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Analytical Assessment of Embodied Energy in Building Materials: A Sustainable Structural Design Perspective in the Libyan Context

*Mohamed Ali karim[a], Abdualraouf Ali Mohamed[b]

[a]Department of Civil and Architectural Engineering, School of Applied Sciences and Engineering, Academy for Postgraduate Studies, Libya
[b]Civil Eng. Department, Faculty of Engineering, Elmergib University, Libya

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A B S T R A C T

This study aims to provide a comprehensive analysis of the concept of Embodied Energy and its central importance in evaluating the sustainability of materials and construction projects within the building sector. Embodied energy is defined as the total energy consumed across the entire lifecycle of a material. This includes raw material extraction, processing, manufacturing, transportation, installation, maintenance, and ultimately, end-of-life considerations (recycling or disposal). The study highlights that embodied energy can represent over 50% of a building's total lifecycle energy consumption, particularly in structures with high operational efficiency. By adopting a Life Cycle Assessment (LCA) methodology, informed design decisions can be made. The study presents analytical data for the embodied energy of common building materials, demonstrating significant variation. Materials such as aluminum and steel show high values compared to concrete and wood. A case study of a residential building in Libya is included, comparing a structural frame system with a load-bearing wall system. The load-bearing wall system demonstrates approximately 18% lower embodied energy. The findings emphasize the importance of early design choices and recommend the adoption of policies supporting the use of materials and systems with low embodied energy to achieve genuine environmental sustainability in the construction sector.

التقييم التحليلي للطاقة الكامنة في مواد البناء: منظور نحو تصميم إنشائي مستدام في السياق الليبي

*محمد علي كريم[a] و عبدالرؤوف علي امهير[b]

[a]قسم الهندسة المدنية والمعمارية، مدرسة العلوم الهندسية والتطبيقية، الاكاديمية الليبية للدراسات العلية- جنزور، دولة ليبيا
[b]قسم الهندسة المدنية ، كلية الهندسة، جامعة المرقب – الخمس ، دولة ليبيا

الكلمات المفتاحية:
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النظام الإنشائي
تحليل طاقة دورة الحياة المباني.

الملخص

لا تهدف هذه الدراسة إلى تقديم تحليل شامل لمفهوم الطاقة الكامنة وأهميته المحورية في تقييم استدامة المواد ومشاريع البناء في قطاع التشييد. تُعرَّف الطاقة الكامنة بأنها مجموع الطاقة المستهلكة عبر دورة حياة المادة بالكامل، بما في ذلك: استخراج المواد الخام، المعالجة، التصنيع، النقل، التركيب، الصيانة، وأخيرًا الاعتبارات المتعلقة بنهاية العمر الافتراضي (إعادة التدوير أو التخلص). تُبرز الدراسة أن الطاقة الكامنة قد تمثل أكثر من 50% من إجمالي استهلاك الطاقة خلال دورة حياة المبنى، خصوصًا في المباني ذات الكفاءة التشغيلية العالية. ومن خلال اعتماد منهجية تقييم دورة الحياة (LCA) يمكن اتخاذ قرارات تصميم مدروسة. تُقدّم الدراسة بيانات تحليلية عن الطاقة الكامنة للمواد الإنشائية الشائعة، مظهرةً تباينًا كبيرًا، حيث تسجل مواد مثل الألمنيوم والصلب قيمًا مرتفعة مقارنةً بـ الخرسانة والخشب. كما تتضمن الدراسة دراسة حالة لمبنى سكني في ليبيا، تمت فيها مقارنة نظام الإطار الإنشائي مع نظام الحوائط الحاملة، حيث أظهر نظام الحوائط الحاملة انخفاضًا في الطاقة الكامنة بنسبة تقارب 18%. تؤكد النتائج على أهمية القرارات التصميمية المبكرة، وتوصي باعتماد سياسات تشجع على استخدام المواد والأنظمة ذات الطاقة الكامنة المنخفضة، لتحقيق استدامة بيئية حقيقية في قطاع البناء.

*Corresponding author:
E-mail addresses: omgaon2x@yahoo.com
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1. Introduction

Embodied Energy serves as a fundamental environmental indicator for evaluating the sustainability of materials and construction projects within the building sector. This is due to its direct impact on the carbon footprint and the total energy consumed throughout a structure's lifecycle. It refers to the sum of energy required for raw material extraction, manufacturing, transportation, installation, maintenance, and finally, recycling or ultimate disposal. Its significance lies in illuminating the indirect environmental impact of materials, which is often overlooked when focusing solely on a building's operational energy consumption.

While most studies over recent decades have focused on operational energy efficiency (e.g., improved insulation and lighting systems), recent research indicates that embodied energy constitutes a notable proportion of the total energy consumed. Some studies suggest that embodied energy can exceed 50% of the total energy over a lifecycle extending beyond fifty years, as demonstrated by Stephan et al. [1]. This is further supported by Ramesh et al. [2], who noted that disregarding embodied energy leads to inaccurate environmental impact assessments.

According to the United States Department of Energy (DOE) [3], residential and commercial buildings alone consume 41% of the total energy produced in the United States. This underscores the importance of adopting a comprehensive approach that covers energy rationalization, improved resource utilization (including water), and the evaluation of emissions resulting from manufacturing and construction processes.

