

Article

Life Cycle Assessment of a Three-Bedroom House in Saudi Arabia

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Abstract: The building sector is one of the crucial stakeholders in the global energy and environmental scenario. Life cycle assessment (LCA) is a tool widely used to evaluate the environmental performance of buildings, materials and activities. Saudi Arabia has a rapidly growing construction sector with over \$1 Trillion of ongoing projects. The housing sector, annually needing over 2.32 million new residential units in coming years, is yet to entertain environmental performance of buildings in its list of priorities. The present work undertakes a LCA study of a three-bedroom modern villa located in Dhahran. Providing the structural details of the villa, an account of the 18 main construction materials in terms of quantity and application has been produced. Embodied energy of these materials has been estimated adopting ‘cradle-to-gate’ approach. Environmental impacts of the materials have been modeled with the help of SimaPro software. The results suggest that concrete accounts for more than 43% of the total embodied energy of the house and is also the predominant material in terms of the overall environmental impacts. Steel is the second most prominent material both in terms of quantity and embodied energy.

Keywords: buildings; sustainability; life cycle assessment; embodied energy; environment; materials

1. Introduction

The world faces stringent environmental challenges of which global warming is the most significant. Over the last century, the global atmospheric temperature has grown by 0.5 °C due to an increased concentration of greenhouse gases (GHG) [1]. Forecasts suggest that unless a serious collective effort is made at the global level, the average atmospheric temperature is expected to further rise by as much as 6 °C by the end of this century [2]. The rise in sea level due to the melting of glaciers is one of the most prominent implications of global warming. Estimates suggest that Antarctica is now annually losing around 160 billion tonnes of ice to the ocean, which is twice previous findings [3]. Climate change as a result of global warming is resulting into wide ranging problems such as seasonal disorder, a pattern of intense and more frequent weather related events such as floods, droughts, storms, heat waves and forest fires. It has been reported that since the advent of the 20th century natural disasters such as floods, storms, earthquakes, bushfires have resulted in an estimated loss of nearly 8 Million lives and over \$7 Trillion of economic loss [4,5]. Future projections suggest that by the year 2060 more than one Billion people around the world might be living in areas at risk of devastating flooding due to climate change [6]. The year 2016 was recorded as the warmest year on

record and the first six months were the planet's warmest half-year since records began in 1880 [7–9]. The average atmospheric temperature in 2016 was recorded to be 1 °C warmer than in the middle of the 20th century and 1.3 °C warmer than in the late 19th century. Also 2016 was the 3rd year in row to set a new record for atmospheric temperature [10]. Realizing the need for a paradigm shift in human activities contributing to global warming, countries across the world are placing an ever greater emphasis on sustainable development. In this respect, through the Paris Agreement, 195 countries have adopted the first-ever universally legally binding global climate deal to avoid dangerous climate change by limiting global warming to well below 2 °C [8].

Buildings, accounting for over 40% of energy use and more than one third of the total GHG emissions at the global level, play a critical role in the global energy and environmental scenario [11–15]. A building consumes energy in its entire life i.e., from construction to decommissioning. This use of energy during a building's life cycle is direct as well as indirect. The direct use of energy encompasses construction, operation, maintenance, renovation, and demolition of a building; whereas the indirect use of energy is related to the production of materials used in construction and installation of equipment [16,17]. The operational phase of buildings is the most significant in terms of life cycle energy consumption. The use of energy in the operational phase has been reported to vary between 40% and 90% depending on various factors including climatic conditions and user behavior [18,19]. For example, in China, residential and office buildings have been reported to be respectively consuming 55% and 78% of their total life cycle energy during their operations [18]. In another case study the operational phase has been reported to be respectively representing 73% and 64% of the life cycle energy and CO₂ emissions [20]. A study in Australia reports the operation of residential buildings to be responsible for 65–90% of the total life cycle energy consumption [19]. In Saudi Arabia, the operational phase of buildings account for almost 80% of the total electricity consumption at the national level [21]. Estimates suggest that since the 1970s the worldwide rate of growth of carbon dioxide (CO₂) emissions has grown at an annual rate of 2.5% and 1.7% for commercial and residential buildings respectively [22,23]. The buildings sector is also responsible for significant non-CO₂ GHG emissions such as halocarbons, CFCs, and hydrofluorocarbons (HFCs). It is also estimated that, in a business as usual scenario, GHG emissions from buildings are likely to more than double in the next 20 years. It is therefore evident that if the desired targets for GHG emissions reductions are to be met, emissions from the building sector need to be greatly reduced. It is vital that, while adding to the overall stock of buildings, the impacts on climate change during the entire life cycle of buildings are mitigated. The building sector has the greatest potential for reducing GHG emissions in comparison to other major emitting sectors. Estimates suggest that with the reliable and commercially available solutions, energy demand in both new and existing buildings can be cut by 30% to 80% [11].

