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Optimizing Evaluation Methods for the Embodied Energy and Carbon Management of Existing Buildings in Egypt

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Abstract: There is an increasing demand for the decarbonization of existing buildings. The development of standardized calculation methods has simplified calculation processes and enabled wider engagement with the topic. As the industry advances, optimization and accounting for regional differences will increase in importance. This paper reviews the key drivers in the field, both locally and internationally, and proposes a performance-based evaluation method specific to local construction in Egypt. The aim of the method is to assist in the renovation of existing buildings by guiding the decision-making process through the proposed evaluation framework. A local case study of an existing multi-story apartment building was used to create a baseline for typical local multi-story residential buildings and demonstrated the effectiveness of the proposed evaluation method. This framework provides the owners of buildings with a decision-making process by which carbon impacts associated with future renovations and operations of existing buildings can be minimized.

Keywords: carbon management; existing buildings; performance-based evaluation; decarbonization

1. Introduction

Energy efficiency and reduced carbon emissions in the built environment are highly sought objectives today. An estimated 40% of total energy consumption worldwide results from the building and construction industry [1]; therefore, the building sector is a significant contributor of carbon as well as other emissions [2]. Accounting for energy embedded in the building process is therefore critical to the optimization process. On a building level, the most commonly used mode of energy accounting in buildings uses either energy analysis or guidelines set by the ISO (International Standardization Organization) for life cycle assessment (LCA) [3]. Using LCA to determine the impact of a building on the environment involves accounting for and calculating all the energy processes involved in the production, maintenance, and demolition of the analyzed building. These processes are generally divided into two distinct categories: embodied energy processes and operational energy processes. The embodied and operational energies then sum up the total life cycle energy (LCE) of a building.

Although the overall impact of a building cannot be assessed solely on either embodied energy or operational energy, the study and optimization of each of the subcomponents would allow for a better understanding of the entire building life cycle. Increased interest in the field has resulted in increased research and literature on these topics. However, while studies have been conducted in many countries, the study of embodied energy in the building industry in Egypt remains a relatively new topic despite its particular importance in hot countries.

As stated by Nebel et al. [4]: "In heating dominated regions, embodied energy represents a relatively low percentage of total life cycle energy, which may not be true for a moderate or cooling dominated region due to the latter's relatively low operational energy."

Compared to the higher operational energies in cold countries (as a result of more extensive heating loads), embodied energy holds a greater share of the LCE in hot and dry countries such as Egypt. As a result, embodied energy reduction in Egypt is of particular significance to the decarbonization of local construction. Furthermore, as discussed by Haynes [5], it is important to differentiate between embodied energy and embodied carbon. For example, while a comparison of embodied energies of two buildings might show that one has higher energy content than the other, energy content alone should not be considered as an indicator of its impact on the environment, as the building with higher embodied energy might use a clean renewable source, whereas the building with lower energy might be based on fossil fuels, having an overall greater environmental impact.

Locally, Egypt would benefit from an increased supply of energy from renewable sources to cover the growing energy demands. Furthermore, a reduction of embodied carbon content through the replacement of current energy sources with clean renewable energy would lead to significantly cleaner construction. Based on energy reports from 2009 published by the Energy Information Administration under the Department of Energy [6], Egypt's main sources of energy were oil and natural gas, accounting for 47% and 48%, respectively, of the country's total energy consumption. Such a high reliance on fossil fuels indicates a high level of embodied carbon in transportation processes, material extraction, and/or manufacturing and processing at first assembly, maintenance, and disassembly. Awareness of current material sourcing and construction processes would enable better decision-making processes for future local building trends. The case study presented below showcases the current building status to help create a basis on which the optimization of future material selection and construction methods can be made.

2. Literature Review

2.1. A General Overview

An overview of the existing literature on embodied energy has shown and confirmed the growing importance and consideration of embodied energy in more energy-conscious construction. Embodied energy, i.e., the amount of energy that goes into creating a final product, assesses and calculates the amount of energy invested into producing the materials used in creating a product, the energy invested in extracting the materials, and all the energy used in transporting, assembling, maintaining, and then demolishing the product. Calculating the embodied energy of a simple product can be simple and straightforward. However, the calculation of the embodied energy of a building, with its vast numbers of components and subcomponents, is far more complex. To accurately calculate a building's embodied energy, every underlying component must be traced back to its original source and account for all the energy invested into its production. Accurate calculation of the embodied energy therefore requires accurate source records, material data, and precision in reporting. A lack of standardization of calculation methods in the past has resulted in embodied energy records varying in accuracy and precision, which also creates difficulties in comparison. The literature has repeatedly shown that existing frameworks of calculation are not stringent enough, resulting in discrepancies in calculations. Even databases such as the Inventory of Carbon Emissions (ICE) database published by the University of Bath—a widely used database for carbon emissions coefficients—is acknowledged (by its authors) to have some degree of inaccuracy in its inventory.