This study aims to analyze embodied energy in building materials based on current databases. It seeks to highlight the significant variation among materials in terms of embodied energy and its influence on design decisions, utilizing statistical models and comparative studies at both local and international levels.

Embodied energy is a core component in Life Cycle Assessment (LCA). This methodology allows for the estimation of energy and resources consumed and emissions generated throughout a facility's lifecycle, including environmental impacts on biodiversity, water, and air. Integrating LCA concepts into the design and implementation phases aids in making informed decisions that contribute to reducing environmental impact and achieving sustainability goals.

This paper relied on a review of scientific literature and data from international and national organizations, including: the International Energy Agency (IEA) [4], the Inventory of Carbon and Energy (ICE) database for building materials [5], the U.S. Environmental Protection Agency (EPA) [6], in addition to scientific journals such as Energy and Buildings and Journal of Cleaner Production. The study also drew upon local studies from Egypt, Saudi Arabia, the UAE, South Africa, and Morocco to provide a realistic regional perspective. This study included a comparison of two structural models for a residential building in Libya: the frame (skeletal) system and the mixed (load-bearing wall and column) system, to measure the impact of changing the structural system on embodied energy.

Results from previous studies show considerable variation in the embodied energy values of materials, as reported in the ICE database (Hammond & Jones, 2008) [5]. Dixit et al. [7] indicated that these values vary depending on geographical location and industrial conditions, calling for unified calculation methodologies. Chastas et al. [8] revealed that wooden buildings have up to 60% less embodied energy compared to concrete and steel structures. Asdrubali et al. [9] noted that using recycled materials reduces embodied energy by 10–25%. Zuo & Zhao [10] concluded that improved supply chain management contributed to lowering embodied energy for green building projects in China.

Ramesh et al. [2] further clarified that traditional concrete systems consume 35% higher embodied energy compared to alternative systems. Thormark [11] demonstrated that material reuse at end-of-life can reduce embodied energy by up to 40%. Alhorr et al. [12] reviewed successful initiatives in the Arabian Gulf for reducing embodied energy through the adoption of local materials and transport efficiency. Cabeza et al. [13] explained the role of life cycle assessment in improving design decisions through dynamic building energy models.

Regionally, international reports, such as those from UNIDO - United Nations Industrial Development Organization [14] and GIZ - Deutsche Gesellschaft for International Zusammenarbeit (German Agency for International Cooperation) [15], indicate that producing one ton of cement in Egypt consumes between 3.5 and 5.5 gigajoules of thermal energy, depending on factory efficiency. This process generates an average of 850 kg of carbon dioxide per ton, making cement one of the most widely used and emissions-intensive materials. The International Energy Agency (IEA) [16] and GCCA – Global Cement and Concrete Association [17] initiatives recommend reducing embodied energy by improving kiln efficiency and using alternative fuels. The Egyptian cement sector accounts for approximately 10% of industrial energy consumption. These data are consistent with the Intergovernmental Panel on Climate Change (IPCC) [18] guidelines for emission factors.

A report by the Emirates Green Building Council (EGBC) [19] showed that using recycled bricks reduces embodied energy by 30%. In Morocco, the Moroccan Agency for Energy Efficiency (AMEE) [20] indicated that compressed earth is a low-energy alternative compared to concrete. A report from the Green Building Council South Africa (GBCSA) [21] revealed that wooden systems reduce energy consumption by 45% compared to traditional alternatives. Analytical data also indicates that materials such as aluminum and iron have high embodied energy levels (155 MJ/kg and 20 MJ/kg respectively), while concrete and wood record lower values (1.1 MJ/kg and 8.5 MJ/kg), making them more suitable for environmental projects. A comparison of structural systems also revealed that using concrete walls with a wooden frame achieves the lowest embodied energy, compared to steel frames. The results confirm that material selection in the early design stages has a significant impact on reducing total embodied energy, and should not be based solely on cost or availability, but on relevant environmental data.

The study highlights the need for policies and design standards that support low-embodied energy materials and hybrid building systems, with the aim of fostering sustainable development. A comparison of the embodied energy for the residential model in Libya showed that the load-bearing wall system required lesser reinforced concrete material compared to the frame system, consuming 380.8 GJ versus 450.681GJ, a difference of 69.881 GJ (equivalent to 19,411 kWh).

Subsequent sections of the study will detail embodied energy data, along with conclusions and practical recommendations aimed at engineers, designers, and decision-makers, to guide design practices toward more sustainable solutions.

2. Methodology for Calculating Energy Consumption in the Building Sectors

With growing interest in optimizing energy consumption within the building sector, specialized scientific methodologies have emerged to calculate and assess the energy used at various stages of a building's lifecycle. This spans from raw material extraction, through manufacturing, construction, and operation, to demolition and recycling. Life Cycle Energy Analysis (LCEA) is among the most prominent scientific tools in this field due to its ability to provide a comprehensive estimate of energy consumption and its associated environmental impacts.

The LCEA methodology is applied in the building sector to cover all energy inputs across three main stages:

- Manufacturing Stage: This includes the production and transportation of materials and systems used in construction or renovation.
- Operational Stage: This covers energy consumption during the building's use, such as for air conditioning, lighting, water, and routine maintenance.
- Demolition Stage: This encompasses dismantling activities and transportation to landfills or recycling facilities.