Life cycle assessment (LCA) is one of the most effective tools being used to improve the energy and environmental profiles of buildings. LCA provides a material and energy balance over the entire life of a material, product or service, determining its interaction with its environment, and assessing its impacts on the environment. There have been a number of LCA tools developed in advanced countries to investigate the energy and environmental performance of materials and activities and to help in decision making by comparing available options [24]. For its effectiveness, LCA is an important part of building and construction projects in the developed world [25]. The academic and research community is also paying significant attention to the LCA studies. Ma et al. have studied the LCA of energy consumption and CO₂ emissions for an office building [20]. Zhang and Wang discuss a hybrid input-output analysis for life-cycle energy consumption and carbon emissions from buildings [26]. Hong et al. have investigated the life cycle energy consumption of buildings using a multi-regional hybrid approach [18]. Heravi et al. examined the energy use during the production and construction of concrete and steel for residential buildings [21]. Guan et al. provided life cycle energy analysis of eight different residential buildings in Australia [19]. Mastrucci et al. have provided a review of LCA studies investigating the environmental impacts of building stocks at several scales, from urban to transnational [27].

The Kingdom of Saudi Arabia (KSA) is the largest country in the Gulf Cooperation Council (GCC) region. It has a sizable and fast growing building sector that is heavily contributing to the energy and environmental stresses facing the country. The country is yet to embrace building sustainability trends and practices. Integration of LCA in building practices can be an effective tool in this respect. The concept of LCA, however, is virtually new to the Saudi construction industry. There is also a clear gap in academic and research work in terms of LCA studies on the building sector of KSA or even neighboring countries in the GCC region with similar construction practices. The present study is therefore a novel and much needed contribution to the knowledge base in the field of LCA. It aims to undertake a LCA of a modern 3-bedroom house in Saudi Arabia focusing on the construction materials. The main objectives of the work are to:

- Carry out an audit of materials involved in the construction of the house
- Quantify the embodied energy of the house
- Examine the associated environmental impacts

The present work undertakes an LCA study of a three bedroom semi-detached villa located in the Dhahran region of Saudi Arabia. It involved both empirical data collection and analysis as well as modelling work. The primary data on the materials involved in the construction process, application of materials and structural details has been collected from the project file including bill of quantity (BOQ). Data was also collated through studying audit reports/records and interviewing relevant personnel including project director, contractor and construction engineer. SimaPro software has been used to model the environmental impacts of the house.

2. LCA and Scope of the Study

Every product, system or activity imposes certain environmental impacts at various stages of its life cycle as indicated in Figure 1. Life cycle assessment (LCA) is a useful tool that serves many purposes such as to: identify ingredients, processes and systems having major contribution in terms of environmental impacts; compare the available options with the aim of minimizing environmental impacts; guide on long-term and strategic planning towards trends in materials and product design. LCA provides a material and energy account covering the full life of an object, activity or service, investigating its interaction with environment. Importance of LCA has been growing in the construction industry across the world. Since LCA adopts a comprehensive and systemic approach to determine environmental performance, it is attracting huge interest across the world by the building and construction sector not only to select environmentally preferable products but also to evaluate and optimize processes and techniques [23,24].

Life cycle assessment can be defined as a process to calculate the environmental impacts related to a product or system by identifying and describing the material and energy used, and wastes released to the environment. The analysis covers the entire life cycle of the product or system, encompassing, extraction and processing of materials; production; distribution; use; maintenance; recycling and final disposal [25]. Generally, a complete life cycle study incorporates four interactive steps: planning; inventory analysis; impact assessment and improvement analysis [28,29]. The International Organization for Standards (ISO) in the ISO 14044 standard describes the four LCA stages as: goal and scope definition; inventory analysis, impact assessment and interpretation [30]. The results and findings of LCA studies are dictated significantly by their planning phase that defines the aim, objectives and the boundaries of investigation. The results also depend on the inventory analysis. The environmental impacts affiliated with energy consumption, for example, vary from one country to another depending on energy mix from different sources i.e., thermal, nuclear and hydropower. LCA studies may vary significantly in terms of their scope and boundaries. For example, the boundaries of LCA studies have varied in terms of focusing on the complete life cycle of a building or a part of it [21,26–28]. In terms of scope, LCA studies have also varied to focus on an individual building material, a set of materials or the complete range of materials needed in a building [31–33]. Similarly,

LCA studies of buildings have also been carried out concentrating individually on the associated energy, environmental impacts or both of these together [19–21].

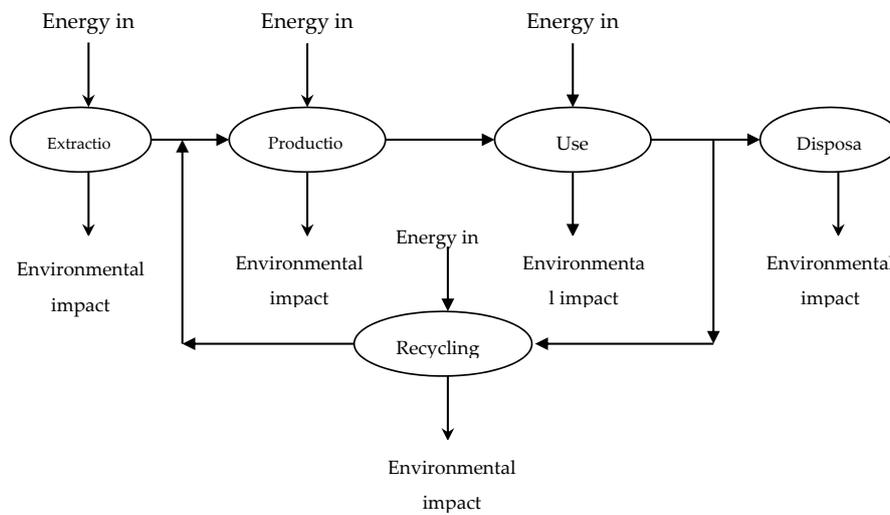


Figure 1. Basic life cycle of a material highlighting the ‘cradle to grave’ approach.

