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Environmental Performance of Residential Buildings: A Life Cycle Assessment Study in Saudi Arabia

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Abstract: The building and construction sector has a huge impact on the environment because of the enormous amounts of natural resources and energy consumed during the life cycle of construction projects. In this study, we evaluated the potential environmental impact of the construction of a villa, from cradle to grave, in the Saudi Arabian context. Centrum voor Milieukunde Leiden (CML) for Centre of Environmental Science of Leiden University-IA baseline v3.03 methods were used to obtain the environmental profile for the impact categories, and Cumulative Energy Demand v1.09 was used to measure the embodied energy of the villa life cycle. The analyzed midpoint impact categories include global warming (GWP100a), ozone layer depletion (ODP), acidification (AP), eutrophication (EP), photochemical oxidation (POCP), and indicator cumulative energy demand (CED). The operation use phase of the villa was found to have the highest global warming potential and acidification with 2.61×10^6 kg CO_2-eq and 1.75×10^4 kg SO_2-eq, respectively. Sensitivity analysis was performed on the Saudi Arabian plans to increase the share of renewable sources and reduce the amount of electricity generated from hydrocarbons, which currently represents 46% of the total installed power, by 2032. The results showed that compared with the current electricity environmental impact, the CO_2 emission from electricity will decrease by 53%, which represents a significant reduction in environmental impact. The findings will help with the life cycle assessment of structures during future planning and for energy conservation.

Keywords: sustainability; buildings; life cycle assessment; materials; greenhouse

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1. Introduction

The global focus on sustainability has increased in recent years given the dangers posed by climate change, global warming, and environmental degradation. Over 85% of the world's primary energy needs are still met using fossil fuels, making them the most significant contributors to greenhouse gas (GHG) emissions [1]. Overall, the efficient and effective use of energy and materials is needed across sectors. The United Nations Sustainability Development Goals for 2030 consolidate many of these challenges and highlight the need for inclusive development through building sustainability, resource conservation, and innovation in development [2]. The building sector is no exception to sustainable development. In developed economies, such as those of the United States and the European Union, buildings account for nearly 40% of all primary energy consumption [3]. An extensive study [4] across building types and climate conditions in the United States showed that interventions in the building sector can result in average energy savings of 29%, thus significantly reducing the overall emissions. In the European Union, the building construction industry annually consumes nearly half of all raw materials and one-third of the water used while generating 25–30% of the waste [5]. Better construction and other sustainable interventions could lead to a 42% reduction in final energy consumption and a reduction of over 35% in greenhouse gas emissions [6]. Similar potential savings can be achieved by countries around the globe. As a signatory to the Paris Agreement [7], Saudi Arabia is committed to reducing its greenhouse emissions through multiple interventions involving renewable energy, carbon capture, and energy efficiency management [8]. The building sector in Saudi Arabia consumes large quantities of materials and energy, with contracts estimated at $52.6 billion awarded in 2019 alone [9]. In Saudi Arabia, buildings consume nearly 80% of the overall electricity generated, with residential buildings accounting for 50% of the total [10]. Hence, there is room for significant energy and emission savings within this sector.

However, it is necessary to comprehend how buildings consume energy and resources throughout their lifetime to identify potential energy-saving interventions. Life cycle assessment (LCA) is an approach commonly employed in this context. This method allows the researcher to study the energy and resource consumption of a certain building starting from the stage of resource extraction up to the demolition of the building and waste management at the end of a building's life cycle [11]. Insights gained from the LCA can lead to optimized resource and energy use at all stages of a building's life cycle, leading to building LCA becoming a distinct area within the practice of life cycle assessment. Building LCA can help tackle specific characteristics that are unique to the construction industry. For example, the choice and sourcing of raw materials needed for construction can impact the energy and environmental footprint of a building. This includes the environmental degradation and energy footprint associated with the extraction, processing, packaging, and transportation of these materials [12]. This preconstruction phase is followed by construction, which generates significant waste and pollution. Because buildings have a long-life cycle, the next operational phase, in general, accounts for the most energy consumption of all phases. Studies estimate this value to be between 40% and 90% of the life cycle energy consumption depending on climatic conditions and usage habits [13,14]. This also includes any impact associated with the building maintenance operations. At the end of the building's life cycle, demolition activities consume energy and generate waste that can be recycled, reused, or sent to landfills. These impact the overall life cycle assessment of buildings [15]. All these stages are analyzed in a complete building LCA. A multitude of such studies can be found in the literature; a few pertaining to residential buildings is discussed below.

Life cycle assessments of residential buildings have been conducted for multiple climatic and economic conditions [16]. A study on various types of residential buildings (multifamily dwellings and single-family dwellings) in Brazil was conducted by Evangelista et al. [17]. The study found that single-family dwellings often have a higher potential environmental impact than multifamily dwellings of similar sizes and standards. In addition, for the same family size, high-standard dwellings have higher environmental costs. The study found that some aspects such as structures, foundations, and coatings have higher environmental costs than others, and that the operational phase is responsible for 80% of the energy demand. This is similar to other reported findings [18] on a three-bedroom house in Scotland, identifying concrete, timber, and tiles as the most energy-intensive materials used in its construction. They are extensively used for foundations, structures, and interior coatings. Evangelista et al., however, did not consider many options for the demolition phase and assumed that the entire building would end up in landfill. A similar study on a single-family home in Sweden showed that production stage and maintenance operations accounted for the largest footprint (67%), while the operational and end-of-life phases together accounted for less than 12% of GHG emissions from the building. This study, however, was extremely subjective as most of Sweden's electricity comes from renewables, and the house was a wooden construction [19]. A study on Canadian residential buildings [20] found a linear correlation between the operational energy footprint and the overall energy footprint of buildings regardless of their differences, much like in another study [18] where high-rise multifamily housing units performed better than single dwellings and low-rise apartments. The relatively high energy footprint associated with the operational phase was also highlighted, in agreement with the results obtained for Canadian houses [21]. The number of studies on buildings from the Middle East [22], Africa [23], and South Asia [24] is limited; much of the literature in this field is restricted to China [25], North America, and Europe [26]. The environmental loads associated with each phase of the entire life cycle of the residential building as defined by the European Committee for Standardization (EN 15804) [27,28]. In 2017, the Saudi Arabian government prepared a strategy called the 2030 Vision. The objective of the Saudi Vision 2030 (SV2030) is to set up renewable and sustainable energy (RnSE) projects to meet the electricity demand—which is expected to surpass 120 GW by 2032—by increasing the use of renewable resources, reducing dependency on fossil fuels, and reducing the country's CO_2 emissions. Concluding the existing research, no building life cycle assessment study, from cradle to grave, has been conducted in the context of Saudi Arabia. Therefore, to fill this gap, an LCA of a residential building in Saudi Arabia should be conducted.