Figure (1) illustrates the boundaries and stages of the LCEA methodology. It considers the energy required at each stage of a building's lifecycle, as well as environmental impacts like greenhouse gas emissions and air and water pollution. Although the concept originated in the 1970s, its systematic application has gradually evolved with increasing awareness of the importance of total energy consumption and its environmental effects [22].

The LCEA methodology relies on categorizing embodied energy into specific types, alongside operational energy and demolition energy, as follows:

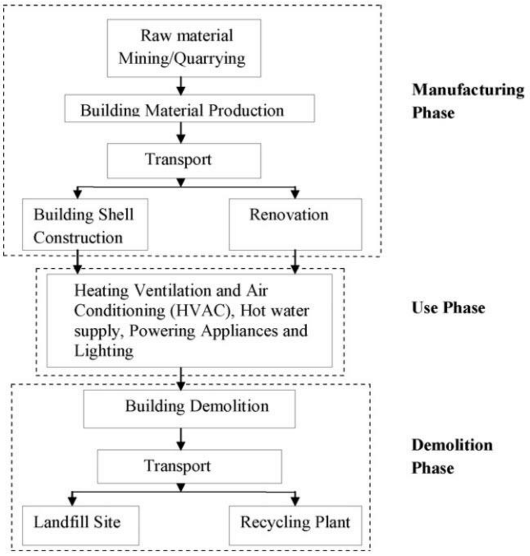

Fig. 1: Stages and Boundaries of Life Cycle Energy Analysis (LCEA)

2.1 Initial Embodied Energy (EEi)

This refers to the energy required to construct a building until its completion. It includes energy used in material production, transportation, and installation. This is calculated mathematically by the relationship:

$$EE_i = \sum(m_i \cdot M_i) + E_c \ldots\ldots\ldots\ldots (1)$$

Where:

EE_i: Initial embodied energy.

M_i: Quantity of construction material (i)

m_i: Energy content per unit of material

E_c: Energy consumed at the construction site

2.2 Recurring Embodied Energy (EEr)

A wide variety of materials are used in building construction. Some of these materials may have a lifespan shorter than that of the building. Consequently, these materials may be replaced or maintained to rehabilitate the building. Buildings also require routine annual maintenance. These activities are referred to as recurring embodied energy, which can be expressed mathematically as:

$$EE_r = \sum m_i . M_i[(L_b/L_{mi}) - 1] \ldots\ldots\ldots\ldots (2)$$

where

L_b: life span of the building

L_{mi} : life span of the material (i)

2.3 Operational Energy (OE)

Operational energy is defined as the energy consumed to maintain comfort levels inside the building, regardless of external weather conditions. This also includes the energy required to operate equipment and appliances used within the building. This is expressed mathematically as:

$$OE = E_{OA} . L_b \ldots\ldots\ldots\ldots (3)$$

Where:

OE : operating energy over the lifespan of the building

EOA : annual operating energy

Lb : life span of the building

2.4 Demolition Energy (DE)

At the end of a building's useful life, it is demolished and transported to landfills or recycling facilities for materials that can be recycled. All these activities require energy, known as demolition energy. This is expressed mathematically by the following relationship:

$$DE = E_D + E_T \ldots\ldots\ldots\ldots (4)$$

Where

E_D: energy incurred for destruction of the building

E_T = energy used for transporting the waste materials

2.5 Life Cycle Energy (LCE)

The total energy consumed over a building's lifecycle (LCE) is the sum of the initial embodied energy, recurring embodied energy, operational energy, and demolition energy, as follows:

$$LCE = EEi + EEr + OE + DE \ldots\ldots\ldots\ldots (5)$$

Table (1) presents initial embodied energy values for common building materials, compiled from various studies by Dixit, M. K. [23]. Within Libya, clear studies detailing the embodied energy of construction materials like cement, concrete blocks, or reinforced concrete are not available. The closest relevant study found in an Arab country was conducted in the Najaf desert [24]. This study aimed to investigate the impact of changing building materials on the embodied energy consumed during the construction process. Table (2) shows the estimated embodied energy values used in that study. These values represent the total embodied energy for the materials included in construction. In residential buildings, materials with relatively low embodied energy, such as cement and aggregates, along with concrete blocks, are used in large quantities. In contrast, materials that consume a significant amount of embodied energy, like steel and aluminium, are used in much smaller quantities by weight or volume.

Table 1: Embodied Energy for Common Building Materials from a Collection of Studies by Dixit, M. K.