2.2. Classification of the Literature

The complexity and relative novelty of the topic has resulted in several published works focusing largely on studying the existing literature. For instance, Zeng and Chini mapped out existing research in a "knowledge map" that enables better understanding of the work done thus far, with the results being the identification of key areas for future work in the field: technology, industry, and optimization [7]. Other work has explored the literature to better comprehend components that need to be accounted for in the pursuit of more accurate embodied energy calculation. The work of Dixit et al. is an example of such work, with the additional attempt to quantify the impacts of each parameter on total embodied energies accounted for [8], while the work of Chastas et al. focuses primarily on existing knowledge associated with the LCE analysis of residential buildings [9].

Further recent literature and work on embodied energy considerations ranges from tool development, assessment of current construction methods, and thorough explorations of existing research on the topic to better understand the extent and limitations of existing knowledge as well as a particular focus on operational energy. A review of the existing literature shows that much of the work in the field can be divided into five main categories: (1) standardization of calculation methods, frameworks, and boundaries; (2) appropriate tool development for more accurate and streamlined embodied energy calculation; (3) application of methods and analysis of case studies by building type; (4) optimization of low/zero carbon (LZC) material use and decarbonization using smart retrofit proposals to lower the overall direct and indirect energy use; (5) scalability of approaches and means of evaluation. The literature indicates a number of opportunities in the industry for developing more accurate and streamlined calculation methods.

2.2.1. Standardization of Methods

A review of the existing literature repeatedly calls for the need to establish standardized calculation methods for estimating accurately embodied energy in buildings. A uniform methodology or set of guidelines to abide by when calculating embodied energy is not currently existent, thereby resulting in discrepancies and variations in energies reported. Standardized third-party building assessment and certification methods such as the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) and the U.K. Building Research Establishment Environmental Assessment Method (BREEAM) developed by the Building Research Establishment in the U.K. standardize environmental-impact and life cycle assessment strategies; however, they are not solely focused on the calculation of embodied energies [9,10].

In terms of the development of standardized methods focusing particularly on embodied energy, the work of Manish Dixit, Jose Fernandez-Solis, Sarel Lavy, and Charles Culp at Texas A&M University is invaluable. The work published includes an extensive overview of the existing literature, and in three different papers published in 2010, 2012, and 2013 they attempt to identify the parameters and existing guidelines that could help establish clearer calculation methodologies, frameworks, and system boundaries for embodied energy calculations. In their first paper, Dixit et al. [11] establish the existing gap in comparable embodied energy databases. Based on this conclusion, their second work then focuses on the existing parameters that could aid in creating a unified protocol or set of guidelines, for a more standardized calculation method in determining embodied energy [12]. Simultaneously, the work also identifies challenges in existing resources and causes of discrepancies and inaccuracies that would need to be minimized in order to reach a more accurate and comparable set of results. Their earlier work published in 2013 proposes a boundary definition to unify the energy processes accounted for in embodied energy calculations. In the meantime, researchers continue to attempt different methodologies for energy accounting. Sharma and Marwaha focus on housing typologies in India [13], while Azari and Abbasabadi study methodologies across different contexts, identifying trends where possible [14].

2.2.2. Tool Development for More Accurate and Streamlined Embodied Energy Calculation

Although a number of different embodied energy calculators are easily accessible, backend methods and data inputs have not been standardized. Established agencies such as the International Finance Corporation have invested in creating platforms (such as EDGE—Excellence in Design for Greater Efficiencies) to assist in the design of more energy and cost-effective building systems [15]. Current shifts towards building information modeling (BIM) in the design process have also created opportunities for developing more suitable and streamlined energy accounting tools within existing toolboxes and software. The recent work of Nizam et al. is an example of this with a focus on the construction phase of the building only—creating a clear boundary and limitation that does not account for post-occupant operational energy [16].

2.2.3. Application of Methods

While some sources worked on optimizing the actual calculation procedure, other sources conducted calculations based on one of the existing methods to draw general conclusions from case studies on different building types. Contextual differences attributed to the locations at which research is conducted have resulted in a wide array of building typologies that have been examined. For instance, Koezjakov et al. studied Dutch residential typologies [17], Praseeda et al. assessed residential buildings in India [18], and other researchers such as Zhu el al. studied residential typologies in China [19].

An example of published case studies is Bruno Lee's, Marija Trecke's, and Jan Hensen's study of industrial halls [20]. They conducted a comparison between the embodied energy of a simple rectangular industrial hall using three different materials, one fully in steel, one in concrete, and one in a hybrid system, and it was concluded that the all-concrete alternative had a largely greater energy content. By contrast, another report published [21] employed an alternative approach to case studies—breaking down the components of the building under examination and determining the components' corresponding embodied energies. Instead of treating buildings as a whole, this breakdown allowed for the clear identification of the building constituents most responsible for embodied energy content. Taking the research a step further, Lotteau et al. focused primarily on the shape of the building form in order to isolate impacts of circular design on the total embodied energy embedded and a building's carbon emissions [22]. With construction methods and materials differing from location to location, much opportunity lies in studying the topic in other new contexts as well as conducting cross-comparisons between results in residential typologies of countries.

