unit chosen is one kilogram of material. As the study relies on average statistics, the applicability of the data to each European nation depends on how well their unique characteristics (such as energy mix, manufacturing techniques, and raw material sources) align with these averages. The life cycle inventories provide a snapshot of the current system processes, without examining their temporal evolution, due to the study's static focus. The manufacturing stage is comprehensively examined, encompassing the extraction and supply of raw materials, associated transportation requirements, and factory manufacturing processes for various construction materials. Furthermore, the transportation of goods from the production plant to the construction site is considered, which typically involves a 20-28 tonne truck, with an average range of 100 km, highlighting the significance of transportation-related energy expenditures and environmental impacts. Furthermore, a sensitivity analysis has been conducted for alternative transportation modes. Table 1 presents the values necessary to assess the impacts of delivering one-tonne using different transportation modes, based on a linear correla-

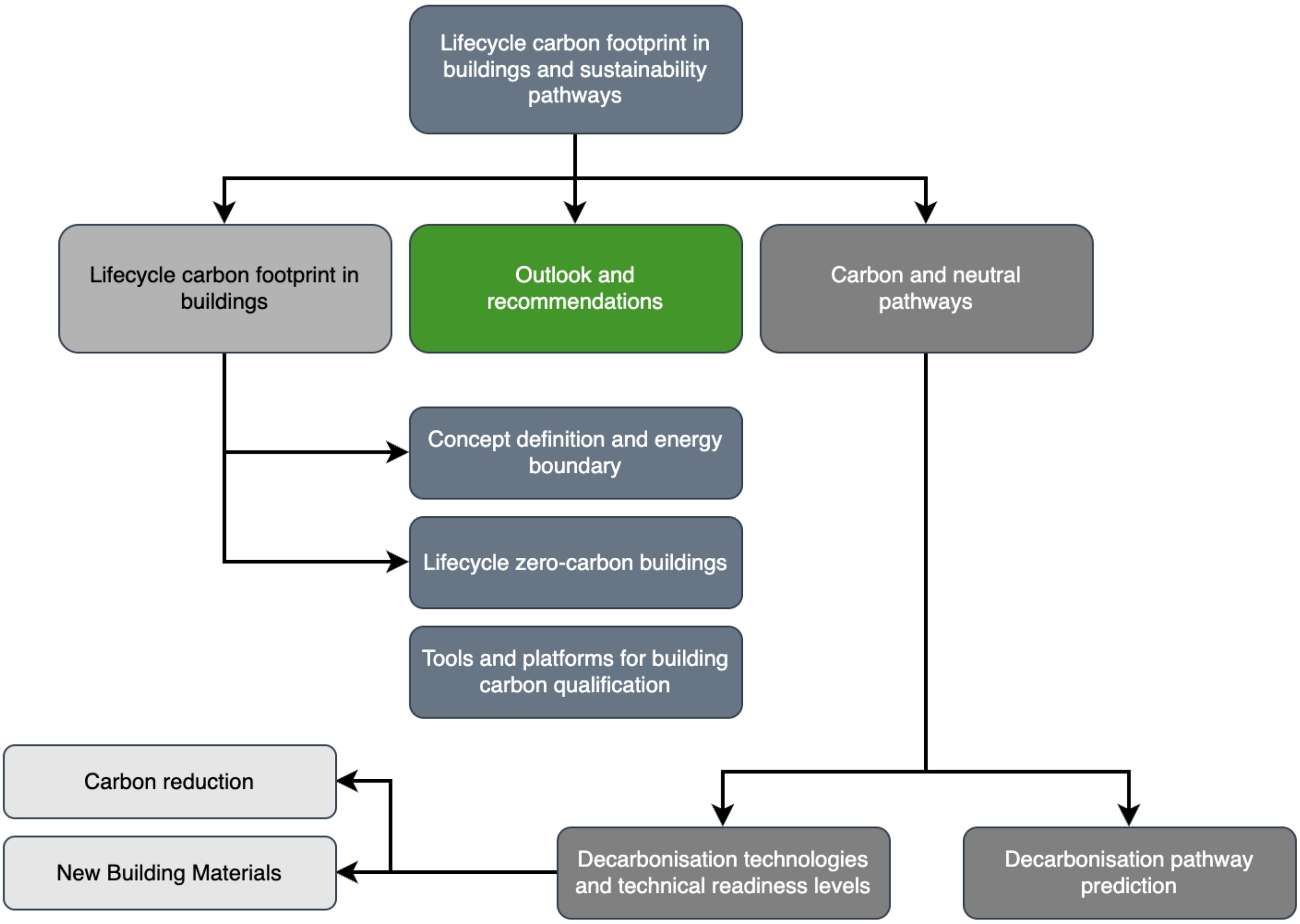

Figure 3. Structures' lifetime carbon footprint and sustainable development.