Source	Embodied Energy in MJ/kg of Building Material								
	Virgin Steel	Cement	Glass	PVC	Gypsum/ Plasterboard	Bricks	Concrete	Timber	Aggregates
Honey & Buchanan (1992)	34.9	8.9	31.5	96	3.1	18.9	1.7	100	-
Kernan (1996)	28	18.7	9.8	2.5	9.9	0.3	105	-	-
Adalberth (1997)	32	88.7	8.6	2	106.7	-	-	-	-
Blanchard & Reppe (1998)	37.3	18.4	77.4	24.5	4.5	1.6	8.3	0.9	3.2
Eaton Et al. (1998)	25.5	2.7	5.8	0.8	-	-	-	-	-
Chen et al. (2001)	32	7.8	16.1	70	8.6	2.5	1	5.2	0.1
Alcorn (2003)	31.3	6.2	15.9	60.9	7.4	2.7	0.9	2.8	0.4
Scheuer et al. (2003)	30.6	3.7	6.8	60.7	0.9	2.7	10.8	94.4	-
Reddy (2004)	42	4.2	1.4	-	-	-	-	-	-
Almeida et al. (2005)	10.1	18.4	4	1.1	100.4	-	-	-	-
Yohanis & Norton (2006)	42	5.9	25.8	-	-	-	-	-	-
Pullen (2007)	55.5	6.6	83.6	121.5	5.4	2.4	11.9	1.7	-
Crawford (2004)	97.5	14.5	141.8	-	-	-	-	-	-
Huberman & Pearlmutter (2008)	35	18	1.2	116	-	-	-	-	-
Hammond & Jones (2008)	35.3	15	1	15	-	-	-	-	-
Hammond and Jones (2011)	31.3	5.2	15	70.6	3.5	3	2.9	7.1	0.1
Ramesh et al. (2013)	28.2	6.7	25.8	158	-	-	-	-	-

Table 2: Embodied Energy for Some Building Materials in the Najaf Desert

Material	EE (MJ/kg)
Plain Concrete	1.15
Reinforced concrete	2.60
Hollow concrete masonry	1.08
Reinforcing steel	35

3- Comparison of Embodied Energy for Two Structural Models of a Simple Residential Building in Libya

This section of the study focuses on a building's structural system and how changing the load-bearing structural system affects the overall embodied energy consumption for a traditional residential building in Libya. Therefore, the focus was placed solely on the energy associated with materials used in the manufacture and construction of the load-bearing structural system. This is because other work items, such as finishing and cladding, have identical values for both systems, leading to consistent energy consumption values in these remaining categories.

The structural frame system relies on reinforced concrete used in manufacturing the load-bearing structural elements, which is the primary material depended upon for safely transferring loads through these elements. In contrast, the load-bearing wall system relies on concrete blocks for safely transferring loads to strip concrete foundations. A comparison was made of the embodied energy only for the load-bearing elements—reinforced concrete and concrete blocks—and the environmental impact of each study model was measured. As noted, this approach was taken due to the similar quantities required for finishing and cladding works, as well as the consistent operational energy values consumed due to the stable climatic conditions surrounding both models.

3.1 Modeling

A conventional residential building (see Figure (2)) has been studied in two cases of proposed structural systems: first, a frame structural system, and secondly, load-bearing walls system.

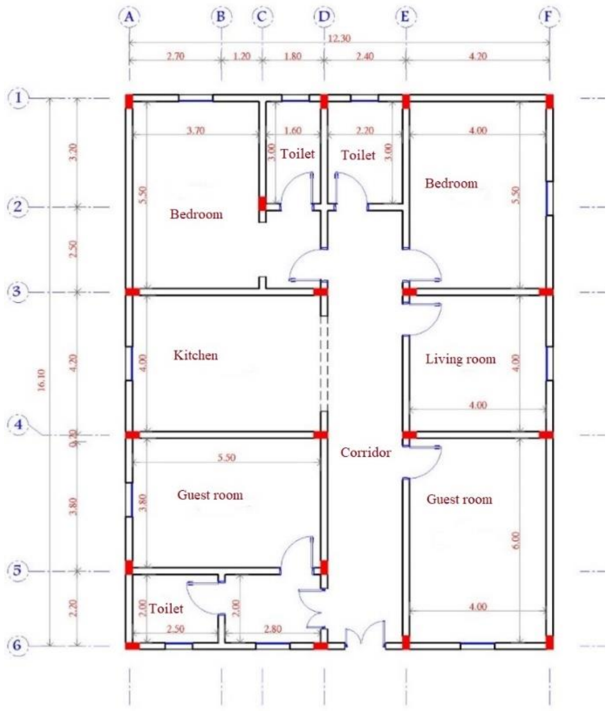

Fig. 2: Plan view of the proposed residential building

3.1.1 Structural analysis and design

The requirements of the American code ACI-318 (American Concrete Institute - Building Code Requirements for Structural Concrete) [25] were used to obtain the initial dimensions of the concrete elements (slabs, beams, columns, and foundations). The dead loads were calculated based on the assumed density characteristics of each part of the building. Live loads were used according to ASCE (American Society of Civil Engineers) [26]. Table (3) illustrates the proposed properties for modeling

Table 3. Proposed properties for structural modeling

Description	Density	Compressive strength	Loads
Reinforced concrete	2400 kg/m3	30 MPa	Self-weight
Rebar		280 MPa	
walls (Masonry blocks)	2000 kg/m3		for the wall with a width of 0.2 m and a height of 3 m = 11.76 kn/m
Roof sloping concrete	2300 kg/m3		Average thickness 7.5 cm =1.70 Kn/m2
Roof live load			0.96 km/m2

SAP2000 software [27] was used for structural analysis and design. Figure (3) illustrates the structural model of the frame system; both columns and beams were modeled as line elements, while roof slabs and foundations were represented by shell elements. Flexible springs were used to represent base soil with a stiffness constant of the springs Ks, which was estimated based on a relationship proposed by Bowles (1997) [28], Ks=9,600 kN/m3, the analysis was carried out to obtain stresses of all frame elements to be used in the process of comparing with the other structural systems.