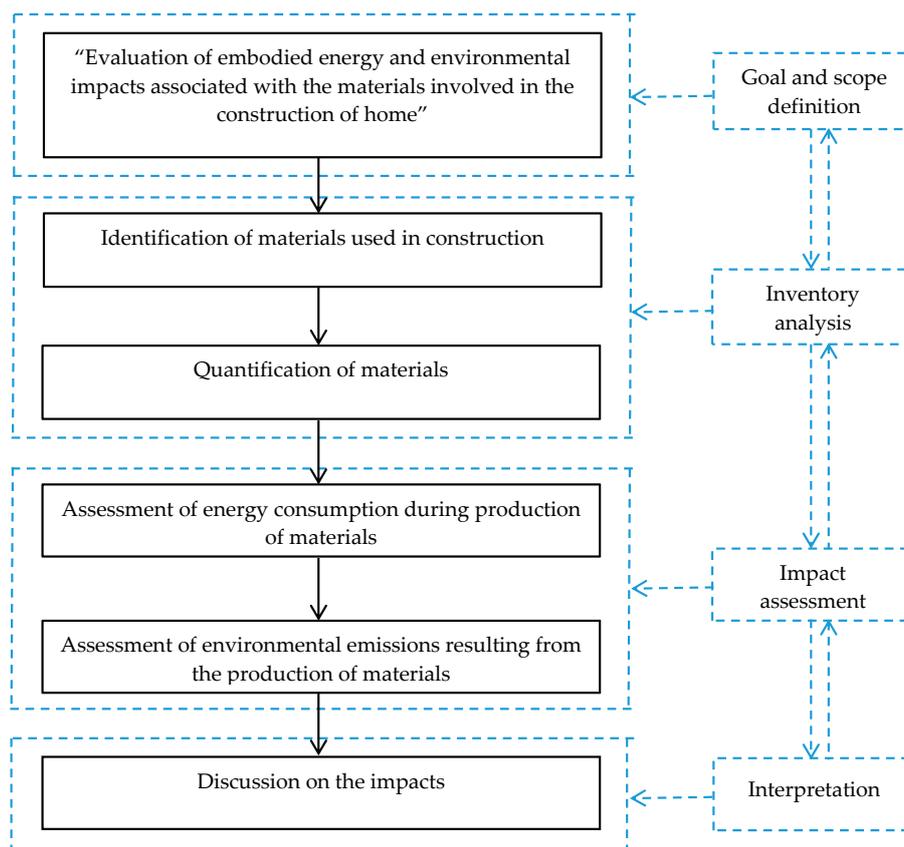


Figure 2. Methodology of the life cycle assessment (LCA) study.

In terms of scope, the present LCA work adopting ‘cradle-to-gate’ approach examines the construction phase of a 3-bedroom house in Saudi Arabia in terms of the involved material and their embodied energy as highlighted in Figure 2. The audit of the materials involved in the construction has been undertaken with the help of bill of quantity (BOQ) file, site surveys, interviews and discussions

with contractors and project management team. The BOQ file was found to be having issues like missing information and lack of clarity about some of the materials and their use. Site surveys, and interviews and discussions with the project team helped to address these gaps. Embodied energy and environmental impacts associated with the construction materials have been investigated with the help of SimaPro software (SaaS, Brisbane, Australia). The functional unit in the study is 1 m² of net floor area.

3. House Structural Details

The 3-bedroom house being studied in this study is within the King Fahd University of Petroleum and Minerals (KFUPM) situated in the Eastern Province of Saudi Arabia. KFUPM has a huge campus encompassing teaching and administration blocks, residences for faculty, staff and students, schools, community centers, warehouses and workshops. Building plans, elevations and section of the studied house are respectively provided in Figures 3–5. Details of the building structural features and key systems are provided in Table 1.