The literature discussed so far shows that LCA can be a valuable tool for optimizing energy consumption in buildings. Given the size of Saudi Arabia's construction industry, significant energy savings can be achieved by better understanding this sector. However, there is a lack of examples in the literature of building LCAs (or a cradle-to-grave study of building energy consumption) pertaining specifically to Saudi Arabia; most studies are limited to Europe and North America. Because residential buildings consume 50% of the electricity generated in Saudi Arabia, in this study, LCA was used to better understand the energy footprint and environmental impact of a typical residential villa. Information obtained from this study will aid industry professionals and government agencies in incorporating environmental health and sustainability into planning and construction.

The aim of this study is to understand the potential environmental impact caused by the whole life cycle of a typical residential building (villa) in the Saudi Arabian context. The reference building taken into consideration is a Saudi Arabian villa built in the capital city, Riyadh, using the latest standards in construction techniques and conventional materials normally used in the local context. Thus, this study focuses on evaluating the potential environmental impact of a villa (a typical Saudi Arabian residential building) in five impact categories and one life cycle indicator: global warming (GWP100a), ozone layer depletion (ODP), acidification (AP), eutrophication (EP), photochemical oxidation (POCP), and indicator cumulative energy demand (CED). This study will help to analyze the performance of Villa buildings with reference to Life cycle assessment implementation.

2. Materials and Methods

The LCA methodology was used to evaluate the environmental impact of a typical residential building in Saudi Arabia considering the whole life cycle, from cradle to grave. The attributional LCA was conducted according to International Organization for Standardization (ISO) 14040 [29] and ISO 14044 [30]. SimaPro software version 9.1 was used to model the LCA [31]. The methods used to obtain the environmental profile of the average villa life cycle included CML-IA baseline v3.03 [32,33] for impact categories and Cumulative Energy Demand v1.09 to calculate the embodied energy in the life cycle of the villa. The CML methodology, developed by the Center of Environmental Science of Leiden University, is widely accepted; EN 15804 [27,28], the core standard for products categorized as construction products, takes the characterization factors from this method and allows for the comparison of results with those of other LCA studies. The midpoint impact categories that were analyzed with CML-IA baseline v3.03 methods were global warming (GWP100a), ozone layer depletion (ODP), acidification (AP), eutrophication (EP), photochemical oxidation (POCP), and indicator cumulative energy demand (CED) following the Cumulative Energy Demand v1.09 method. The villa was modeled using Revit software (Chetu, Plantation, FL, USA), the widely used building information modeling software. Data were obtained from local construction firms via questionnaires and interviews, ensuring the villa is representative of the current average residential building in Saudi Arabia. The Ecoinvent version 3.2 database [34] was used to model upstream processes and is globally recognized as one of the most consistent Life Cycle Inventory (LCI) databases available. The step wise methodology of this research can be expressed as:

Step.1: Selection of Case Study Area-Villa
Step.2: Description of Villa Characteristics
Step.3: Defining the System Boundaries
Step.4: Life Cycle Inventory and Assumptions
Step.5: Results and Assessment
Step.6: Decision Making.

2.1. Selection of Case Study Area-Villa

This study is designed to assess the potential environmental impact caused by the life cycle of a single-family house, called a villa, in the Saudi Arabian context. Because all stages are specific to the Saudi Arabian context, a comparison with similar buildings located in different regions was performed. Finally, because Saudi Arabia is committed to reducing its greenhouse emissions through multiple interventions—one of which is implementing renewable energy—a sensitivity analysis was conducted to assess how the reduction in the electricity impact would affect the building's life cycle. Similar to other studies [35–37] and the principles of Product Category Rule (PCR) 2014:02 for buildings [38], in this investigation, the functional unit (FU) is a villa with a total gross floor area (GFA) of 387 m^2 and a lifespan of 50 years.

2.2. Description of Villa Characteristics

The assessed villa is an average single-family building with a concrete-based structure. The GFA is 387 m^2. It is a two-floor villa with an open space on the second floor and five bedrooms and bathrooms. The building plans are provided in Figures 1–3.

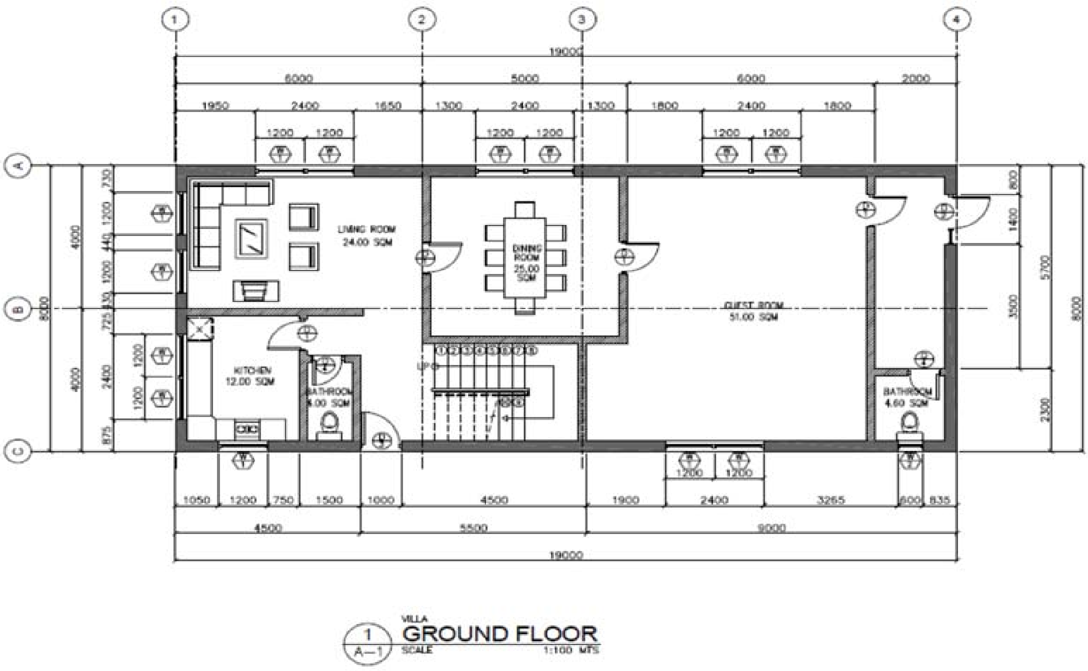


Figure 1. Villa ground floor plan.