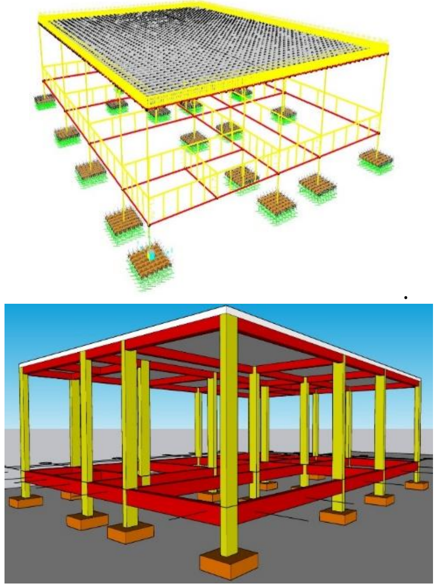

Fig. 3: SAP2000 modeling for frame structural system

On the other hand, using cement masonry units in the construction of load-bearing walls is subject to some requirements set by building specifications and codes; according to which the masonry units can be considered acceptable and reliable in transferring loads across the wall. The thickness of the internal and external parts (shells) of the masonry unit are considered one of the most important elements on which cement masonry are classified. Mathematical relationships for the mechanics of materials strength, through which stresses can be calculated, depend on the geometric and physical properties of the studied element, such that by varying the gross net area (An) of the masonry unit or by changing the moment of inertia in one of the main directions Ix or Iy, the stress value for the same acting load changes significantly. Therefore, the many specifications and building codes have developed a set of indicative tables that give geometric characteristics of cement masonry walls. These characteristics also differ depending on the nature of the wall's support, whether it is supported horizontally or vertically. Likewise, the thickness of the mortar used in construction significantly affects the geometric properties of the wall section. Consequently, the American specifications specify that the minimum thickness of the mortar must be 9.50 mm, and the difference in increase or decrease in thickness should not exceed what is stated in the specification for building mortar ASTM- C270 (ASTM International - Standard Specification for Mortar for Unit Masonry) [29]. However, the masonry commonly used in construction work in the state of Libya has dimensions of (400×200×200 mm), these geometric characteristics simulate that in American specifications ASTM 90-06 (ASTM International - Standard Specification for Loadbearing Concrete Masonry Units) [30]. Modulus of Elasticity (Em) is another important factor in determining the stiffness of structural elements, according to a study [31] which was later adopted by the American Code ACI 530-13, Moreover, the American specifications of walls constructing, and Building Code Requirements for Masonry Structures (TMS 402-13/ACI 530-13/ASCE 5-13 - The Masonry Society / American Concrete Institute / American Society of Civil Engineers) [32], propose an experimental formula to calculate the elasticity modulus Em based on the maximum compressive strength of cement masonry. It is worth noting that the design stresses in the load-bearing wall did not exceed 1.0 MPa. Table (4) demonstrates physical and mechanical properties of the materials used in defining the model, including walls, beams, roof, and strip foundation (see Figure (4)).

Table 4: Physical and mechanical properties of the materials for structural modelling

Element	Element model	Parameter	Value
Masonry Wall	Membrane Element	Weight per Unit Volume	2,000 kgf/m^3
		Modula's Of Elasticity	11,790 Mpa
		Poisson's Ratio	0.20
		Compressive Strength f'_m	13.10 Mpa
		Weight Modifier	2.276465
		Modula's Of Elasticity ($E_m = 900 * f'_m$)	11,790 Mpa
Concrete Elements (Slabs, Footings &	Shell element & line element	Weight per Unit Volume	2,400 kgf/m^3
		Modula's Of Elasticity	24855.60 Mpa
		Poisson's Ratio	0.20
		Compressive Strength	30 Mpa

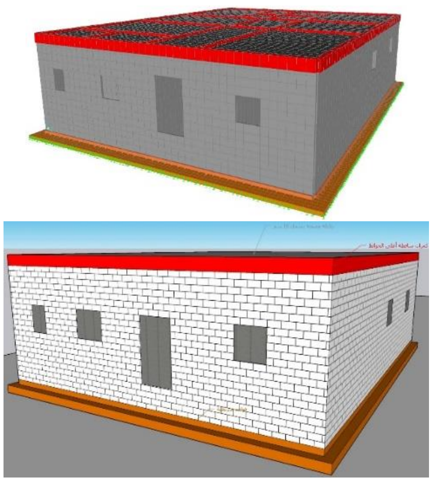

Fig. 4: SAP2000 modeling for load-bearing walls system

4. Significance of the main findings

Embodied energy represents a significant and potentially unexpected portion of a building's total lifecycle energy consumption, especially in structures with high operational efficiency. This makes it a crucial factor in achieving true sustainability. Thoughtful material selection during early design stages is vital for reducing this energy, as vast differences exist between various materials. This necessitates moving beyond traditional cost criteria to incorporate environmental impact. Furthermore, adopting sustainable hybrid systems promotes a shift towards more environmentally friendly infrastructure at both local and global levels. The tabulated embodied energy data for common building materials (refer to Table (5)) highlights the following key findings from this study:

1- Importance of Embodied Energy: Embodied energy is an essential environmental indicator for evaluating the sustainability of materials and projects, due to its significant impact on the carbon footprint and energy consumption throughout a facility's lifecycle.
2- Significant Impact on Total Energy Consumption: Embodied energy can account for a large percentage (over 50%) of a building's total energy consumption over 50 years, particularly in highly operationally efficient buildings.
3- Material Variation: There is considerable variation in embodied energy among different materials. Materials such as aluminum and steel have very high embodied energy, while concrete and wood exhibit relatively low embodied energy values.
4- Crucial Role of Early Design Choices: Decisions regarding material and structural system selection in the early project stages play a critical role in reducing overall embodied energy and improving the project's total environmental performance.
5- Role of Life Cycle Assessment (LCA): Integrating LCA concepts is fundamental during design and implementation phases to make informed decisions that contribute to reducing environmental impact and achieving sustainability goals.
6- Shift Towards Hybrid Systems: Studies show that using hybrid structural systems, such as concrete walls with wooden frameworks, can achieve the lowest levels of embodied energy, promoting solutions that combine sustainability and durability.
7- Moving Beyond Cost and Availability Criteria: Material selection decisions should not be limited to cost and availability criteria alone. They must also include data on embodied energy and inherent carbon emissions.
8- Need for Supportive Policies and Standards: The necessity of adopting policies and design standards that support theuse of low-embodied energy materials is highlighted to enhance sustainable practices in the building and road sectors.
9- Regional and Local Considerations:
   - Material Source: Embodied energy can vary significantly based on the distance materials are transported. Local materials typically have lower transportation embodied energy.
   - Manufacturing Methods: The efficiency of manufacturing processes and energy consumption differs among countries and factories.
   - Climate: Climate influences a building's operational energy requirements, and thus the balance between embodied and operational energy over a building's lifecycle. In hot regions, focusing on effective insulation to reduce operational energy may be more crucial, but this must be balanced with the embodied energy of the insulation materials themselves.
   - Available Resources: Some regions may encourage the use of specific materials due to their local abundance (sand and cement) or scarcity (wood in certain areas).
10- Table (5) presents the indicative embodied energy values derived from this study's comprehensive analysis.

11. Embodied Energy of Two Structural Models for a Simple Residential Building in Libya. Based on the embodied energy values in Table (2) and by quantifying the reinforced concrete and concrete block units for both structural systems, the difference in embodied energy values can be measured. Considering Table (2), the energy consumed for reinforcing steel is several times higher compared to plain concrete. A difference of 18% between the two study models is observed, which is a relatively small percentage. However, this percentage could increase with an increase in the quantity of reinforced concrete in the frame model due to architectural or

aesthetic requirements. This percentage becomes significantly impactful if measured across all residential buildings planned for construction in Libya. Table (6) shows that the frame system consumes approximately 18% more embodied energy compared to the load-bearing wall system. This difference is mainly due to the increased quantity of reinforced concrete used in the frame system, which is among the materials with the highest embodied energy consumption, especially with steel as a key component. For instance, the embodied energy of steel used in reinforcement is about 35 MJ/kg, significantly higher than that recorded for concrete or concrete blocks. The production process for reinforced concrete also consumes high energy linked to cement, transportation, and on-site operations such as formwork, pouring, and curing. Furthermore, actual embodied energy values are affected by project location; the greater the distance between the site and material sources (such as cement, block, or steel factories), the higher the energy consumed in transportation.