2.2.4. Optimization of Materials

Another series of works acting in parallel to those of the previous two is the attempt to optimize material selection itself when minimizing embodied carbon. Work in this field ranges from the selection of a single material and its optimization to the analysis of certain systems or entire buildings. These works try to identify the components that would result in reduced embodied energy and suggest possible alternatives to functional equivalents with higher energy or carbon contents. Research studies such as that of Venkatarama and Jagadish [23] have tested the variations and differences in embodied energy content in a range of different brick types, mortars, and floor or roof systems. Their conclusions list the different material types tested in order from highest to lowest embodied energy content, the results of which allow for energy-conscious selection of materials by designers. Other studies such as that of Shukla et al. [24] were based on the scale of a home, comparing the embodied energy of an adobe home to that of a traditionally constructed home built out of concrete, cement, and burnt brick. The outcome of the test showed that the use of adobe reduced the embodied energy per 100 m^2 of built-up area by 245 GJ, showing the significance of material selection on the overall energy content. Other researchers such as Ramesh, Yeo et al., and Crishna et al. [25–27] tackled more specific topics local to a particular area: the use of vernacular materials for construction [25], the optimization of reinforced concrete through consideration of the embodied energy within [26], and the amount of embodied energy found in various types of stone used in construction in the U.K. [27]. Looking at the life cycle of buildings, other researchers sought to reduce operational costs and energies by optimizing the choice of materials for different building components. Utama and Gheewala, for instance, examined the use of local building materials and their relationship to reducing the demand for energy in one-landed homes in Indonesia. Their work suggests the use of double-walls with bamboo filling or sugar mill ash for bricks as examples of alternatives to replace materials of higher energy content for walls [28]. A paper of similar direction by Radhi [29] focused on wall-cladding systems, testing the carbon emission reductions in terms of reduced embodied and operational energies. Here the tests are based on a case study building in the United Arab Emirates (UAE) testing a variety of cladding materials. Stucco, aluminum siding, and vinyl siding are among some of the materials tested. Results show a maximum CO_2 reduction when exterior insulation and finishing systems (EIFSs) are used, and the lowest reductions occur when a masonry veneer is used.

2.2.5. Scalability of Methods

Other published works such as that by Emmanuel and Baker look at the larger picture. Davies and Osmani suggested a list a set of "drivers" that could push construction towards a lower embodied carbon content [30]. These suggestions, as discussed by Emmanuel and Baker [31], can be divided into three main categories: financial, technical, and legislative. These "drivers" are a parallel route to carbon reduction in construction. Where research in the reduction of embodied energy and carbon emissions focuses on the micro-scale of an individual building, larger-scale incentives such as these could have a profound effect on neighborhood, district, and city scales. With the implementation of such incentives, research being done in narrower fields could be taken from theory or single case studies to potential large-scale implementation.

2.3. Data and Research Needed Locally

Localizing the literature review to the Middle East and more specifically Egypt, the search identifies a large gap in the published literature. Differences between local building techniques, building materials, their extraction processes, and their maintenance and transportation are all parameters that would significantly alter the expected embodied energies calculated when compared to results conducted in other countries. Differences in construction approaches and techniques reflecting local needs, trends, climatic zones, economic constraints, and material availability are all parameters affecting the embodied energy of a building. When checked against existing studies conducted in other countries such as those done in Australia, India, the U.K., or the U.S., local results would output differences in the final embodied energy and carbon computed.

3. Methods

The local and international literature indicates the need for localized standards for the calculation of embodied energy and the development of a framework for calculation specific to Egypt. This is further confirmed since the optimization of construction materials, alternative construction systems, and even transportation processes locally are contingent on the establishment of a fixed framework or calculation methodology to enable comparison. In the absence of comparative studies locally, a residential apartment building was selected as a case study to calculate the total embodied energy of the building and compare it to similar buildings worldwide. This case study was intended to act as a prototype for the calculation of embodied energy of a building, acting as an initial benchmark to introduce embodied energy calculation in the local research market. Two retrofit scenarios were then studied to understand the impact on carbon emissions using a performance-based calculation method. A set of conclusions and future areas of research to advance this work are documented herein.

3.1. Proposed Framework

The structure of the proposed framework is similar to previous frameworks in the literature, but building life cycle stages were added. The main drivers of embodied energy visible across the building life from construction to obsolescence were made visible. This resulted in three main drivers visible in the framework: energy embodied in construction (CE), energy embodied in transportation (TE), and energy embodied in the material (ME). The calculation method followed a simple data input method using a carbon calculator to output the sum total embodied energy. The framework is comprised of the input building design parameters: the embodied energy component (EE), the operational energy (OE) component, and the output energy component, which is the total of EE and OE (Figure 1).