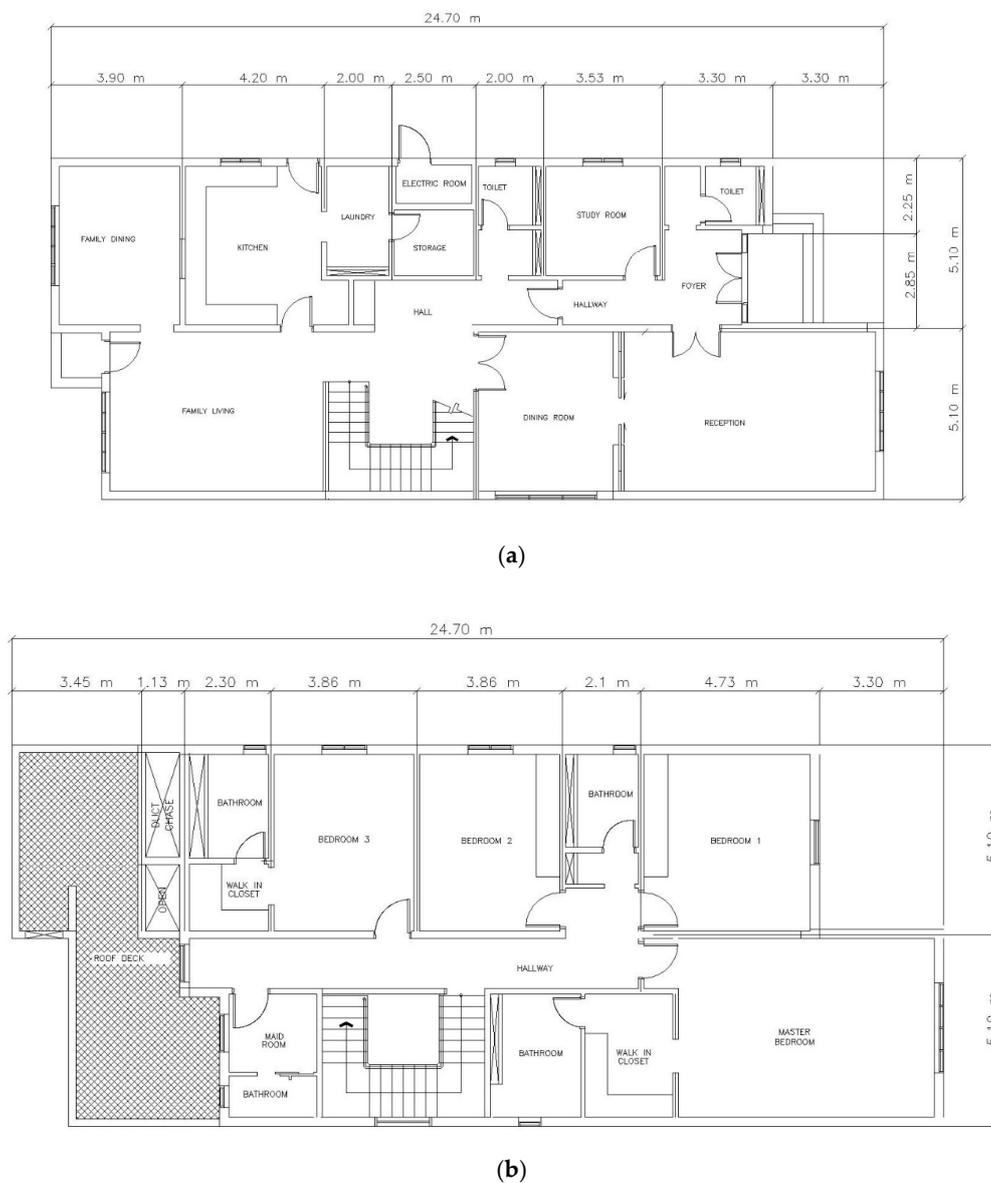


Figure 3. Building floor plans. (a) Ground floor; (b) First floor.

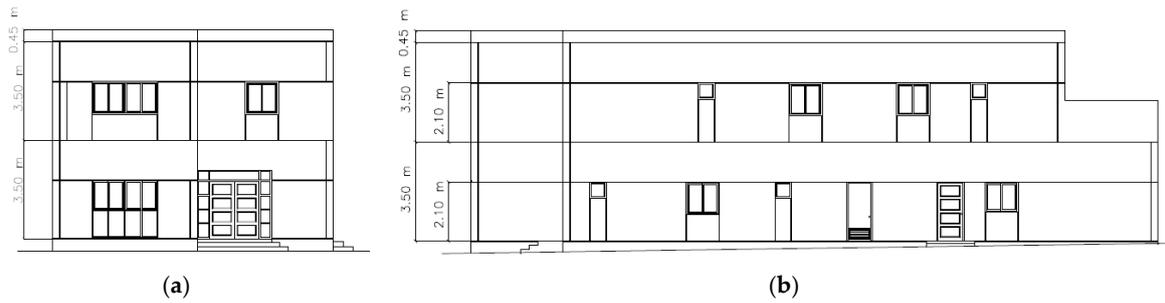


Figure 4. Building elevations. (a) Front elevation; (b) Side elevation.

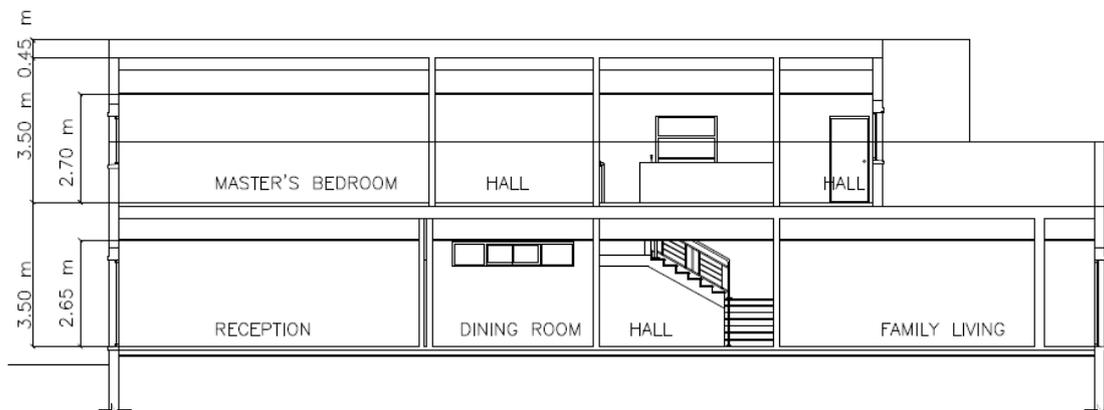


Figure 5. Section view of the house.