Table 5: Embodied Energy Data for Common Building Materials

Material	Approximate Embodied Energy (MJ/kg)	Notes
Portland Cement	4 - 6	Cement is a key component in concrete. Its production process is energy-intensive due to the high temperatures (>1400∘C) required for clinkerization in kilns, consuming significant thermal and electrical energy. This explains part of concrete's embodied energy.
Brick (Fired Clay)	2 - 4	Varies based on manufacturing method and firing temperature. Energy is primarily consumed in the drying and firing stages (up to 1200∘C) within kilns, affecting both thermal and electrical demands.
Hollow Concrete Masonry	1.0 - 2.5	Composed of cement, sand, and water. Embodied energy is higher than aggregates but lower than fired brick, with a significant portion attributed to cement production. Its hollow nature reduces material mass, thus lowering embodied energy per unit volume compared to solid concrete blocks.
Glass (for Windows)	15 - 20	Glass manufacturing (float glass process) requires high temperatures (>1500∘C) to melt raw materials (silica sand, soda ash, limestone), consuming substantial thermal energy.
Ceramic/Porcelain	10 - 20	Manufacturing processes demand significant energy for kilns (firing temperatures often exceeding 1000∘C) and drying. The energy intensity is dependent on the specific ceramic body, glazes, and firing cycles.
Cement Tiles/Terrazzo	2 - 5	Lower than ceramic as they do not require high-temperature firing. Energy consumption is primarily associated with cement production, mixing, pressing, and curing, with less thermal input compared to fired materials.
Mineral Wool (Insulation)	10 - 15	Used as an insulating material. Its manufacturing process involves melting rocks or slag at high temperatures (>1400∘C) and then spinning the molten material into fibers, consuming considerable thermal and electrical energy.
Polystyrene (Insulation)	70 - 100	A petroleum-derived insulating material (e.g., expanded polystyrene - EPS, extruded polystyrene - XPS). Its production process involves polymerization of styrene monomers, which is an energy-intensive chemical process, followed by expansion or extrusion.
Copper (for Wires & Pipes)	60 - 100	Extracting and processing copper requires substantial energy. This includes energy for mining, ore concentration, smelting (pyrometallurgical or hydrometallurgical processes at high temperatures), and refining (electrolytic refining).
Gypsum Board	2 - 3	A common material for interior finishes. Its manufacturing process is less energy-intensive compared to metals, primarily involving calcination of gypsum (at 120−170∘C), mixing with water and additives, and drying.
Sand and Aggregates	0.02 - 0.1	Very low embodied energy as these are natural materials requiring minimal extraction and initial processing (e.g., washing, sorting, crushing). The majority of embodied energy comes from transportation from quarry to site.
Plain Concrete	0.8 - 1.5	Significantly affected by cement content, as cement production is the most energy-intensive component. Higher cement ratios lead to higher embodied energy. The mixing and curing processes require relatively low energy input.
Reinforced Concrete	1.5 – 3.0	Higher than plain concrete due to the inclusion of steel reinforcement. This figure represents the average embodied energy of the composite material, weighted by the mass ratio and individual embodied energies of concrete and steel components.
Reinforcing Steel Bars	20 - 40	Primarily manufactured from iron ore via the Blast Furnace/Basic Oxygen Furnace (BOF) route or from recycled scrap steel via the Electric Arc Furnace (EAF) route. The BOF process is more energy-intensive (30−40 MJ/kg), while EAF with high recycled content is less so.
Recycled Content Reinforcing Steel Bars	10 - 15	These values represent rebar produced predominantly via the Electric Arc Furnace (EAF) method, utilizing a high percentage of recycled steel scrap. This significantly reduces embodied energy compared to virgin steel production, as it bypasses the energy-intensive ore reduction step.
Steel Sections	20 - 40	Similar to rebar, structural steel sections are produced via BOF or EAF processes. The higher end of the range is for virgin steel production, while values closer to 10-15 MJ/kg are typical for steel sections made with a high recycled content in EAFs.
Asphalt Concrete	3 - 11	Depends on asphalt type (hot, warm, cold) and the ratio of aggregates and binders. A significant portion of embodied energy comes from heating the mix and manufacturing petroleum-based binders. Using recycled asphalt pavement (RAP) and warm mixes (WMA) can significantly reduce this value.

PVC Pipes	70 - 90	Polyvinyl chloride (PVC) is a common plastic material. Polymer manufacturing processes, involving the synthesis of vinyl chloride monomer (VCM) from ethylene and chlorine, followed by polymerization, require significant energy, in addition to shaping and finishing operations.
HDPE Pipes	60 - 80	High-density polyethylene (HDPE) is another common plastic material for pipes. Its embodied energy is comparable to PVC and also depends on the polymerization of ethylene monomers and subsequent shaping processes (extrusion). It is often preferred for its flexibility and durability.
Paints	10 - 30	Depends on composition (water-based or oil-based), type of binder, pigments, and solvents. The embodied energy includes the chemical synthesis of polymers and pigments, and the energy for mixing and packaging.
Plaster/Render	0.5 - 1.5	Lime- or cement-based materials are relatively low in embodied energy. Production involves calcination of limestone (for lime) or cement production, followed by mixing and hydration.
Wood Flooring (Engineered)	10 - 20	Higher than raw timber due to processing (cutting, milling, drying), adhesive production, and lamination for composite layers. The energy for adhesives can be a notable contributor.
Ground Granulated Blast-Furnace Slag (GGBS)	0.1 - 1.6	A byproduct of iron manufacturing. Its embodied energy is very low because it is a waste product that requires minimal additional processing (primarily grinding) to become a cementitious material.
Fly Ash	0.0 - 0.9	A byproduct of coal combustion in power plants. Its embodied energy is typically considered very low, often approaching zero if viewed as a waste product requiring only collection and minimal processing (drying, classification). The value is highly dependent on transportation distance.
Silica Fume	0.1 - 0.2	A byproduct of silicon or ferrosilicon alloy production. Its embodied energy is extremely low as it is collected directly from industrial furnaces as a fine powder, requiring minimal further processing beyond collection and packaging.

Table 6: Comparison of Embodied Energy Values for Frame and Load-Bearing Wall Systems

Structural System	Quantity Material		Embodied Energy		Total Embodied Energy (GJ)	*Normalized Embodied Energy
	Reinforced Concrete (tone)	Masonry Units (tone)	Reinforced Concrete (MJ)	Masonry Units (MJ)		
Frame System	140.59	78.84	365,534	85,147.2	450.681	1.183
Bearing Walls	106.608	95.976	277,180.8	103,654.08	380.835	1

*Embodied energy is normalized to smallest value.

11.1 Environmental Performance Comparison of Structural Systems

Environmental comparison between structural systems is a critical step in assessing the impact of construction materials on embodied energy and carbon emissions. Table (7) highlights the key differences between the frame system and the load-bearing wall system in terms of environmental efficiency and energy consumption, providing guidance for more sustainable design decisions.