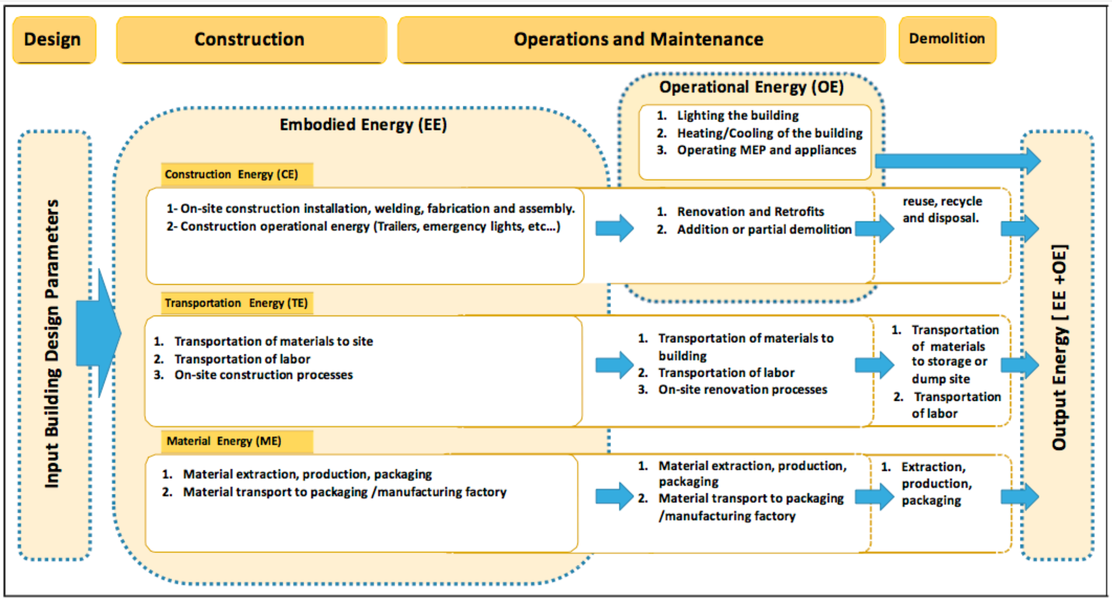

Figure 1. The proposed framework.

3.2. Methodology and Reasoning for Tool Selection

After reviewing a series of calculators available online to calculate the embodied energy and carbon content, the calculator created by the Environmental Agency was selected to conduct the base-line carbon study. Since the assessment of the initial carbon content in the existing residential building is only a portion of determining the impact of the building's entire life cycle, a suitable calculator had to be selected that would fit within the larger framework opted for and explained previously. The calculator provided by the Environmental Agency allowed for the calculation of pure initial embodied energy (irrespective of the operational and demolition energies) and the embodied energy from "cradle to gate" including the carbon emitted during transportation processes.

The spreadsheet calculator provides an extensive list of construction materials within each material category (for example, quarried material as listed below). Materials were broken down into various possible aggregate types—asphalt, clay, and stone types—and were immediately linked with the material's associated carbon coefficient (Table 1). A summary of each individual material's carbon footprint and the category's total impact was generated through the calculator (Table 1).

Since there are no calculators modified specifically to Egypt or the Middle East region, the calculator was used with caution and with awareness that the carbon emission factors embedded will provide results that are not adapted regionally. The basic case study provides a baseline using default embodied carbon coefficients. An adapted version of this material-based calculator could also be developed specifically to Egypt by inputting total material quantities and listing materials in order of those most typically found in local multi-story residential buildings. Embedded within the calculator would also be country-specific embodied carbon coefficients that would enable more accurate results as well as local emission factors for every unit of distance traveled by road, rail, or ship to its final destination in Egypt.

Table 1. Building's quarried materials footprint—Environmental Agency calculator.

Category	Construction Material	Unit Conversion or Density	Embodied tCO_2e per Tonne of Material	Quantity (tonnes)	Distance between Source of Supply and Site (km)	Mode of Transport	Footprint (Tonnes Fossil CO_2e)		
							Embodied	Transport	Sum
Quarried Material	Quarried aggregate	2.0 tonnes/m^3	0.005	**472**	**70**	**Road**	2.360	3.526	5.886
	Recycled aggregate	2.0 tonnes/m^3	0.005				0.000	0.000	0.000
	Marine aggregate	2.0 tonnes/m^3	0.008				0.000	0.000	0.000
	Asphalt, 4% (bitumen) binder content (by mass)	1.7 tonnes/m^3	0.066				0.000	0.000	0.000
	Asphalt, 5% (bitumen) binder content	1.7 tonnes/m^3	0.071				0.000	0.000	0.000
	Asphalt, 6% (bitumen) binder content	1.7 tonnes/m^3	0.076				0.000	0.000	0.000
	Asphalt, 7% (bitumen) binder content	1.7 tonnes/m^3	0.081				0.000	0.000	0.000
	Asphalt, 8% (bitumen) binder content	1.7 tonnes/m^3	0.086				0.000	0.000	0.000
	Bitumen	2.4 tonnes/m^3	0.490	**26**	**1500**	**Road**	12.897	4.213	17.110
	Bricks	1.9 tonnes/m^3	0.240				0.000	0.000	0.000
	Clay: general (simple baked products)	1.9 tonnes/m^3	0.240	**5168**	**70**	**Road**	1240.320	38.607	1278.927
	Clay tile	2.4 tonnes/m^3	0.480	**175**	**70**	**Road**	84.096	1.309	85.405
	Vitrified clay pipe DN 100 & DN 150	2.4 tonnes/m^3	0.460				0.000	0.000	0.000
	Vitrified clay pipe DN 200 & DN 300	2.4 tonnes/m^3	0.500				0.000	0.000	0.000
	Vitrified clay pipe DN 500	2.4 tonnes/m^3	0.550				0.000	0.000	0.000
	Ceramics: general	1.9 tonnes/m^3	0.700	**23**	**140**	**Road**	15.960	0.341	16.301
	Ceramics: Tiles and Cladding Panels	2.2 tonnes/m^3	0.780	**35**	**140**	**Road**	27.456	0.526	27.982
	Sand	1.2 tonnes/m^3	0.005	**275**	**70**	**Road**	1.401	2.053	3.454
	Soil - general / rammed soil	1.7 tonnes/m^3	0.024				0.000	0.000	0.000
	Stone: general	2.0 tonnes/m^3	0.079				0.000	0.000	0.000
	Granite	2.9 tonnes/m^3	0.700	**73**	**870**	**Road**	50.750	6.731	57.481
	Limestone	2.2 tonnes/m^3	0.090				0.000	0.000	0.000
	Sandstone	2.2 tonnes/m^3	0.060				0.000	0.000	0.000
	Shale	2.7 tonnes/m^3	0.002				0.000	0.000	0.000
	Slate	2.7 tonnes/m^3	0.035				0.000	0.000	0.000
	Sub-total			**6247**			**1435.2**	**57.3**	**1492.5**