Table 1. Main structural details of the house.

Building Features	Description
Location	Dhahran (Coordinates: 26.27° N, 50.15° E)
Orientation	East facing front elevation
Shape	Rectangular
Celing Height	3.5 m
Floor Area	367.3 m ² (Gross); 210.0 m ² (Ground Floor); 167.3 m ² (First Floor)
Window Wall Ratio	10%
Foundation	Continuous concrete footing for the perimeter wall and isolated concrete footings
Floors	Ground floor: 125 mm reinforced concrete slab; first floor: 300 mm reinforced concrete slab; finishing: rooms: porcelaine tiles; bathrooms and kitchens: ceramic tiles
Exterior Walls	16 mm Plaster (Dense) + 100 mm Concrete Block (Medium) + 50 mm Extruded Polystyrene + 100 mm Concrete Block (Medium) + 13 mm Plaster (Lightweight)
Interior Walls	200 mm CMU; 150 mm CMU without insulation; plaster from both sides
Roof	40 mm Concrete Tiles + 0.2 mm Polyethylene + 50 mm Extruded Polystyrene + 4 mm Bitumen Felt + 59 mm Cement Screed + 300 mm Reinforced Concrete (Cast, Dense)
Windows	Double glazed aluminium, 4 mm tinted glass–12 mm air gap–4 mm tinted glass
HVAC	Two package units (Constant-Volume DX AC) each serving one floor

CMU: Concrete masonry units; DX: Direct expansion; AC: Air conditioner.

The selected house, built in 2013, is a typical modern villa. It represents the vast majority of residential buildings in the country in terms of construction material.

4. Materials

The house studied in this study has concrete based structure. External walls are made of concrete masonry units (CMU) while reinforced concrete is used for roofs, columns, beams and stairs etc. Other materials with significant contribution include steel, aluminium glass, wood, polyvinyl chloride (PVC), insulations, paints, ceramic and cement tiles and galvanized iron sheets. Inventory of the materials used in the construction of the house has been mainly obtained from the project BOQ file. Building drawings and project specification, manufacturer products description and published standards were also consulted. The process of calculating the material quantities was not straight forward because important details were missing from the BOQ file. Missing details have been acquired through interviews and discussion as well as standards and guidelines. Details of the 18 main employed materials have been provided in Table 2 along with their application and quantity.

Table 2. Overview of building material inventory.

	Material/Component	Usage	Unit	Quantity	Density (kg/m ³)	Weight (kg)
1	Concrete	Ready mix concrete (roof, columns, beams, footings, stairs)	m ³	413.2	2450	1,012,340
2	Steel re-bars	Reinforcement (structural elements)	m ³	-	-	32,173
3	Concrete masonry units (CMU)	Exterior and interior walls	PCs	26,350	12.4 kg/block	327,450
4	Glass	Windows	m ³	0.36	2500	900
5	Aluminum	Framing	m ³	0.13	2700	361
6	Wood	Doors and cabinets	m ³	4.91	800	3928
7	Porcelain	Room tiles	m ²	575	25 kg/m ²	14,375
8	Ceramic	Bathroom and kitchen tiles	m ²	331	12 kg/m ²	3972
9	Cement	Rooftop tiles	m ³	12	2400	28,800
10	Plaster	Exterior and interior walls	m ³	70.5	1800	126,900
11	Gypsum	Wall and ceiling	m ³	3.74	12.3	46
12	Polystyrene (EPS)	Thermal insulation	m ³	58.9	32	1885
13	Fiber board	Ducting	m ³	17.8	48	854
14	Polyethylene	Vapor barrier (foundation and roof)	m ³	0.1	955	95.5
15	Bitumen					
	Membrane	Water proofing (envelop)	m ²	825	4.7 kg/m ²	3878
	Paint	Water proofing (foundation)	L	-	-	2800
16	Galvanized iron sheets	Duct work	m ²	279	6.2 kg/m ²	1728
17	Paint					
	White Paint	Interior	m ²	1577.8	-	160
	Textured paint	Exterior	m ²	620.54	-	591
18	Polyvinyle chloride (PVC)—plumbing	Sewer pipe, potable and hot water system, gas piping system	m	3809	-	3308

5. Embodied Energy

An embodied energy analysis of the materials has been carried out using ‘cradle to gate’ boundary conditions. Embodied energy values are calculated in SimaPro (v: 8.05.13) using Cumulative Energy Demand method 1.04. Some of the materials are used in more than one form. Concrete, for example, is used as concrete masonry units as well as ready mix reinforced concrete. Similarly bitumen is used as membrane as well as spray paint. The material audit reveals that concrete is the single largest material both in terms of mass and embodied energy as shown in Table 3. Overall, concrete accounts for over 43% of the total embodied energy followed by steel that has a share of over 19% as shown in

Figure 6. In terms of embodied energy per unit mass, however, concrete and plaster have least values while polystyrene is on the top of the list.