tion as shown in equation (1). This correlation uses coefficients (mi) applied to each transportation mode and the distance traveled (di) in kilometers.

$$Transport\ Impact = m_1 + m_2 + m_3 \quad (1)\ [13]$$

The final disposal stage takes into account the impacts of building demolition and the most common techniques for material disposal [33], including land-filling and incineration. However, only copper and aluminum were considered for direct recycling at the construction site. According to the Ecoinvent method, the newly produced secondary material from recycling the primary material receives the full benefit of the reduced environmental effects, while the primary material itself is not credited with any environmental savings.

Figure 3 illustrates the methodological framework employed in this study to assess the lifecycle carbon footprint of buildings and identify pathways to sustainability. The analysis aimed to provide a comprehensive framework for decision-making by evaluating three distinct impact categories for various building materials. In countries where water resources are scarce, the water demand will have a more pronounced impact on environmental assessments. This is because water scarcity can significantly influence the weighting of variables in aggregated metrics, such as the Eco-indicator 99 overall score. As a result, single ratings derived from a weighted sum of multiple variables may be subject to a degree of subjectivity, as the relative importance of water resources can vary significantly depending on regional context and availability [34].

Instead, a functional unit of one kilogram of material was chosen. While this can be a useful starting point for building a life cycle assessment (LCA), it is important to note that comparing the relative merits of two materials with different physical characteristics is not meaningful. This is mostly because the materials under comparison have to fulfill a set of specifications or serve a certain purpose. A building is considered a Zero-Energy Building (ZEB) when its total energy consumption is offset by an equivalent amount of renewable energy. However, the exact definition of ZEBs is a subject of ongoing debate, as it depends on the time frame and energy system boundaries considered. Figure 4 illustrates an integrated building energy system with multiple energy boundaries.

Specifically, ZEBs are defined by a balance between total energy outputs (comprising energy consumption and grid export energy) and total energy inputs (consisting of renewable energy and grid import energy). However, the amount of each material needed to fulfill this function may vary due to differences in their physical properties. For instance, a comparative analysis of columns constructed