3.3. Performance-Based Evaluation (PBE)

To encourage the usage of performance-based evaluation (PBE) of the existing buildings, it is essential to shift the current regulatory systems from a prescriptive to a performance-based approach. A prescriptive approach "describes the way [in which] a building asset has to be constructed instead of the ends of the building process, and it is related with type and quality of materials, method of construction, [and] workmanship." Such an approach is strictly mandated by law, codes, standards, and regulations, and it is based on past experience and consolidated know-how. Using a PBE approach does not preclude the use of prescriptive specifications. Although the benefits of the adopting of a PBE approach are significant, it is recognized that employing a performance-based approach at any stage in the building process is more complex and more expensive than using a simpler prescriptive route. Thus, the application of this approach should not be regarded as an end in itself. When simple buildings are concerned or well-proven technologies are used, the use of prescriptive codes is more effective, more efficient, faster, or less costly, so prescriptive specifications will continue to be useful in many situations. Therefore, to better utilize the above framework, a newer generation of tools is required to have the ability to simulate not only the operational energy but also the overall LCE inclusive of the EE and OE through the integration of both carbon calculators and performance-based simulation tools (Figure 2).

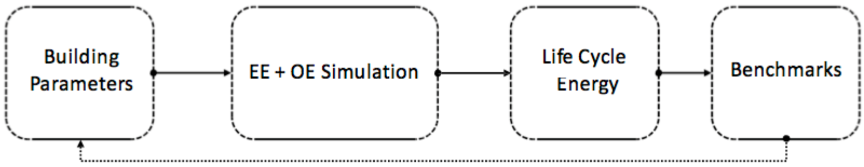

Figure 2. A performance-based evaluation (PBE) approach.

4. Results

4.1. Building Information

The case study is comprised of a four-story residential building located in New Cairo, Egypt. New Cairo is considered to have a desert climate. There is virtually no rainfall during the year, and the climate is classified as Group B: Hot desert climate (BWh) by the Köppen–Geiger system. The average annual temperature is 20.8 °C, and about 28 mm of precipitation falls annually. The building consists of 40 apartments ranging from 100 to 204 m^2 each, amounting to a total area of 6339 m^2 of net usable residential space. Other spaces encompassed within the building include an underground garage and storage, a main lobby area, outdoor gardens, and a laundry facility to serve the residents, totaling a final area of 12,610 m^2. The structural design of the building is a standard reinforced concrete skeleton structure with exterior and interior brick walls, typical of Egypt. The envelope of the building consists of red-brick external walls (25 cm in thickness) that are held together using ordinary mortar ("Portland cement"). In terms of finishing, the exterior wall finish is coated with plaster and three coats of paint. Doors within the building are divided into three material types: metal doors, aluminum doors, and wooden doors. Windows are all made of aluminum, and aluminum screens are used throughout the building complex to regulate the amount of direct sunlight allowed into the building. An initial baseline energy evaluation of the building using the ENERGY STAR Portfolio Manager [32] indicates a baseline score of 83 for the building and a Green House Gas (GHG) emission intensity of 58.9 (Table 2).

Table 2. Baseline energy evaluation using Energy Star.

Metrics Summary		
Metric	**Aug 2018 (Energy Baseline)**	**Aug 2018 (Energy Current)**
ENERGY STAR Score (1–100)	83	83
Source EUI (GJ/m^2)	1.3	1.3
Site EUI (GJ/m^2)	0.47	0.47
Energy Cost ($)	Not Available	Not Available
Total GHG Emissions Intensity (kgCO_2e/m^2)	58.9	58.9
Water Use (All Water Sources) (m^3)	6865.90	6865.90
Total Waste (Disposed and Diverted) (Metric Tons)	Not Available	Not Available

Furthermore, the data entry into the selected Environmental Agency calculator indicates carbon emissions to be at 3663.8 tons of fossil CO_2e broken down as shown in Figure 3. According to the calculation method, the emissions are estimated to be within ±25% of the actual expected value. Comparing the results to similar calculations conducted by other research entities, the results seem to fall within acceptable ranges (Figure 4). It should be noted, however, that the calculators again use U.S.-based backend data regarding emissions and transportation and would require adjustment to location-specific data on energy and materials used locally for more accurate results.