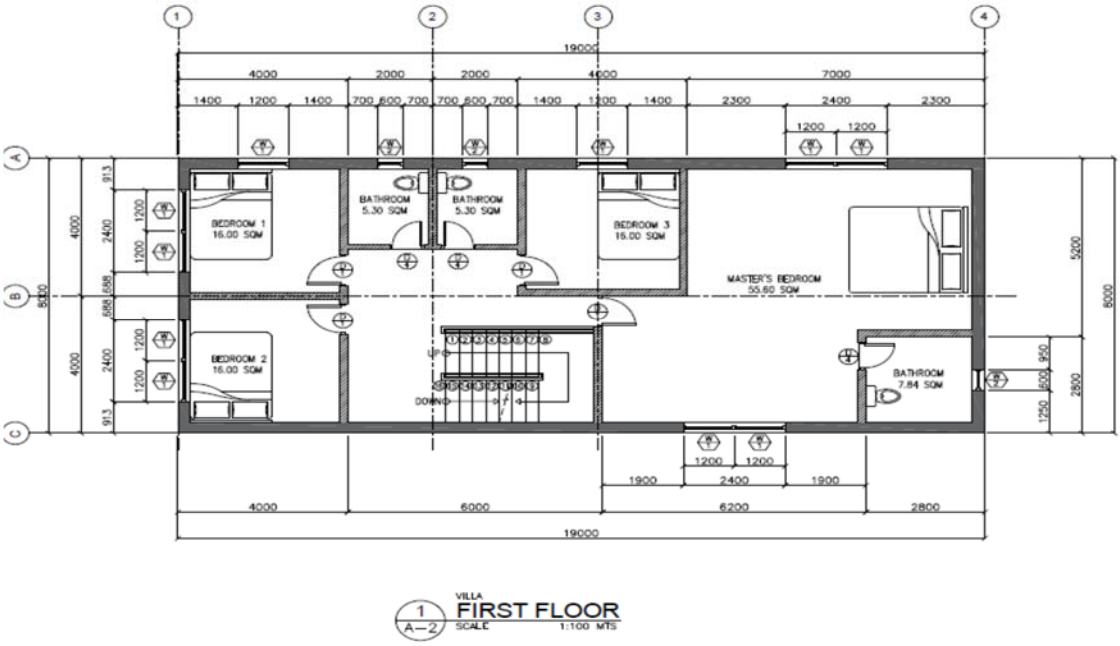


Figure 2. Villa first floor plan.

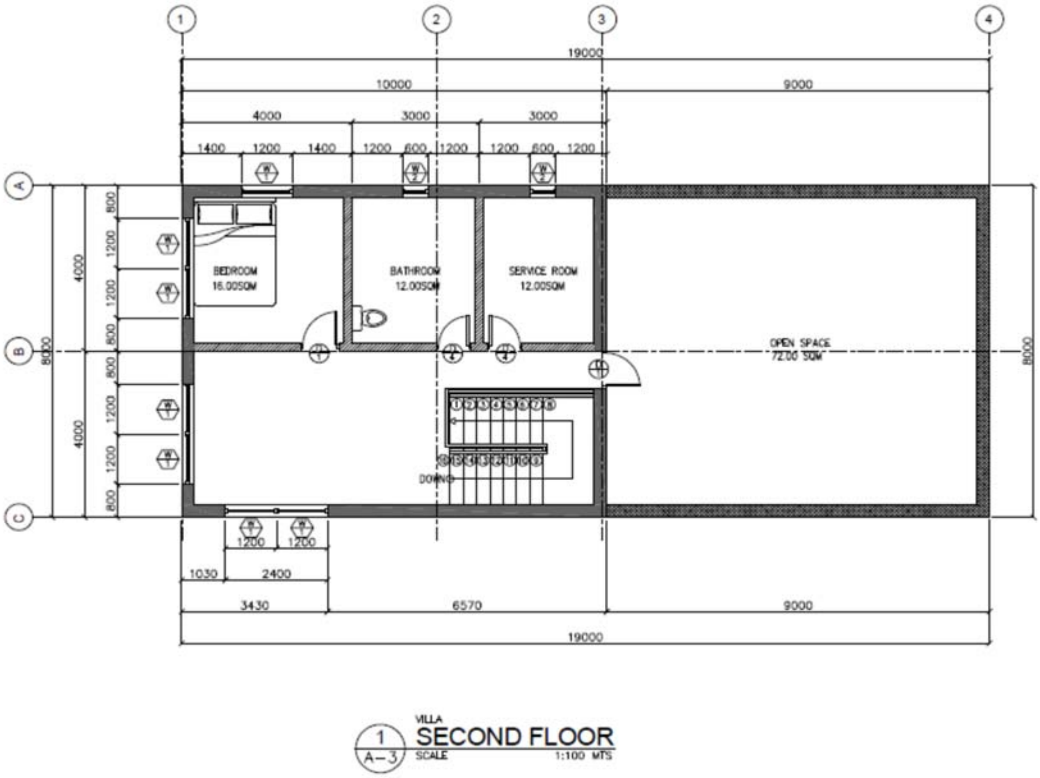


Figure 3. Villa second floor plan.

The villa was built mainly with concrete. In Table 1, the building components are described in terms of materials and quantities. Both the foundation and structure were made of reinforced concrete, whereas walls, both internal and external, were built with concrete blocks. The external concrete blocks contain extruded polystyrene (XPS), which provides thermal insulation to the building. Other materials used in villa construction were ceramic tiles, cement tiles, bitumen to provide waterproofing, gypsum plasterboards for ceilings, and paint, among others. The domestic appliances, such as washing machines, refrigerators, cooking appliances, and heating, ventilation, and air conditioning (HVAC), were excluded in line with EN 15804 as they represent less than 1% of the total mass input in the construction stage.

Table 1. Villa Components and Material Inventory.

Building Component	Component/Material	Units	Quantity
Foundation	Reinforced concrete slab on grade	m^3	20.75
Structure	Reinforced concrete	m^3	138.7
Roof and Open space	Layers: 20 mm cement tile + 40 mm mortar layer + 50 mm XPS + 10 mm bitumen sheet + 4 mm bitumen coating	m^2	138.60
Ceiling	12.5 mm gypsum board on metal furring + paint	m^2	322.81
Exterior walls and parapet	400 mm × 200 mm × 300 mm concrete block with insulation + adhesive mortar + 2 faced 20 mm cement plaster + ladder mesh	m^2	303.3
	200 mm parapet wall	m^2	23
	Paint	m^2	519.65
Internal walls	400 mm × 200 mm × 150 mm hollow concrete block + adhesive mortar + 2 faced 20 mm cement plaster + ladder mesh	m^2	231
	Paint	m^2	821.60
Floor and wall tiles	Dry areas: 10 mm ceramic tile + 40 mm mortar	m^2	302.2
	Wet areas: 10 mm ceramic tile + 40 mm mortar + 2 layered 5 mm bitumen sheet + 4 mm bitumen coating	m^2	30.78
	Wall tiles: 10 mm ceramic tile + 4 mm bitumen coating	m^2	81.258
Windows	Double glazed window with aluminum frame	windows	37
Doors	Steel door	doors	2
	Wood door	doors	16
Stairs	Welded tubular stainless steel	m	13.5
Electrical network	Cooper wire	m	360

2.3. *Defining the System Boundaries*

A cradle-to-grave evaluation was conducted for the whole life cycle of the villa within the system boundaries defined in Figure 4. Figure 4 shows the life cycle phases of the constructed building in conformance with UNE 15804 [25].

The pre-use phase consisted of the subphases of material production comprising raw material supply, transportation, and manufacturing (modules A1-A3 of EN 15804), and that of building construction, which consisted of the transport and assembly of components, energy consumption related to land soil preparation and excavation, and building material waste generation (modules A4–A5 of EN 15804). During the use stage, the operational use of energy and water are considered along with the repainting of the building and replacement of the floor (modules B6, B7, B2, and B4 of EN 15804). At the end of their life cycles, buildings are demolished, and building materials are transported and managed into landfill (modules C1, C2, and C4 of EN 15804) [39].