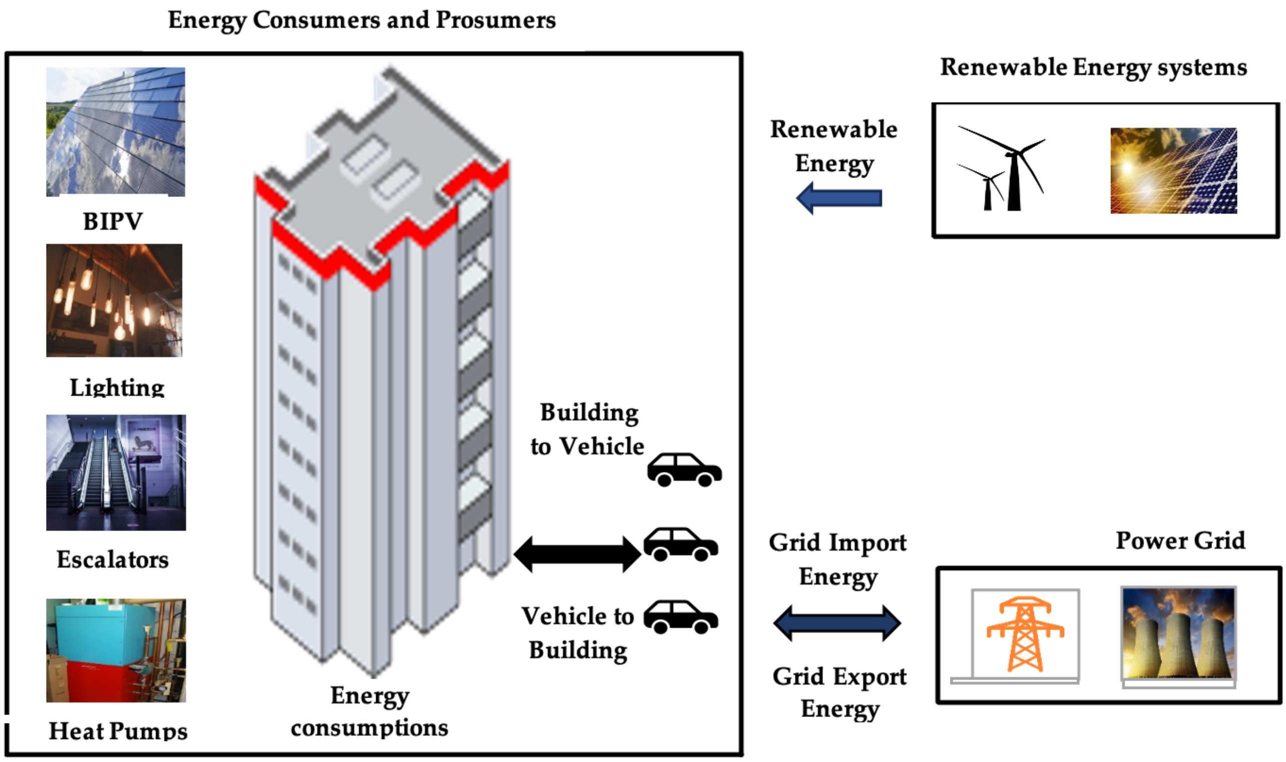

Figure 4. The integrated building energy systems.

from steel, reinforced concrete, and compressed earth blocks reveals that their embodied energy values are comparable, despite the disparate material properties. This phenomenon can be attributed to the fact that the high strength-to-weight ratio of steel, which is energy-intensive to produce, is offset by the relatively lower energy intensity of the block materials. When these columns are designed to bear the same netload, the differences in material properties are neutralized, resulting in similar embodied energy values across the three materials. This highlights the importance of considering the functional equivalence of materials in assessing their environmental impacts.

4. Results and Discussion

The results of the grouped LCA studies are presented in Table 2-6, categorized by the different building material typologies evaluated. It is crucial to note that the impact results are expressed per kilogram of material. If the functional unit were changed to one cubic meter of material, the effects might differ due to variations in material densities. Within this category, ceramic floor tiles exhibit the highest primary energy demand, primarily due to the substantial consumption of natural gas during the manufacturing process. This is a notable finding, as the production of ceramic floor tiles requires a significant amount of energy, largely attributed to the fuel-intensive firing process, which relies heavily on natural gas. As a result, the primary energy demand for ceramic floor tiles is considerably higher compared to other materials in this group. Up to 80% of the total energy consumption in the industrial facility occurs during the kiln firing stage.

Additionally, ceramic floor tiles require 7.5 times more water than ceramic roof tiles and bricks, primarily due to evaporation during cooling operations. However, the reliance on imported white-pigmented clay for ceramic floor tile production in countries like Nigeria, where red-pigmented clay is plentiful, increases the primary energy demand and associated emissions by a factor of 1.6%. This highlights the potential benefits of incentivizing manufacturers to utilize locally available clays, which would not only reduce the environmental impact but also promote sustainability. Implementing reward mechanisms for manufacturers that adopt regional clay sourcing could be a strategic approach to mitigating the environmental effects of ceramic production and fostering a more sustainable industry

A comparative analysis of outdoor pavement options reveals that selecting quarry tiles over ceramic tiles can significantly reduce primary energy consumption and greenhouse gas emissions. Specifically, quarry tiles offer a substantial primary energy savings of 14.13 MJ-Eq/kg, equivalent to an 84% reduction, and a notable decrease in emissions of 0.68 kg CO2-Eq/kg, representing a 70% reduction. Based on these findings, it is recommended to opt for quarry tiles as a more sustainable and environmentally friendly alternative for outdoor pavement applications. However, fiber cement is not the most suitable option for roofing due to its high impact, and concrete tiles are generally preferred over ceramic tiles. Nevertheless, ceramic tiles offer savings compared to fiber cement roofs, with a reduction of 7.10 MJ-Eq/kg (60%), and compared to concrete tiles, savings can reach 2.10 MJ-Eq/kg (42%).