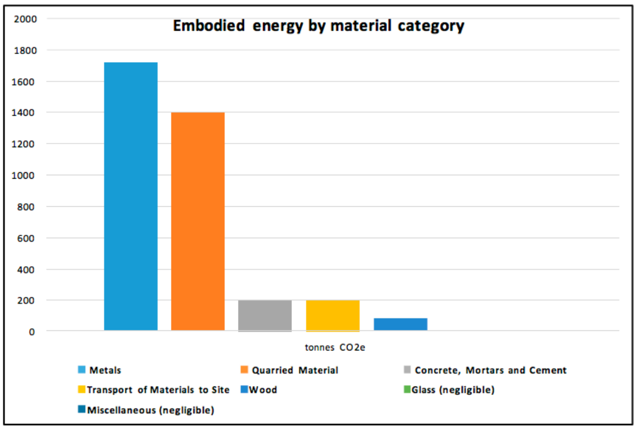

Figure 3. Embodied energy (EE) by material category.

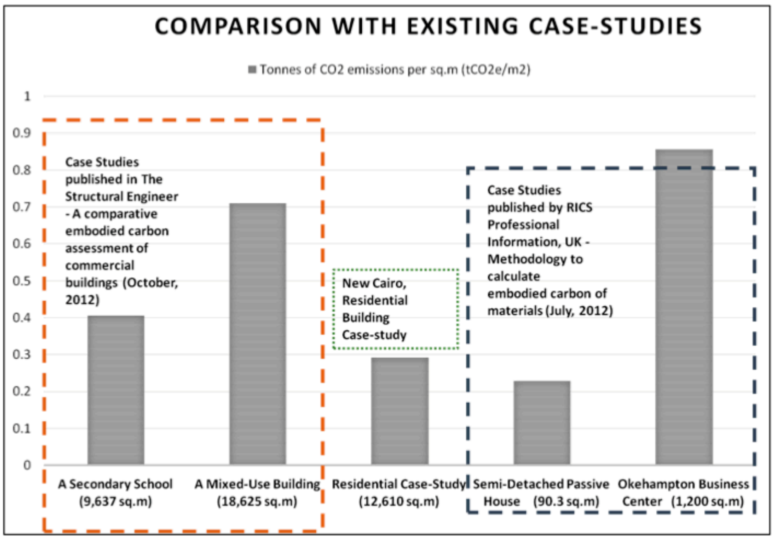

Figure 4. Comparison with existing case studies.

4.2. Limitations Faced and Assumptions Made

Limitations faced while conducting the case study included the absence of a tool specific to Egypt. Differences in geographic location signify differences in local materials, local production processes, and the amounts of carbon emitted in transportation and energy production. These differences result in carbon emission coefficients that differ from region to region and would therefore require tailored calculators that use regionally suitable coefficients. Emission factors tabulated by the ICE—Inventory of Carbon Emissions—are specific to processes and emissions in the U.K. This therefore indicates an expected inaccuracy in results when using the calculator for a building in the Middle East. Furthermore, among the inconveniences that were encountered while conducting calculations, reported quantities were rarely reported as a weight. Instead, reported quantities varied in units (square meters, linear meters) and in the number of individual units, all of which had to be converted to obtain the tonnage of materials used. Where sufficient specifications were not provided, realistic assumptions were made with regard to any missing dimensions. As paints were reported in term of surface area coverage, a standard assumption was made that every liter of paint covers an area of 12 m^2. Regarding the sources of the materials, where clear reference to the origin of the material was not made and where re-tracing the specific origin of the batch of material on-site was not possible, an acceptable assumption was made from among a list of known places of import. Accordingly, steel was assumed to be imported from China arriving by boat through the Ain Sokhna Port. Aluminum was assumed to be coming in from a production facility 100 km North of Luxor, totaling a transportation distance of about 578 km to the site. Similarly, glass was assumed to be brought in from a production facility in Ain el Sokhna, which is 140 km from the point of origin.

5. Discussion and Further Research

Throughout the research process, several gaps in the field of embodied energy were identified. Among topics of further potential research and study are the following:

1. The establishment of a parallel carbon emission coefficient inventory, such as that of the University of Bath (ICE—Inventory of Carbon and Energy), that is specific to the local region [33];
2. Alternatives to high embodied energy construction materials that are currently extensively used in the Egyptian construction market such as reinforced concrete slabs, cement mortars, and burnt clay bricks;
3. The search for alternative, renewable resources to substitute current high carbon content energy sources (high embodied energy does not necessarily mean high embodied carbon);
4. The creation of a set of guidelines for designing low embodied energy buildings;
5. Advancement of the capabilities of simulation tools to cover a wider scope of the building life cycle.