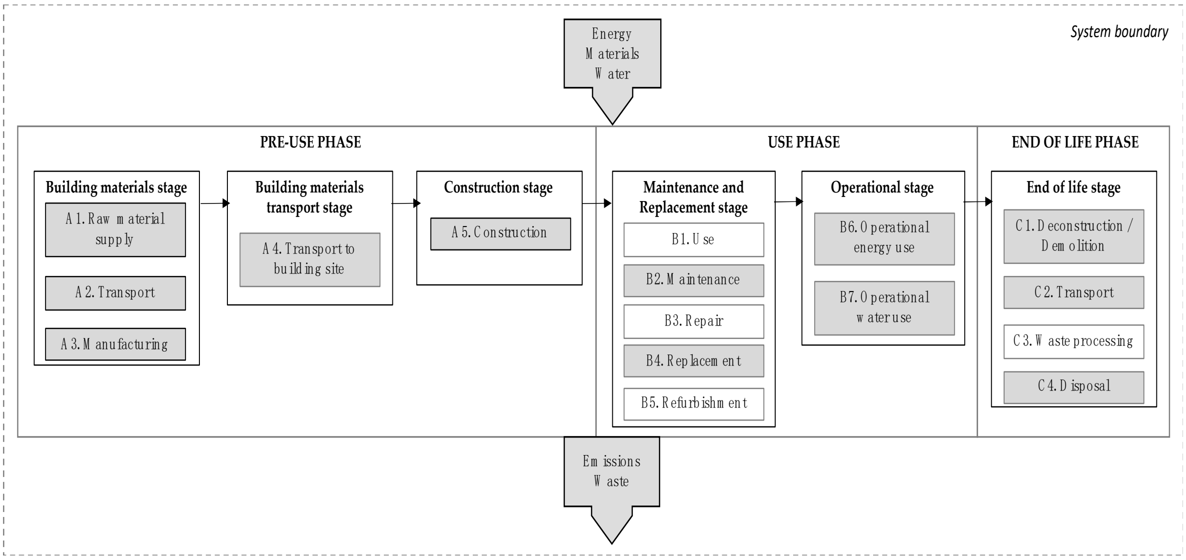


Figure 4. Life cycle assessment (LCA) system boundary based on EN 15804 modularity (included modules are shaded) and stages defined for the villa assessment.

The use phase includes any emissions to the environment (module B1); technical operations on the building: maintenance, repair, replacement, and refurbishment (respectively module B2 to B5); and operation of the building, divided into operational energy use (module B6) and operational water use (module B7). Only maintenance and replacement operations and operational energy and water use are considered relevant for the villa use phase.

At the end of its life, the entire building is deposited as waste in landfill, which means that the C3 module of waste processing is not relevant in this system.

Other life cycle processes were omitted because they account for less than 1% of the total environmental impact, and data availability was limited for infrastructure, construction, production equipment, and tools that are not directly consumed in the construction process; as well as for employee-related activities such as transport to and from work, packaging of construction products and packaging waste produced during the A5 module, communication installations, villa equipment, HVAC, and lamps.

2.4. Life Cycle Inventory and Assumptions

The inputs and outputs used to calculate the environmental impact of the average villa were compiled from the building's bill of materials. Specific data collected from local construction firms via questionnaires and interviews were used to model each life cycle stage and taken as representative of the Saudi Arabian construction process for this type of building. Generic data that were not based on measures or direct calculations for the specific processes or stages were obtained from the Ecoinvent version 3.2 database. The hypothesis of the Ecoinvent database was assumed, even though some processes were adapted to the Saudi Arabian context. Detailed process data were considered in this study during the life cycle for each material during manufacturing, transportation, and disposal [40,41].

2.4.1. Building Materials Stage

Quantities of materials specified in the bill of materials were used to model the building materials stage (Table 1). Because no specific information was available on the manufacturing of the construction products in Saudi Arabia and previous stages, the Ecoinvent database was used. The datasets were modified to include the Saudi Arabian electricity mix and water supply as recommended by other studies [40].

2.4.2. Building Materials Transport Stage

The scenario for the transportation stage was set from the local construction sector experience. The transportation distance was assumed to be 50 km from the manufacturer to the construction site for all materials because all materials would have been obtained from Riyadh's second industrial city. Materials transportation from manufacturers to the construction site was assumed to be carried by an average 16–32 ton truck.

2.4.3. Construction Stage

In the construction phase, waste material was added as an additional 10% of the overall quantity for the bill of quantities because during this stage, the wastage rate is assumed to be 10%. For this additional 10%, the same assumptions were used for the building materials and transportation stages. In Saudi Arabia, the common practice for building waste is the landfill process. Hence, the construction waste was assumed to be transported 50 km for disposal. Waste generated via transportation and management was assumed to be carried by an average 16–32 ton truck.

In the construction stage, the soil preparation and excavation were included based on the bill of materials information.

2.4.4. Maintenance and Replacement Stage

The proposed scenario for the use stage, which refers to technical operations, covers both maintenance and replacement. Based on the service life of components and materials and the building lifespan, the external walls will be repainted twice, while internal walls will be repainted three times. The replacement tasks cover the replacement of floor tiles and all layers that conform to the floor (twice during the building lifespan) and wall tiles (once) along with the required materials. The materials used for replacement and maintenance were assumed to be transported 50 km by an average of 3.5–7.5-ton truck. The replacement materials waste was assumed to be transported and disposed of. The same scenario defined in the construction stage was used in this stage.

2.4.5. Operational Stage

The energy consumption for the villa was collected by Energy Plus software conducting a one-year simulation based on the villa's characteristics. The data obtained and used for the scenario in the operational stage are shown in Table 2. It was assumed that the villa would be occupied by six people and the temperature inside the villa would be 21.3 °C for comfort. The most demanding uses are cooling, accounting for 62% of the electricity demand, and interior lighting, accounting for 14% of the consumption.

Table 2. End-use energy consumption (one-year simulation). GFA, gross floor area.

End Use	Electricity Consumption (kWh/year)
Cooling	29,221.30
Interior Lighting	6367.27
Exterior Lighting	2185.08
Interior Equipment	3719.76
Fans	1791.72
Pumps	0.57
Water Systems	3743.88
Total	47,029.58
Total/GFA (kWh/m^2)	121.52

Water is consumed during the operational stage. The tap water Ecoinvent dataset was modeled to consider part of the water supply coming from groundwater and the other part from seawater in Saudi Arabia.

2.4.6. End-of-Life Stage

In Saudi Arabia, the common practice for Construction and demolition waste (CDW) is the landfill process. Hence, the scenario that models the end-of-life stage states that the building is dismantled and all building materials are transported by truck and disposed of.