Table 2. LCA Analysis of Brick and Tile Materials' Carbon Footprint.

Building Product	Density (kg/m^3)	Thermal conductivity (W/mK)	Primary energy demand (MJ–Eq/kg)	Global Warming Potential (kg CO_2–Eq/kg)	Water demand (l/kg)
Typical brick	2010	1.2	4.034	0.31	2.101
Light clay brick	1102	0.31	5.984	−0.005	1.391
Sand-lime brick	2030	1.1	2.202	0.211	2.989
Ceramic tile	1900	0.98	16.70	0.934	13.87
Quarry tile	1980	2.01	2.200	0.301	2.998
Ceramic roof tile	1990	0.99	5.011	0.398	2.397
Concrete roof tile	2402	2.02	3.143	0.313	4.034
Fiber cement roof slate	2100	0.49	12.01	1.401	19.897

Table 3. Sustainability Assessment of Common Insulation Materials.

Building Product	Density (kg/m^3)	Thermal conductivity (W/mK)	Primary energy demand (MJ–Eq/kg)	Global Warming Potential (kg CO_2–Eq/kg)	Water demand (l/kg)
EPS foam slab	40	0.0402	112.502	6.874	20.840
Rock wool	70	0.039	30.001	2.023	31.978
Polyurethane	40	0.0289	104.21	7.004	351.756
Cork slab	160	0.050	49.978	1.108	29.689
Cellulose fibre	60	0.0387	9.975	2.044	19.956
Wood wool	190	0.10	19.875	0.132	3.002

Additionally, using silico-calcareous bricks (composed of 90% lime and 10% sand) or light clay bricks (made from 85% clay and 15% straw) can significantly lessen the environmental impact. Although light clay bricks have a relatively high primary energy demand, it's important to note that 45% of this energy comes from biomass due to the straw content. Moreover, light clay bricks have a nearly neutral CO_2 balance, emitting only 0.3kg of CO_2 per kg when used in place of ordinary bricks. Notably, technological advancements in ceramic production have the potential to significantly mitigate existing environmental impacts. Recent advancements in ceramic production technology have led to significant reductions in primary power consumption. Notable examples of these developments include the implementation of cogeneration systems, which achieve a 10% reduction in primary power consumption, the adoption of high-speed burners for product preheating and drying that harness waste heat from kiln smoke, and the replacement of outdated intermittent kilns with modern tunnel kilns, which offer a 20% improvement in energy efficiency. These innovations demonstrate the potential for sustainable improvements in ceramic manufacturing processes.

4.1. Insulating Materials for Sustainable Buildings

It is crucial to highlight those natural materials like cork, wood fiber, sheep's wool, and recycled materials like cellulose fiber have a substantially lower environmental impact on buildings compared to standard insulation materials with high industrial processing, such as EPS. Notably, natural origin insulation like sheep's wool emits 98% less CO_2 equivalent per kilogram when disposed of through burning, compared to EPS or polyurethane insulation, which emits an average of 7 kg CO_2/Eq/kg due to high petroleum usage. Moreover, if recycled at the end of its service life, natural insulation can even become a carbon sink. Therefore, it is imperative to support a significant shift in building architecture and structural design that prioritizes constructability and facilitates easier disassembly of buildings, promoting a more circular and sustainable approach to construction.

The demand for sheep's wool has declined in modern times due to the rising popularity of synthetic materials, which are often considered challenging to utilize and are frequently viewed as "waste products." However, by harnessing this "waste" and transforming it into an affordable and abundant raw material, the establishment of wool production enterprises can foster balanced and sustainable growth in rural areas. One of the primary uses of wool is as thermal insulation in buildings. Meanwhile, cork - which is harvested from trees every season - is another eco-friendly option, particularly when sourced from Nigerian farms and forests. This not only preserves a high-value ecosystem that might otherwise disappear but also ensures no harm comes to the trees. Although cork tiles have a slightly higher primary energy consumption, it's essential to note that over 50% of their energy comes from biomass, making their actual impact relatively minimal.