Table 7: Environmental efficiency - differences of frame structural system and the load-bearing structural system

Item	Frame System	Load-Bearing Wall System
Basic Materials	Reinforced concrete in large quantities+ Concrete masonry	Concrete masonry + less Reinforced concrete
Embodied Energy	450.681GJ	380.8 GJ
Difference Percentage	Consumes 18% more	Consumes 18% less
Carbon Footprint	Higher due to steel (35 MJ/kg) and cement use	Lower due to block usage and reduced steel
Project Prevalence	Common in multi-story buildings	Up to three story, more suitable for simple residential buildings
Reusability	Lower due to integrated elements	Higher in some precast systems
Long-Term Environmental Impact	Increases emissions throughout the supply chain	Reduces emissions when using local, low-energy materials

5- Conclusions

This study highlights the scientific and practical importance of Embodied Energy as a central factor in assessing the environmental footprint of buildings. Contrary to the historical focus on operational energy efficiency, recent research demonstrates that embodied energy—the total energy required for raw material extraction, manufacturing, transportation, installation, maintenance, and end-of-life—can constitute over 50% of a building's total lifecycle energy consumption, especially in facilities designed for high operational efficiency. This strongly supports the necessity of integrating comprehensive Life Cycle Assessment (LCA) as an essential part of the structural design process.

Analytical data shows significant variations in embodied energy values among common building materials. While materials like plain concrete have relatively low embodied energy, ranging between 0.8-1.5 MJ/kg, and reinforced concrete is slightly higher at 1.5-2.5 MJ/kg due to the addition of steel (which can have an embodied energy of 20 MJ/kg), materials such as aluminum and steel record much higher values. This variation confirms that early design choices, particularly concerning material and structural system selection, have a direct and crucial impact on reducing a project's overall environmental impact.

On an applied level, the study provides an example from the Libyan context, where a comparison between two structural systems for a residential building show that the load-bearing wall system consumes approximately 18% less embodied energy compared to the traditional frame system. This difference, primarily attributed to the reduced quantity of reinforced concrete used in the load-bearing wall system, is highly significant when considering national housing projects. Accordingly, the study emphasizes the need to move beyond initial cost and availability as exclusive decision-making points, giving paramount importance to embodied energy data and inherent carbon emissions. The study also recommends the formulation and adoption of policies and design standards that support the use of low-embodied energy materials and encourage hybrid and sustainable structural systems, aiming to accelerate the transition towards more environmentally sustainable infrastructure in the region.

6-Recommendations

These recommendations aim to guide design and implementation practices toward more sustainable and environmentally efficient solutions:

1- Integrate Life Cycle Assessment (LCA) Early in the Design Process:

- For Engineers and Designers: LCA methodology should be adopted as a mandatory tool from the initial stages of conceptual design. Utilize available LCA software and tools (such as BIM software supported by LCA data) to evaluate the total environmental impact, including embodied energy, for various material and structural system options before making final decisions.
- For Policymakers: Establish mandatory regulations and standards that require major construction projects to conduct LCA analyses and submit transparent environmental reports highlighting embodied energy indicators and carbon emissions.

2- Prioritize Low-Embodied Energy Materials and Sustainable Sources:

- For Engineers and Designers: Give high priority to materials characterized by low embodied energy (concrete with low cement content, wood, hollow concrete blocks) whenever possible, without compromising structural durability and safety. Explore and use local materials as much as possible to reduce transportation embodied energy.
- For Policymakers: Offer incentives (such as tax exemptions or financial support) for projects that adopt sustainable building materials with low embodied energy. Encourage research and development in innovative materials with a low environmental footprint.

3- Adopt Hybrid and Innovative Structural Systems:

- For Engineers and Designers: Study the feasibility of hybrid structural systems (using wooden frameworks with concrete walls, or integrating precast concrete elements) to reduce overall reliance on energy-intensive materials like steel and traditional reinforced concrete, while maintaining required structural performance.
- For Policymakers: Amend and update local construction codes and standards to encourage and facilitate the use of hybrid systems and alternative, innovative materials that have proven effective in reducing embodied energy.

4- Enhance Resource Efficiency and Support the Circular Economy:

- For Engineers and Designers: Focus on designing buildings that allow for easy disassembly and material reuse at the end of their lifecycle (Design for Disassembly). Increase the use of recycled materials (recycled aggregate in concrete, recycled bricks).
- For Policymakers: Support infrastructure for recycling construction materials and encourage industries that produce building materials from waste or recycled materials through supportive policies and clear targets.

5- Develop Accurate Local and Regional Embodied Energy Databases:

- For All Stakeholders: Given the significant differences in embodied energy values across regions (due to manufacturing methods, energy sources, distances), investing in the creation and updating of accurate local and regional databases for common building materials is essential. This will provide reliable data for engineers, designers, and policymakers within the Libyan and Arab contexts.
- For Research Institutions and Universities: Conduct more applied studies to assess the embodied energy of locally produced materials in Libya and the region.

6- Raise Awareness, Provide Training, and Build Capacity:

- For All Stakeholders: Launch intensive awareness campaigns for engineers, engineering students, contractors, and real estate developers on the importance of embodied energy and how to assess and reduce it. Integrate the concept of embodied energy and LCA more deeply into academic curricula and professional training programs.

By implementing these recommendations, the construction sector in Libya and the region can effectively contribute to achieving sustainable development goals, reducing carbon footprint, and building a more environmentally efficient future.

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