3. Results and Discussion

The life cycle of the villa was divided into the following stages as aligned with the European core rules for the product category of construction products EN 15804 and the construction sector: product (building materials), building materials transport, construction, operational, maintenance and replacement, and end of life. The midpoint impact categories that were analyzed with CML-IA baseline v3.03 methods were global warming (GWP100a), ozone layer depletion (ODP), acidification (AP), eutrophication (EP), photochemical oxidation (POCP), and indicator cumulative energy demand (CED) following the Cumulative Energy Demand v1.09 method.

3.1. Life Cycle Impact Assessment

3.1.1. Main Findings

Table 3 presents the results of the life cycle of the villa from a cradle-to-grave perspective for the functional unit and m^2 (GFA). Figure 5 depicts the contribution of each life cycle stage. The results show that for all impact categories, the operational use stage is the most important stage, with a contribution ranging from 91% (photochemical oxidation) to 96% (ozone depletion and acidification). A total of 7.26 tons CO_2-eq per m^2 (GFA) were potentially emitted during the villa life cycle, and 6.76 tons CO_2-eq were from the operational use stage, electricity, and water consumed over 50 years. The impact of the operational stage was obtained mainly from electricity consumption, which was modeled on an annual basis using Energy Plus. The obtained data show that 47,030 kWh was consumed annually, representing 122 kWh/m^2 (GFA). Of the total electricity consumed, 62% was used for cooling, whereas 14% was used for interior lighting. The villa was composed of 695 tons of materials, but the building materials stage, that is, the material supply and manufacturing, represented a maximum of 6% of the life cycle impact in the category of photochemical oxidation. This stage is analyzed in detail in the next section. The transport of building materials to the construction site did not have a significant impact considering the whole building life cycle, accounting for less than 1% of all impact categories. The transport distance was assumed as 50 km because factories are in Riyadh, the second industrial city, so all transport operations were optimized. During the construction stage, 10% of building materials were assumed to be transformed into waste materials. Thus, the extra number of materials is consumed as part of this stage as well as in waste transport and the management of landfills. Some other operations were included, such as excavation. Therefore, the contribution of this stage was highly dependent on the building material stage, but its contribution to the total life cycle of the villa was less than 1% for all impact categories and indicators. The maintenance and replacement stages considered the replacement of some building elements that have a shorter lifespan than that of the building. In this case, two relevant substitutions of floor tiles and one substitution of wall tiles and painting works of external and internal walls were considered. Even though the amount of material consumed during the use of the building was relevant—almost 12 tons of materials—the contribution of this stage was, at most, 1.5% of the impact of the photochemical oxidation impact category.

Table 3. Life cycle impact assessment (LCIA) of the life cycle of the villa considering a lifespan of 50 years (per FU) and per m^2 of GFA.

Impact Category or Indicator	Acronym	Units	Total per FU	Total per GFA (m^2)
Global warming	GWP 100 years	kg CO_2-eq	2,807,943.8	7255.668734
Ozone layer depletion	ODP	kg CFC-11-eq	0.35283721	0.000911724
Photochemical oxidation	POCP	kg C_2H_4	782.15594	2.02107478
Acidification	AP	kg SO_2-eq	18,279.348	47.23345736
Eutrophication	EP	kg PO_4^{3-}-eq	1577.4363	4.076062791
Cumulative energy demand	CED	MJ	43,015,866.13	111,152.1089

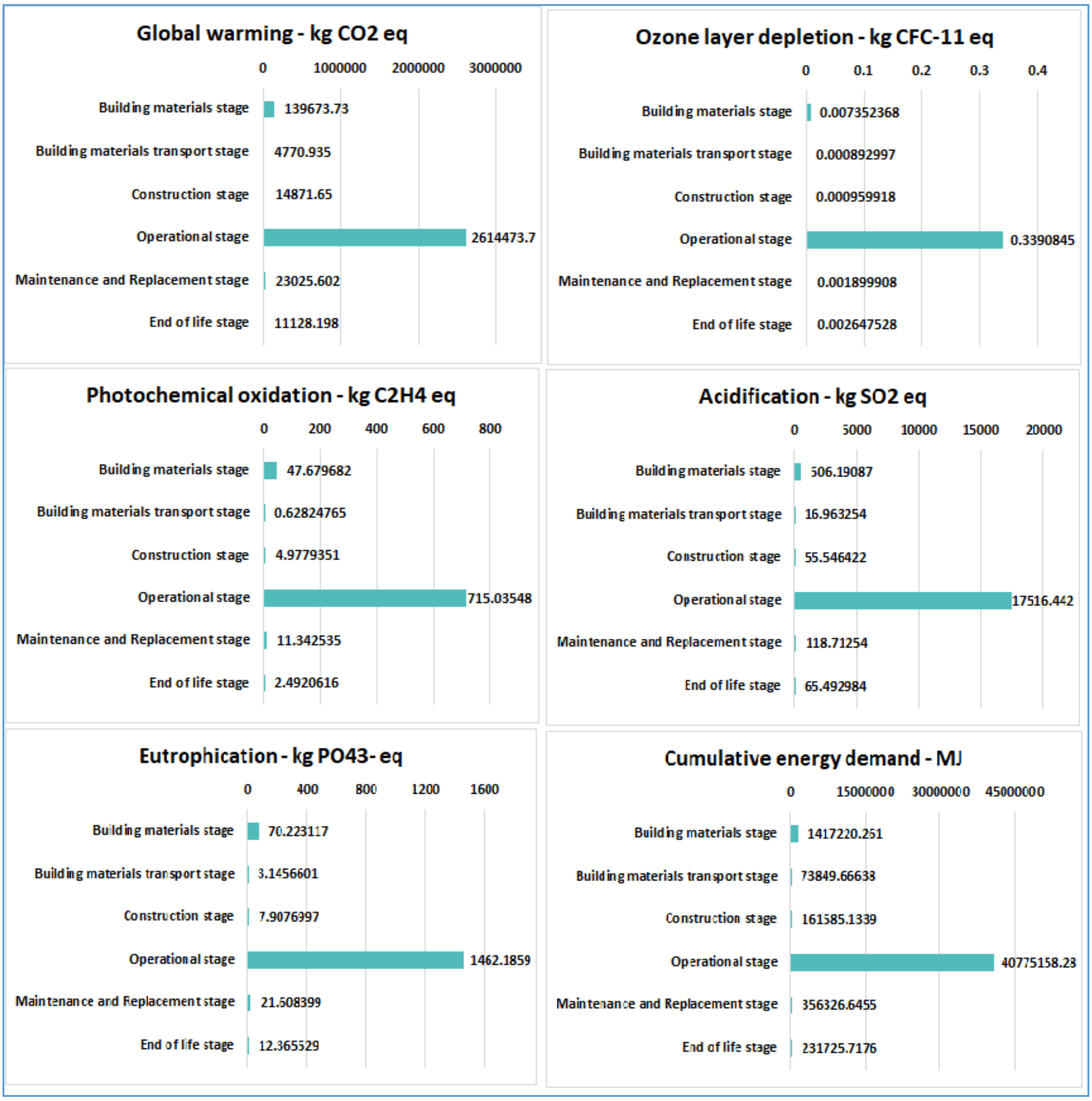


Figure 5. Contribution of each life cycle stage to the FU environmental impact.