The insulating material analysis revealed that stiff polyurethane foam and expanded polystyrene tiles have the most significant environmental impacts as shown in Table 3. Their manufacturing processes require substantial

Table 4. Environmental Performance of Cement and Concrete in Building Construction.

Building Product	Density (kg/m^3)	Thermal conductivity (W/mK)	Primary energy demand (MJ–Eq/kg)	Global Warming Potential (kg CO_2–Eq/kg)	Water demand (l/kg)
Cement	3231	1.39	3.763	0.819	4.013
Cement mortar	2037	1.1	1.967	0.241	2.965
Reinforced concrete	3051	1.9	2.011	0.179	3.142
Concrete	2435	2.01	0.976	0.137	1.976

resources, including natural gas and oil, resulting in the highest primary energy consumption and water footprint, primarily due to water evaporation during cooling processes. Furthermore, these operations and the ultimate disposal of the products in municipal incinerators contribute to increased global warming potential. In contrast, rock wool has a significantly lower impact, with a primary energy demand that is four times lower, a carbon footprint that is 4.7 times lower, and a water footprint that is 8.4 times lower. However, it is essential to acknowledge that the production of rock wool inherently requires the consumption of coal and the utilization of phenolic resins, which possess a high specific environmental impact due to the energy-intensive process of fusing basaltic rock. This highlights the need to consider the environmental implications of rock wool production, particularly its carbon footprint and resource usage.

Despite the availability of eco-friendly alternatives, conventional insulation remains the dominant choice due to its established commercial network and lower upfront cost. However, this inertia is often perpetuated by designers who are either unaware of or skeptical about the benefits of natural and recycled insulating materials. To overcome this, governments and administrations should actively promote the adoption of these ecological insulation options, which offer equivalent or superior insulation performance and thermal comfort. By doing so, they can help establish a robust commercial network for eco-friendly insulation that can compete with traditional insulation materials on equal footing.

4.2. Cement and concrete

Table 4 shows that cement, primarily used to manufacture clinker, has a greater environmental impact than cement mortar (a mixture of cement and sand) and concrete (a mixture of cement, gravel, and water). Although cement has a significant environmental impact, it can be mitigated by supplementing it with less disruptive materials, such as sand, gravel, or water. While the impact per kilogram of these materials is relatively low, their high density means that the effect is amplified when expressed per cubic meter of material. Moreover, it is crucial to recognize that these materials typically constitute a substantial proportion (40-60%) of a standard building's total weight, which consequently increases the building's overall environmental footprint. This highlights the importance of considering the cumulative environmental effects of building materials in construction. The environmental impact of reinforced concrete is significantly higher than that of mass concrete, primarily due to the addition of corrugated steel, which substantially increases the impact. This results in a notable increase of 700 MJeEq/t (63%) in primary energy demand and a 42 kg/t (31%) rise in emissions. Interestingly, using lime mortars instead of cement mortars could be a more environmentally friendly option, as lime mortars allow buildings to "breathe" more easily and absorb a significant amount of CO2 during the setting process - up to 62% of the emissions from decarbonization and combustion processes. In contrast, cement mortars absorb less than 2% of these emissions.

As previously discussed, the clinker manufacturing process has a profound influence on the life cycle assessment of cement-based products. Given that clinker serves as the primary raw material for all cement-based products, its production process plays a critical role in determining the overall environmental impact of these products. Therefore, in order to mitigate the environmental footprint of cement-based products, it is imperative that the cement industry prioritizes the use of alternative materials and fuels over traditional resources and fossil fuels in the production of clinker. This strategic shift towards more sustainable practices is crucial for reducing the environmental impact of clinker production and, by extension, the broader range of cement-based products. Notably, while most European countries have made significant progress in this area, with alternative fuels accounting for over 35% of clinker production (reaching as high as 80% in the Netherlands), other countries like Spain still lag behind, with alternative fuels making up less than 5% of clinker production.

The use of alternative fuels in the cement industry offers a transformative approach to waste management, where various waste types that would otherwise be landfilled or incinerated can be evaluated for energy recovery. The findings of this analysis unequivocally demonstrate the potential for waste to be valorized as resources, thereby enabling the closure of the material loop—a core principle underpinning the development of industrial ecology. To realize this objective, governmental entities must play a pivotal role in promoting the utilization of alternative fuels in cement manufacturing facilities by

Table 5. Sustainability Assessment of Wood Products.