To enable more accurate results, calculators using embodied carbon coefficients specific to the region would need to be used. In addition, they could be pre-set to a typical structural system according to the building type of each region to further simplify calculation processes. The calculator below illustrates a proposed template for multi-story buildings in Egypt. The proposed method separates the embodied carbon found in the building skeleton and envelope (Table 3) from the building's interior finishing (Table 4) and uses a typical reinforced concrete column and slab structure as a pre-set default. The building is further broken down into individual building components to enable the calculation and separation of total embodied energy by component. This enables the clear identification of building components with the highest embodied energy totals and highlights those that would result in the highest embodied energy reductions if optimized.

Table 3. Calculation of EE in building skeleton and envelope (by building component).

	Building Skeleton + Envelope								**Total Embodied (per Component)**	**TOTAL EE/Skeleton + Envelope**
	Component	**Total**	**Layers/Elements**	**Distance from Source**	**Mode of Trasport**	**Quantity (per 1)**	**EE Coefficient**	**EE (per 1)**		
Typical Multi-Storey Residential Building	RC Floor Slabs	5	Steel		Road/Rail/Ship	in m^3	coefficient - steel		X	The Skeleton + Envelope's Total Embodied Energy (XXXX)
			Concrete		Road/Rail/Ship		coefficient			
			Insulation		Road/Rail/Ship					
			Cement		Road/Rail/Ship					
	RC Columns	30	Columns		Road/Rail/Ship				Y	
			Material layer 2		Road/Rail/Ship					
			Material layer 3		Road/Rail/Ship					
	Exterior Walls	(in meters run)	Bricks		Road/Rail/Ship				Z	
			Mortar		Road/Rail/Ship					
			Cladding		Road/Rail/Ship					
	Doors	(no. of doors)	Wood		Road/Rail/Ship				X1	
			Hinges		Road/Rail/Ship					
			Handles		Road/Rail/Ship					
	Window Type 1	(no. of windows)	Alumninum 1		Road/Rail/Ship				Y1	
			Hinges		Road/Rail/Ship					
			Handles		Road/Rail/Ship					
	Window Type 2	(no. of windows)	Alumninum 2		Road/Rail/Ship				Z1	
			Hinges		Road/Rail/Ship					
			Handles		Road/Rail/Ship					
	External Shading	(no. of structures)	Material layer 1		Road/Rail/Ship				X2	
			Material layer 2		Road/Rail/Ship					
	Additional Comp. 1	(no.)	Material layer 1		Road/Rail/Ship				Y2	
			Material layer 2		Road/Rail/Ship					
	Additional Comp. 2	(no.)	Material layer 1		Road/Rail/Ship				Z2	
			Material layer 2		Road/Rail/Ship					
	Other	(no.)	Material layer 1		Road/Rail/Ship				X3	

Table 4. Calculation of EE in building fixed and interior finishing (by building component).

	Building Fixed - Interior Finishing								Total Embodied (per Component)	TOTAL EE/ Interior
	Component	**Total**	**Layers/Elements**	**Distance from Source**	**Mode of Trasport**	**Quantity (per 1)**	**EE Coefficient**	**EE (per 1)**		
Typical Multi-Storey Residential Building	Interior Walls	15 m (in plan)	Brick		Road/Rail/Ship	in m^3	coefficient - steel		X	Interior Finishing Embodied Energy (XXXX)
			Cement		Road/Rail/Ship					
			Paint 1		Road/Rail/Ship					
			Paint 2		Road/Rail/Ship					
	Interior Partitions	3 m (in plan)	Material layer 1		Road/Rail/Ship				Y	
			Material layer 2		Road/Rail/Ship					
			Material layer 3		Road/Rail/Ship					
	Living Room Finishing	in m^2	Sand		Road/Rail/Ship	kg/tonnes (per m^2)	coefficient - sand		Z	
			Cement		Road/Rail/Ship	kg/tonnes (per m^2)	coeff. - cement			
			(Select) Final Finish		Road/Rail/Ship					
	Bedroom 1 Surface Finishing	Ceiling (Area m^2)	Paint type 1		Road/Rail/Ship				XX	
		Wall Surface (Area m^2)	Paint type 2		Road/Rail/Ship					
		Floor Finish	Sand		Road/Rail/Ship					
			Cement		Road/Rail/Ship					
			(Select) Final Finish		Road/Rail/Ship					
	Bathroom 1 Surface Finishing	Ceiling Paint	Paint type 2		Road/Rail/Ship				YY	
		Wall Finish	Cement		Road/Rail/Ship					
			Ceramic Tiles		Road/Rail/Ship					
		Floor Finish	Sand		Road/Rail/Ship					
			Cement		Road/Rail/Ship					
			(Select) Final Finish		Road/Rail/Ship					