At the end of the life cycle, it was assumed that all the building materials were landfilled because this the current protocol for handling construction and demolition waste in Saudi Arabia. However, the impact of this stage contributes to less than 1% of the total life cycle impact.

A graphical explanation of these factors is provided for analysis of the impact of indicators.

3.1.2. Building Materials Stage Impact Assessment

The LCA was developed from the villa bill of materials, so the specific contribution of the building elements is analyzed in Table 4 for each impact category. The average villa has a reinforced concrete structure, whereby the external and internal walls are made of concrete and, in this study, concrete blocks. Therefore, the most important material was concrete because it represented 83% of the building weight, 57% of the structure and foundation, 19% of the external walls, and 8% of the internal walls.

Table 4. Contribution of building elements to the LCIA of building materials stage.

Impact Category or Indicator	GWP 100 years	ODP	POCP	AP	EP	CED
Foundation	8%	7%	6%	6%	6%	6%
Structure	49%	48%	58%	47%	49%	46%
Roof and open space	0.9%	1.1%	0.9%	0.9%	0.6%	2.0%
Ceiling	1.7%	1.7%	2.6%	2.4%	1.8%	2.0%
Exterior walls and parapet	21%	20%	14%	18%	19%	20%
Internal walls	13%	14%	11%	13%	16%	13%
Floor and wall tiles	3%	4%	2%	4%	2%	4%
Windows	2%	3%	2%	4%	2%	3%
Doors	0.9%	1.1%	1.1%	1.6%	1.3%	2.9%
Stairs	0.9%	0.8%	1.0%	1.5%	0.9%	1.3%
Electrical network	0.04%	0.05%	0.4%	1.0%	2.0%	0.1%

In terms of contribution to the environmental impact of building materials, the same weight relation was followed. Table 4 shows that the contribution of the structure and foundation ranges from 52% of the impact of the material's cumulative energy demand to 64% for the photochemical oxidation impact category.

The structure and foundation are followed by exterior and parapet walls, with a contribution ranging from 14% (photochemical oxidation) to 21% (global warming), and internal walls, with an impact ranging from 11% (photochemical oxidation) to 16% (eutrophication).

In terms of the type of materials and their contribution to global warming (GWP), concrete accounted for 36% of the impact while contributing 83% of the building's weight. Steel, used mainly as reinforcement rebar, had a significant contribution of 34%, despite representing only 3% of the total consumed material. Approximately 13% of the impact came from cement mortar and plaster, which accounted for 11% of the materials' weight. Cement and mortar are used in several building elements, such as roof or floor, but the majority of the quantity is used in internal and external walls to plaster both faces of the concrete blocks and to paste them.

3.2. Sensitivity Analysis—2030 Vision

In Section 3.1, the results showed that the main life cycle stage contributing to the environmental impact was the operational use stage, where electricity and water were mainly consumed and wastewater was generated. For all categories, the impact came from electricity, contributing at least 70% (eutrophication). Currently, Saudi Arabia is highly dependent on fossil fuels to produce electricity. The electricity mix of the country is 1.072 kg CO_2-eq/kWh (obtained from the Ecoinvent v3.2 dataset and CML-IA baseline method).

In 2017, the Saudi Arabian government prepared a strategy called the 2030 Vision. The objective of the Saudi Vision 2030 (SV2030) is to set up renewable and sustainable energy (RnSE) projects to meet the electricity demand—which is expected to surpass 120 GW by

2032—by increasing the use of renewable resources, reducing dependency on fossil fuels, and reducing the country's CO_2 emissions.

In this sensitivity analysis, we modeled the impact of the electricity mix based on the share of energy sources proposed by the King Abdullah City for Atomic and Renewable Energy (K.A.CARE) to deliver clean energy by 2032, that is, 9 GW of wind, 41 GW of solar (25 GW of concentrated solar and 16 solar photovoltaic (PV) cells), 17.6. GW nuclear, 1 GW geothermal, and 3 GW WtE sources, with a total 60 GW hydrocarbon capacity to meet the expected future energy demand and supply [42,43]. Thus, power mix resources by 2032 are planned to be 41% from renewable sources (12% PV cells, 19% concentrated solar, 7% wind, 1% geothermal, and 2% from WtE), 13% nuclear, and 46% hydrocarbon. Based on the 2032 scenario, the carbon footprint of the electricity mix would be 0.501 kg CO_2-eq/kWh, which is 53% lower than the current impact.

Considering that a villa would consume 47,030 kWh annually based on the calculations with EnergyPlus, significant environmental savings could be achieved every year by improving the electricity carbon intensity.

Table 5 compares the current annual operational use stage and the 2030 vision operational use stage together with the reduction of the impact by implementing the strategy.

Table 5. Environmental impact of annual operational use stage with current electricity mix and 2030 Vision.

Impact Category	Units per Year	Current Operational Use Stage	2030 Vision Operational Use Stage	Variation 2030 Vision Compared to Current Situation
GWP 100 years	kg CO_2-eq	52,289.474	25,465.652	−51%
ODP	kg CFC-11-eq	0.00678169	0.003886419	−43%
POCP	kg C_2H_4	14.3007096	6.8689938	−52%
AP	kg SO_2-eq	350.32884	167.201548	−52%
EP	kg PO_4^{3-}-eq	29.243718	18.3043584	−37%
CED	MJ	815,503.1655	525,875.8671	−36%

The increase in the share of renewable sources in the Saudi Arabian electricity mix contributes to a reduction in the operational impact on a yearly basis, with a minimum of 36% for eutrophication and a maximum of 52% for photochemical oxidation and acidification.

Decarbonizing the electricity generated in Saudi Arabia that is used in the residential sector could positively impact the life cycle of the villa. It could produce up to half of the impact, which is the maximum reduction obtained, for the acidification impact category (Table 6 and Figure 6).

Table 6. Environmental impact of the villa's life cycle with current electricity mix and 2030 Vision.

Impact Category	Units per Year	Current Villa	Villa with 2030 Vision Operational Stage	Variation 2030 Vision Compared to Current Situation
GWP 100 years	kg CO_2-eq	2,807,943.8	1,466,752.7	−48%
ODP	kg CFC-11-eq	0.35283721	0.20807369	−41%
POCP	kg C_2H_4	782.15594	410.57015	−48%
AP	kg SO_2-eq	18,279.348	9122.9835	−50%
EP	kg PO_4^{3-}-eq	1577.4363	1030.4683	−35%
CED	MJ	43,015,866.13	28,534,501.27	−34%