Table 3. Embodied energy of materials involved in house construction.

Material/Component	Weight (kg)	Embodied Energy (MJ)
Concrete	1,012,340	1,692,805
Plaster	126,900	221,039
Steel re-bars	32,173	74,7732
Cement	28,800	60,971
Ceramics	18,347	240,081
Bitumen	6678	276,677
Wood	3928	45,135
Polyvinyle chloride (PVC)—plumbing	3308	267,668
Polystyrene (EPS)	1885	199,495
Galvanized iron sheets	1728	6818
Glass	900	11,804
Fiber board	854	33,185
Paint	751	56,022
Aluminum	361	29,164
Polyethylene	96	9054
Gypsum	46	4233

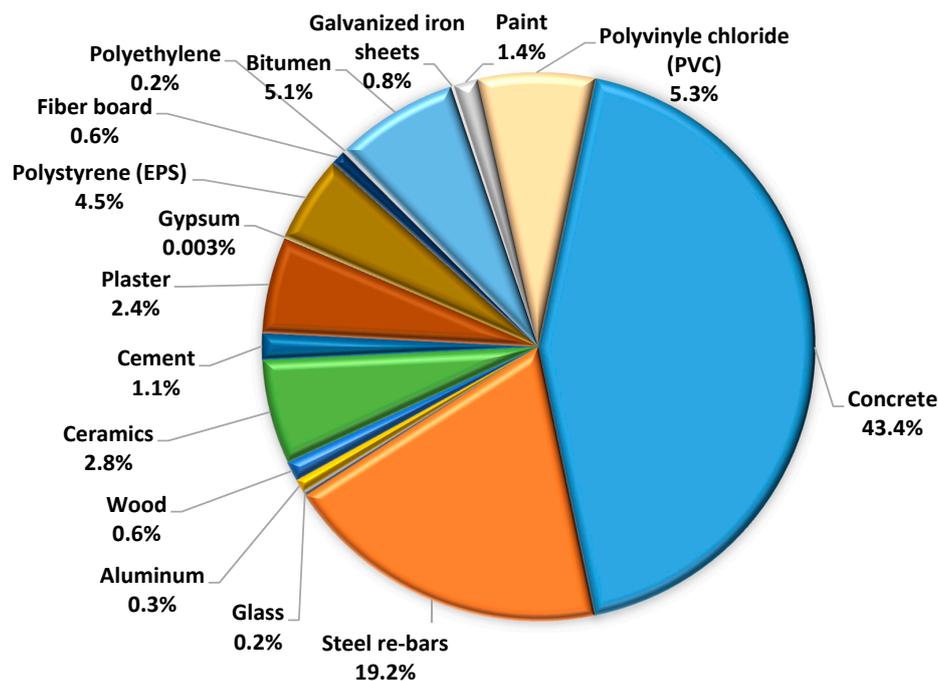


Figure 6. Distribution of the house embodied energy by the type of materials.

6. Environmental Impacts

As part of the LCA study an environmental impact assessment of the materials used in the construction of the house has also been carried out. The inventory data modeling is performed through a LCA software, SimaPro. Within SimaPro, Ecoinvent database (v: 3.0) is used for material modelling, and Environmental Product Declaration (EPD) method has been used as the impact assessment technique. EPD is recommended by EN 15804 with a complete guideline for estimating environmental impacts and has been used in several LCA studies [34,35]. Generally, EPD method is used for creation of environmental impacts declaration and is considered important for the reporting in the product

category rules. It considers a damage oriented approach and includes the impact categories related to the endpoint approach i.e., Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP), Photochemical Oxidation Potential (POCP), Ozone Depletion Potential (ODP), and Abiotic Depletion Factor (ADF). An overview of the results indicates that concrete is the most environmentally harmful material followed by steel in terms of AP, EP and GWP. In terms of POCP, ODP and ADF, steel, ceramics and polystyrene are the leading materials respectively as shown in Figure 7. Polystyrene, used as thermal insulation, is however, the predominant contributor in terms of ozone depletion impacts followed by concrete. The production of polystyrene used to employ chlorofluorocarbons (CFCs), a substance with huge ODP, as the expanding agent until 1987. However after the use of CFCs was banned, polystyrene is now being produced from hydro chlorofluorocarbons (HCFCs) which is still resulting into significant ODP.