Building Product	Density (kg/m³)	Thermal conductivity (W/mK)	Primary energy demand (MJ–Eq/kg)	Global Warming Potential (kg CO_2–Eq/kg)	Water demand (l/kg)
Sawn timber,softwood, planed, kiln dried	700	0.2	21.120	0.2900	4.9950
Sawn timber, softwood, planed, air dried	700	0.2	17.956	0.3010	4.2021
Glued laminated timber, indoor use	700	0.2	26.915	0.4902	7.9865
Particle board, indoor use	700	0.2	35.056	0.0400	9.0241
Oriented strand board	700	0.2	35.798	0.5930	25.023

Table 6. Environmental Impact Analysis of Common Building Products.

Building Product	Density (kg/m³)	Thermal conductivity (W/mK)	Primary energy demand (MJ–Eq/kg)	Global Warming Potential (kg CO_2–Eq/kg)	Water demand (l/kg)
Reinforcing steel	8000	50	23.987	2.013	25.867
Aluminium	3000	240	140.02	9.021	214.304
Polyvinylchloride	1400	0.20	71.787	3.997	512.345
Flat glass	2600	1.0	16.023	1. 223	17.241
Copper	9012	380	36.232	2.000	78.103

implementing supportive policies and legislation. Such regulatory frameworks will be instrumental in fostering the transition toward a more circular economy, where waste is reconceptualized as a valuable resource, and the environmental impacts associated with traditional cement production are mitigated. By 2050, cemments CO_2 emissions could decrease by half compared to 1990 levels, based on a comparison between current energy consumption (2900-3200 MJ/t) and theoretical energy consumption (1700-1800 MJ/t), assuming continued technical advancements. Clinker manufacturing facilities should adopt various technical improvement strategies to achieve this reduction, such as optimizing furnace residual heat utilization, reducing sintering temperature, and eventually implementing fluidized bed technology.

4.3. The Benefits of Wood Trusses in Building Design

Wood-based building materials generally have a lower environmental impact, particularly those that require minimal industrial processing. Notably, biomass is the primary energy source for these products, accounting for 69-83% of their total primary energy requirement. Due to the reduced industrial processing as shown in Table 5, the carbon footprint of these materials is nearly neutral. Furthermore, if these products are recycled or reused instead of being incinerated at the end of their life cycle, they can even achieve a negative carbon balance. It's important to note that laminated wood, for example, can absorb up to 582 kg of CO_2 per m3 if left undisturbed at the end of its life cycle, whereas steel and reinforced concrete emit significantly more CO_2, at 12,087 kg and 458 kg respectively.

In light of the unequivocal environmental benefits and enhanced fire resistance of wooden structures, a compelling case can be made for revising current construction legislation to prioritize the design and construction of wooden buildings over those made of reinforced concrete. This regulatory shift would not only contribute to a more sustainable built environment but also align with the growing body of research highlighting the advantages of wood as a building material. By incentivizing the use of wood in construction, policymakers can play a crucial role in reducing the environmental footprint of the building sector and promoting a more resilient and sustainable future. Notably, in the current context of investing significant financial resources in carbon capture and storage technologies in power plants, it is essential to recognize that using structural wood in buildings represents a prior form of carbon capture and storage. The wood absorbs CO_2 from the atmosphere during the tree's growth phase, which is then stored for the building's entire lifespan (at least 50 years).

Additionally, if the wood is reused or recycled after its initial service life, this carbon sequestration can be extended even further, provided that sustainable forestry practices are employed. The use of wooden structures in buildings effectively turns them into "CO_2 warehouses," which warrants support from administrations. Although the impact of these products is relatively small, there is still room for improvement, particularly in replacing traditional urea- and melamine-formaldehyde resins with natural resins that meet the same standards. The substitution of synthetic resins with natural alternatives has the potential to yield significant reductions in equivalent CO_2 emissions, ranging from 18% in the case of laminated wood to 46% for fiberboard, contingent upon the quantity of resin utilized. Moreover, the traditional practice of harvesting natural resins is declining in many regions, creating an opportunity for the development of innovative resin-farming methods that could generate employment and revenue streams in rural and isolated areas. The cultivation of natural resins for various wood products could not only mitigate environmental impacts but also contribute to the socioeconomic development of marginalized communities. Additionally, by simply increasing the supply of wood and utilizing outdoor drying methods in suitable climates and seasons with humidity levels up to 20-30% equivalent CO_2 emissions could be reduced by 11%.