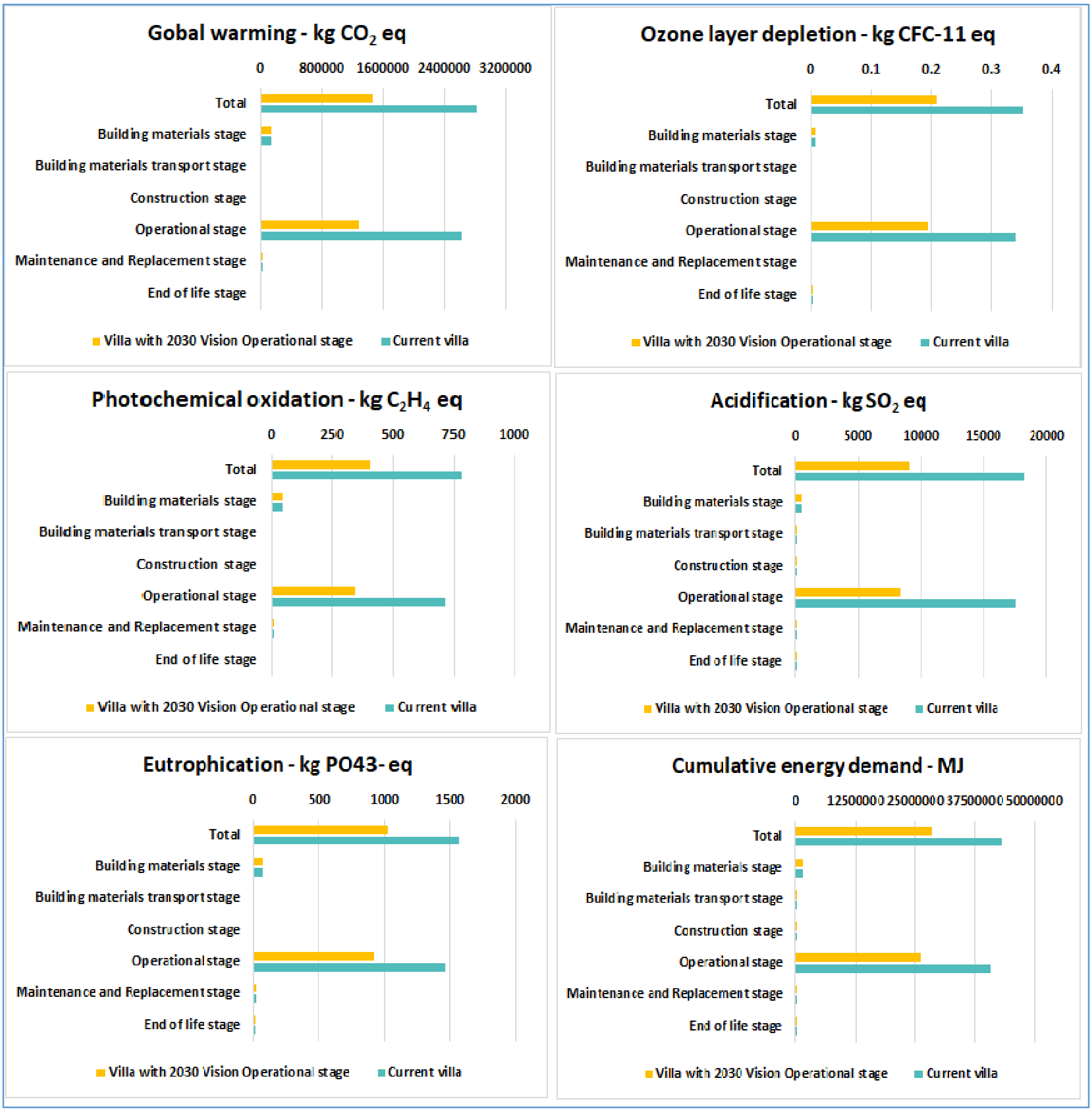


Figure 6. GWP, ODP, POCP, AP, EP, and CED impacts by LCA stage, expressed per FU considering the current villa and a villa during the 2030 Vision operational stage.

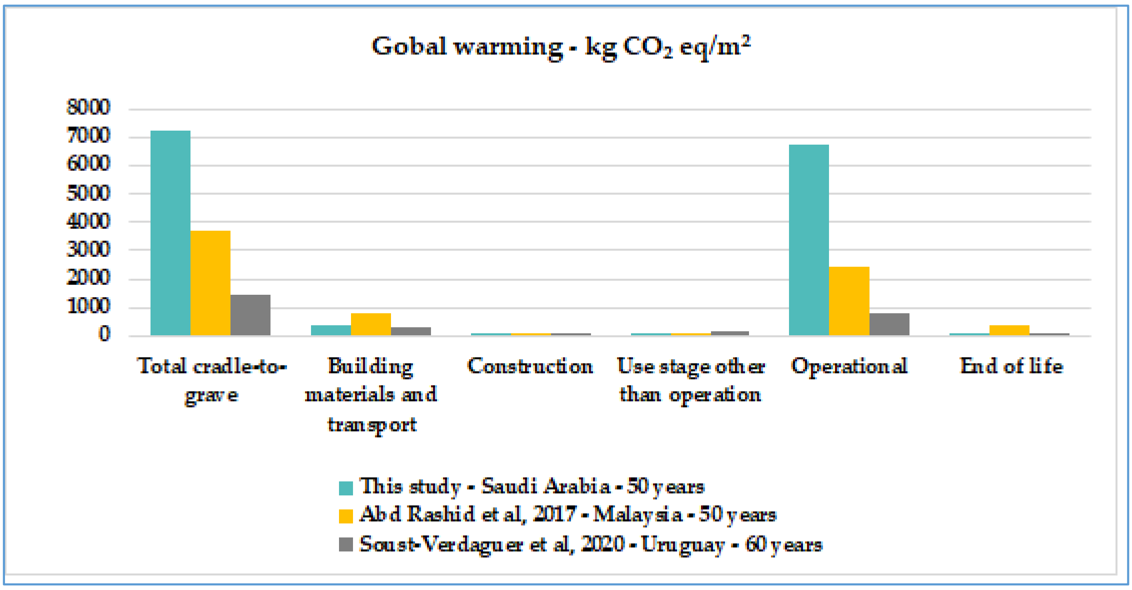
Even though the benefits of improving the electricity mix per kWh per year and for 50 years are important, the operational stage under the improved mix would have remained the stage with the largest impact on the life cycle of the villa, with a contribution from 84% (photochemical oxidation) to 93% (ozone layer depletion), as shown in Figure 6.