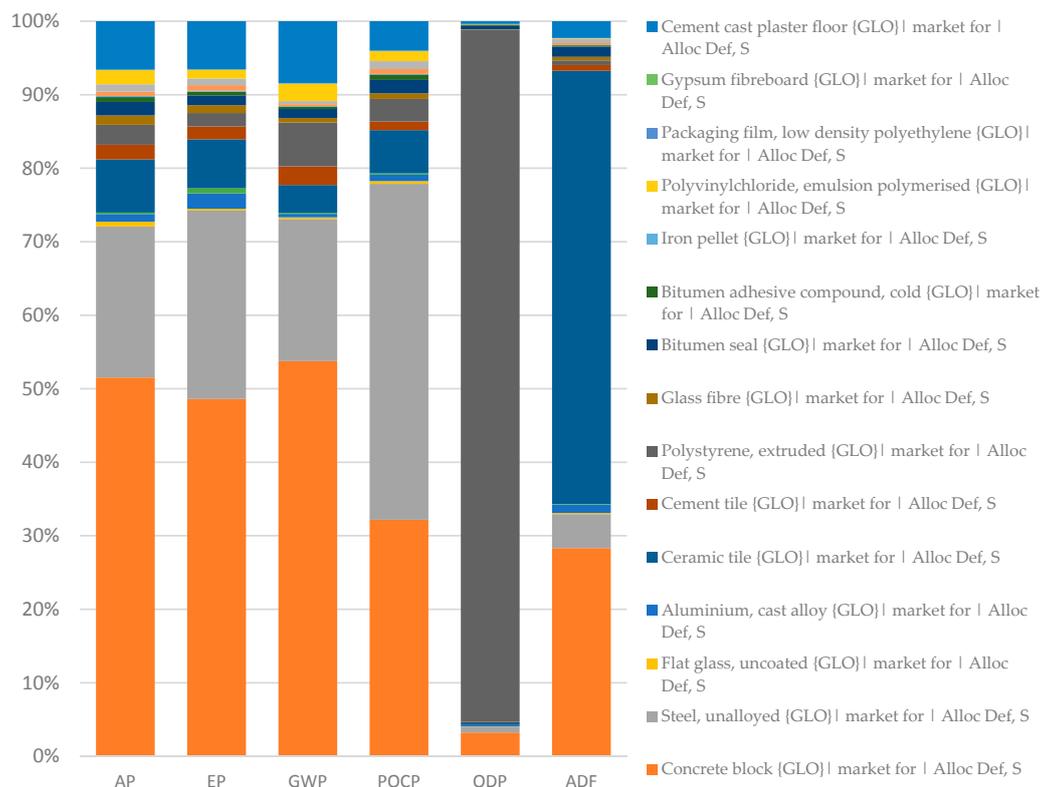


Figure 7. Environmental impacts of materials.

7. Discussion

Domestic buildings constitute the bulk of the building stock across the world and thus their energy and environmental performances are predominant [36]. The GCC region has a vast and fast growing construction sector with ongoing projects worth around \$2.5 Trillion [37]. Accounting for 43% of this total investment, Saudi Arabia is experiencing a rapid growth in the construction sector and residential buildings constitute over 90% of the total new projects [38]. While around 70% of the Saudi population is under the age of 30 years, estimates suggest that KSA needs to build 2.32 million new homes by 2020 to satisfy the requirements of the surging population [13]. Traditionally, the energy and environmental performance of buildings has not been a priority for the construction industry stakeholders. Presently the building industry accounts for 80% of the electricity being consumed in KSA. Domestic buildings consume more than 50% of the total electricity [13]. These figures are much higher than the global average, and advocate for an improvement in the current building construction and use practices. A 100% reliance on fossil fuels makes the situation more alarming from the environmental perspective. The country is already emitting almost four times the CO₂ as compared to the global average figure

of 5 metric ton/capita [38]. The rapid growth trends in the construction industry are set to add to the associated environmental stresses. The building sector therefore has to play an important role in addressing the energy and environmental challenges the country is facing. This can be achieved by switching to energy efficient and environmentally friendly solutions both during the construction and operational phase of buildings. In recent years there has been a growing realisation amongst the Saudi policy making circles to improve the energy efficiency and sustainability standards across all sectors in the country especially in buildings. In 2016, it was made mandatory for all new residential buildings to have thermal insulation in order to qualify for connection to the national electric grid [39]. Traditionally, the country has had heavily subsidized utility tariffs [12,40,41]. This situation however is fast changing as electricity prices are undergoing a major rationalization process. The year 2016 saw the first tariff increment in 15 years as electricity prices increased by up to 45% [42]. Further hikes in tariff are being forecasted, as according to the Vision 2030 policy framework, by year 2020, utility subsidies are set to be cut by around 54 Billion US\$ [43]. The trend in increasing the electricity tariff is expected to also motivate the building sector to adopt sustainability measures.

Since 1950s the life style in Saudi Arabia has greatly changed. The society has seen a transformation from a Bedouin lifestyle to a modern urban one. The nature of dwellings has been completely revolutionized. For example tents and shelters, that used to be a common housing feature, are almost nonexistent now. Traditional dwellings, employing vernacular architectural techniques such as courtyards and wind towers, were made of construction materials including clay (adobe), coral, limestone, and wood. These have been replaced by concrete and steel built housing, exhibiting weaker thermal characteristics [44]. The modern buildings, also owing to their huge air conditioning load, have a comparatively large energy and environmental footprint.