4.4. Exploring More Sustainable Products

The environmental impact of certain regularly used building materials, like steel, aluminum, copper, PVC, and glass, is substantial because of their high energy consumption and the raw materials required for their whole life cycles. Additionally, these materials are produced by fully globalized industries, further increasing the environmental impact through transportation. Specifically, 32,000 kg*km of aluminum, 13,800 kg*km of copper, 6,800 kg*km of steel, and 2,500 kg*km of glass must be transported as shown in Table 6. Aluminum is particularly notable for its high energy demand, especially in the form of electricity, which increases both its primary energy consumption and global warming potential. Similarly, PVC production involves a considerable water footprint due to water evaporation during various cooling processes. The shift from primary to secondary production for metals like steel, aluminum, and copper has contributed to reduced environmental impacts. However, high-impact secondary sector operations like pyrometallurgy and electrolysis have resulted in increased energy expenditures for metal extraction and the depletion of deposits of iron, bauxite, and copper.

The establishment of international agreements that limit mineral extraction and offer incentives for the growth of secondary industries is crucial for facilitating the transformation of waste into valuable resources, thereby conserving the planet's mineral reserves. Such agreements can play a vital role in promoting a circular economy, where waste is reconceptualized as a resource, and the extraction of primary minerals is reduced. By prioritizing the development of secondary industries, which focus on the recovery and recycling of materials, we can mitigate the environmental impacts associated with mineral extraction and promote a more sustainable and resource-efficient future. As a result, producing secondary steel reduces CO_2Eq emissions by 1.2 kg (74%) per kilogram, compared to primary steel production. Similarly, secondary copper production decreases emissions by 2 kg CO_2 Eq/kg (64%), and secondary aluminum production by 11.3 kg CO_2 Eq/kg (92%), compared to their primary production counterparts.

5. Conclusion

Adopting best practices and innovation in production is essential to reduce the depletion of natural resources. This includes closing material loops by reusing process waste, prioritizing recycling, minimizing transportation, and relying on locally available resources wherever possible. The study provides updated estimates of the environmental impacts of selected building materials, revealing that medium-term impacts are generally 20–30% higher than those reported in earlier research. These differences stem from the broader system boundaries and alternative Life Cycle Assessment (LCA) approaches used. For example, the Global Warming Potential of a typical brick was found to be 23% higher, largely because previous studies considered different fuel scenarios and excluded certain life-cycle stages. The results also show clear trends related to mineral resource use, underscoring the need to expand and harmonize construction material databases so they better reflect national industry characteristics. More reliable, product-specific data will enable more accurate LCAs, improving the assessment of whole-building environmental performance and supporting more informed sustainability decisions.

A major barrier to circularity in construction is that many materials ultimately end up in landfills or incinerators due to difficulties in separation during demolition. Promoting recycling therefore requires a shift toward design strategies that prioritize disassembly and end-of-life recovery, such as reversible connections and modular construction. This approach, already common in the automotive sector, would facilitate material reuse and significantly reduce waste. At the same time, sustainable building strategies must be grounded in a comprehensive understanding of consumption dynamics to avoid rebound effects and ensure real reductions in resource use. Achieving this may involve broader systemic considerations such as limiting new construction and exploring alternative development pathways while future research should further investigate the wider social, economic, and energy implications and assess the integration of emerging renewable technologies to support a more resource-efficient built environment.

6. Declarations

6.1. Author Contributions

Oluwaseyi Omotayo Alabi: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft; **Adeoti Oyegbori Laoye:** Writing - Review & Editing, Visualization, Supervision, Project administration, Funding acquisition.

6.2. Institutional Review Board Statement

Not applicable.

6.3. Informed Consent Statement

Not applicable.

6.4. Data Availability Statement

No data availability.

6.5. Acknowledgment

Not applicable.

6.6. Conflicts of Interest

The authors declare no conflicts of interest.

7. References

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