Table 4. *Cont.*

	Building Fixed - Interior Finishing								Total Embodied (per Component)	TOTAL EE/ Interior
	Component	**Total**	**Layers/Elements**	**Distance from Source**	**Mode of Trasport**	**Quantity (per 1)**	**EE Coefficient**	**EE (per 1)**		
Typical Multi-Storey Residential Building	Bedroom 2 Surface Finishing	Ceiling (Area m^2)	Paint type 1		Road/Rail/Ship				XX	Interior Finishing Embodied Energy (XXXX)
		Wall Surface (Area m^2)	Paint type 2		Road/Rail/Ship					
		Floor Finish	Sand		Road/Rail/Ship					
			Cement		Road/Rail/Ship					
			(Select) Final Finish		Road/Rail/Ship					
	Bathroom 2 Surface Finishing	Ceiling Paint	Paint type 2		Road/Rail/Ship				YY	
		Wall Finish	Cement		Road/Rail/Ship					
			Ceramic Tiles		Road/Rail/Ship					
		Floor Finish	Sand		Road/Rail/Ship					
			Cement		Road/Rail/Ship					
			(Select) Final Finish		Road/Rail/Ship					
	Kitchen Surface Finishing	Ceiling (Area m^2)	Paint type 1		Road/Rail/Ship				XX	
		Wall Surface (Area m^2)	Paint type 2		Road/Rail/Ship					
		Floor Finish	Sand		Road/Rail/Ship					
			Cement		Road/Rail/Ship					
			(Select) Final Finish		Road/Rail/Ship					
	Other	Material layer 1	Material layer 1		Road/Rail/Ship				Z1	

6. Conclusions

The significance of embodied energy has not yet been addressed in full in Egypt. As its importance grows internationally, however, investment in local research on the topic will become more needed. Furthermore, research on embodied energy is especially important in a hot country such as Egypt, where its ratio with respect to the total life cycle energy, compared to an equivalent building in a colder country, is larger. As a result, the development and optimization of calculators similar to those proposed in this paper will be key to easing embodied energy calculations with respect to the local market and to a more widespread engagement with the topic. Further engagement would also allow designers, developers, and contractors to attempt the decarbonization of buildings as per the categories and stages summarized below.

6.1. Decarbonizing Existing Buildings

When decarbonizing a building, it is important to note that a building passes through many processes before reaching the end of its lifetime and its point of demolition or reuse. At each of these stages, different mechanical and non-mechanical processes take place, each of which consume energy and add to the total embodied energy content. With all these processes taking place, there is ample opportunity at each of these instances to reduce the amount of energy being expended and the amount of carbon being embedded.

6.1.1. Decarbonization of Operational Energy Processes

When looking at existing buildings, because the possibilities in terms of material replacement are limited, most research has focused on the reduction of carbon content through the reduction of operational energy. Amidst the limited amount of work on decarbonizing existing buildings, research explaining different methods of reducing energy consumption in buildings is limited. Depending on local climatic conditions, heating and cooling load reductions are approached differently. Other aspects, however, remain the same for all regions. Among the recommendations made are the installation of control systems that allow users to monitor and adjust temperatures according to their needs, the replacement of high energy consuming lights by installing low carbon emitting light sources such as LED lamps, and the use of more efficient appliances, electronic devices, and machinery. In temperate, cooler climates, the addition of insulation to all large surfaces to reduce heat loss is also a major factor. According to the Energy Saving Trust [34], the insulation of walls, lofts, and flooring, in that order, contributes the most to savings in terms of carbon emissions when compared to the insulation of other elements. It can be placed internally or externally depending on the building type and height, and windows can be secured through the installation of secondary glazing systems, the use of double glazing or triple glazing, and draught-proofing against unintended leakages. While in cooler, more temperate climates the focus is on reducing heat from escaping, in hot climates the goal is to increase air movement and prevent more heat from entering. The use of vegetation and shading structures to increase airflow through reduced temperatures around the building is essential. Furthermore, vegetation-based solutions are among the recommendations made to reduce heat admitted into buildings and can be employed in the form of surrounding vegetation, planting roof gardens, and the use of landscape. Water features on the roof are also highly recommended to prevent exposed roof surfaces. Vegetation on the roof is in fact recommended in both hot and cold climates.

6.1.2. Decarbonization of Material Energy and Construction Processes

In an existing building, the flexibility and impact of this section is relatively limited because the building has already undergone most construction processes and materials have already been consumed. However, potential exists during maintenance and refurbishment. Below are some recommendations that can be conducted during refurbishment.

1. Materials in need of replacement can be exchanged with similar materials of lower embodied energy and carbon emissions. These materials could be sourced locally to reduce transport energy, could have low extraction energies, and may have low processing energies. In addition, they would preferably have an expected lifetime as long as the expected lifetime of the building or longer and/or would be capable of being reused or recycled at the end of the building's lifetime.
2. Construction processes during all maintenance works should be kept as minimal as possible without endangering the safety of the building (which would then require more intervention).
3. All minor and major works should employ minimal energy expenditures.

6.1.3. Decarbonization of Demolition Processes

The end of the building life cycle is reached when the building under consideration undergoes demolition or when its original components are reused or recycled towards a new building or purpose. For an existing structure whose structural system and materials are already in existence, decarbonization can be employed by demolition and disassembly processes that are as energy- and time-efficient as possible. A low energy consuming technique of disassembly over a long period of time could very well amount to the same amount of energy expended by a high energy content demolition method; hence, the factor of time is an important consideration.

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