Presently, the concept of LCA is virtually nonexistent in the Saudi building sector. Assessment of the environmental performance of buildings and construction projects is neither a requirement nor it is practiced. An overview of LCA studies in the building sector across the world [16] reveals that most of the studies are carried out in developed countries and there is no notable contribution coming from the GCC region in general and Saudi Arabia in particular as highlighted in Figure 8. To improve the sustainability standards of its large and fast growing building sector, it is crucial for Saudi Arabia to take into account the environmental performance of buildings as an integral part of construction practices. LCA can be a very useful tool in this respect. It can help evaluate and reduce the environmental impacts of buildings, materials, and activities in the construction sector.

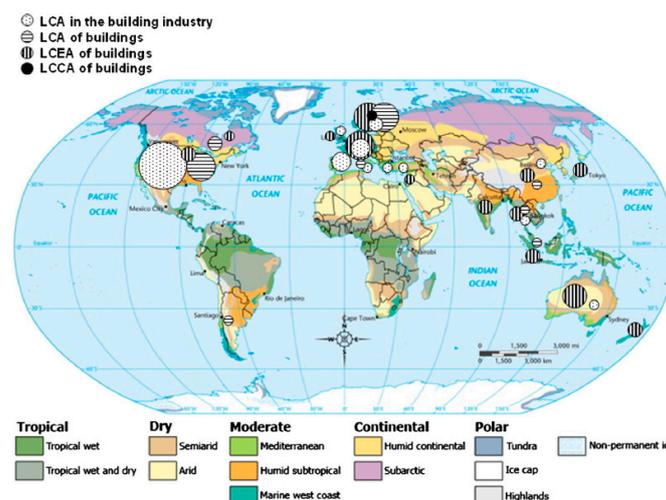


Figure 8. Geographic concentration of LCA studies carried out across the world.

Understanding the embodied impacts of materials allows the building sector to choose better materials in order to reduce the life cycle impacts of buildings [45]. Embodied energy and

environmental impacts of materials are greatly influenced by the parameters involved in their production processes which vary from place to place. The present work is the first LCA study on buildings not only in KSA but in the whole GCC region. It has focused on the construction phase of a 3-bedroom house by investigating the materials involved in terms of their embodied energy and associated environmental impacts. After the operational phase, construction is the second most important part of the entire life cycle of buildings in terms of energy consumption and environmental impacts. The construction phase also influences the operational phase of buildings—for example, improved thermal insulation of the building-envelope helps reduce the energy consumption and subsequent environmental emissions during the use of buildings [13,46,47]. The relationship between the construction and operational phases of a building would depend upon various factors including the nature of construction materials and building design, climatic conditions, user behaviour and the considered lifespan of buildings. An LCA study from Australia indicates that the construction phase may account for up to 30% of the life cycle energy consumption of buildings for a 50-year life span [18]. Another study from Australia reports the embodied energy during the construction phase of buildings accounts for 27% of their life cycle energy for a lifespan of 100 years [48]. Another study comparing five different buildings from China, Thailand and Australia has reported the embodied energy to be in the range of 13% to 46% of their total life cycle energy consumption for a lifespan of 50 years [20].

In the absence of local databases, the present study uses the universal databases for embodied energy and environmental impact assessments. To promote the application of LCA in the GCC region, it will be helpful to develop an embodied energy database of wide ranging construction materials taking into account local production and processing parameters. To develop a local database, the regulation and standardization of materials, equipment and construction activities also need to be improved.

8. Conclusions

The studied 3-bedroom house is a typical modern residential villa with a concrete based structure. Findings of the life LCA reveal that, quantitatively, concrete accounts for over 91% of the total materials used in building. The embodied energy value of the house in terms of functional unit has been estimated to be 10,370 MJ/m². Concrete is found to be responsible for 43.4% of the total embodied energy going into the house. In terms of unit mass, concrete and plaster jointly have the lowest embodied energy value, 1.7 MJ/kg. It is also evident from the fact that concrete's overall share in terms of the total embodied energy is lower than its share in terms of mass. Steel, an integral part of concrete structures, is the second most prominent material both in terms of its quantitative and embodied energy share. Polystyrene, polyethylene, and gypsum lead the list of materials in terms of embodied energy values with respective figures of 106 MJ/kg, 95 MJ/kg and 92 MJ/kg. The results of the environmental impacts assessment indicate that concrete is the most burdensome material followed by steel in terms of Acidification Potential (AP), Eutrophication Potential (EP), and Global Warming Potential (GWP). In terms of Photochemical Oxidation Potential (POCP), Ozone Depletion Potential (ODP), and Abiotic Depletion Factor (ADF), steel, ceramics and polystyrene are the leading materials respectively. Environmental impacts of buildings are not presently being adhered to in the KSA. The findings of this study will educate the construction industry about the environmental impacts of the main construction materials being used in KSA. The study recommends further studies to be carried out exploring the scope for other more environmentally friendly materials. Similarly, construction methods and techniques should also be investigated in order to improve the sustainability standards of buildings.

Author Contributions: Muhammad Asif and Mian Mobeen Shaukat conceived the idea and designed the framework for the LCA analysis. Ammar Homoud Ahmad Dehwah and Hassan Saeed Khan collected the data. Farhan Ashraf and Muhammad Asif performed the LCA and modeling. Muhammad Asif and Muhammad Tahir Hassan wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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