3.3. Comparison with Previous Studies

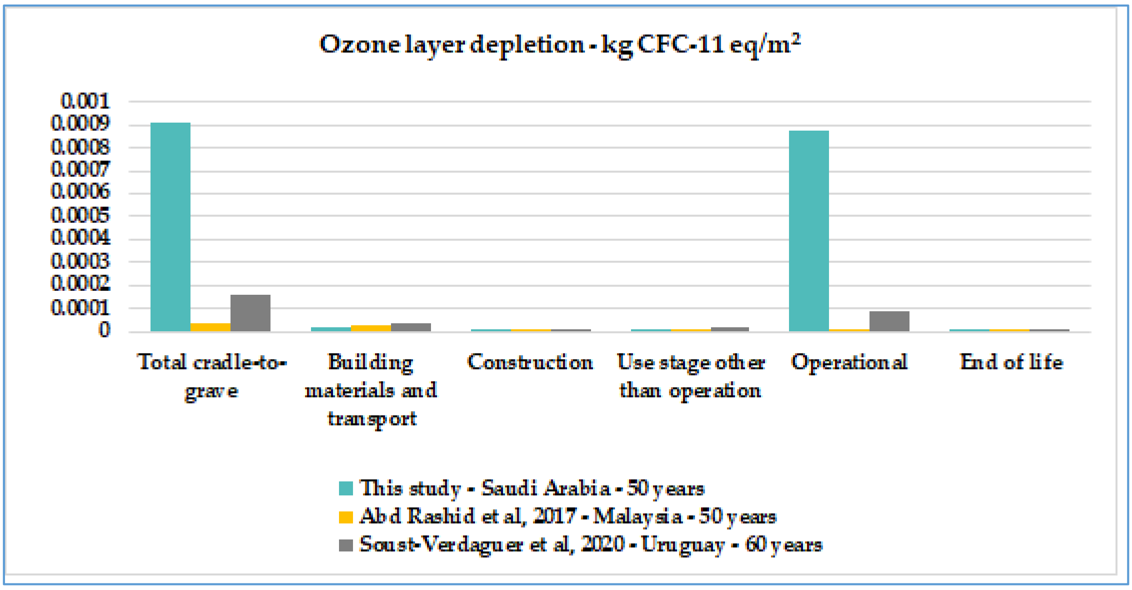
From the obtained results, it can be seen that the impact of the Saudi Arabian villa is highly dependent on the region where it is located because the energy demand is mainly dedicated to maintaining thermal comfort (Table 2). As suggested in ISO 14044, data validation is an element of LCA methodology that could be performed by comparing the results with those of other published research studies. Because no LCA study has previously been conducted from cradle to grave in Saudi Arabia, we attempted to compare our results to those of other studies in different regions that considered similar materials and scope.

A cradle-to-grave comparison with a residential building in Malaysia [40] and Uruguay [44] was performed considering the impact of GWP, ODP, AP, and EP, as the three studies used the same LCA method, CM -baseline, and the scopes were similar, which makes the results relatively comparable.

The comparison of these four impact categories with those of other studies is presented in Figure 7.

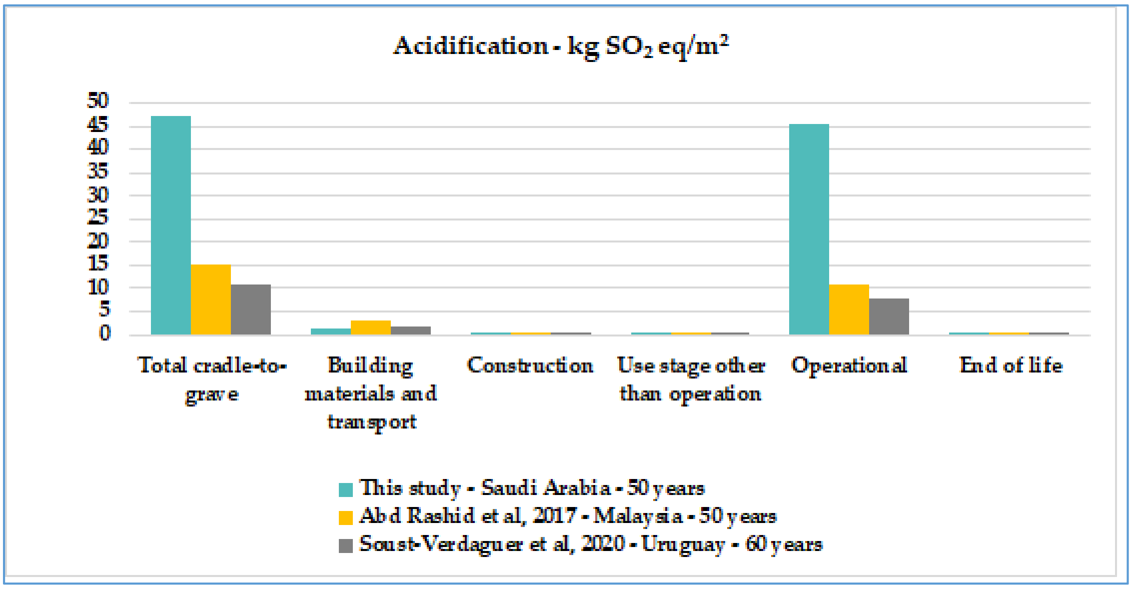


(**a**)

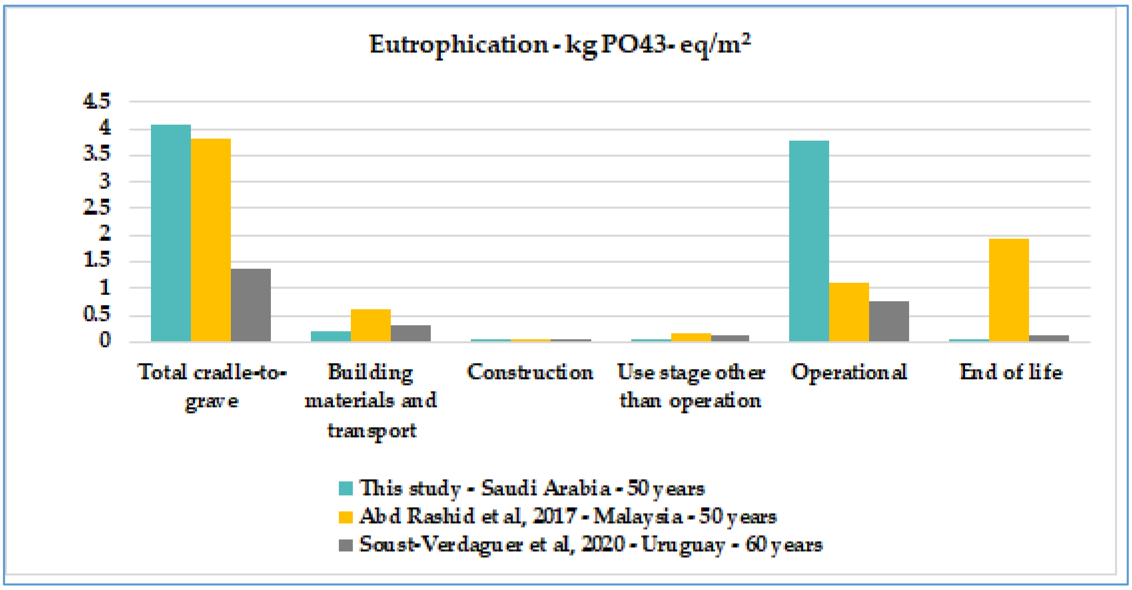


(**b**)

Figure 7. *Cont.*



(**c**)



(**d**)

Figure 7. Comparison of (**a**) GWP, (**b**) ODP, (**c**) AP, and (**d**) EP impacts from cradle to grave of a Saudi Arabian villa with those of residential buildings from other studies in Malaysia and Uruguay that covered the entire building life cycle.

The three buildings are residential. The Malaysian case assessed a 246 m^2 GFA building, with a building frame structure of reinforced concrete and clay bricks as the building envelope. The LCA referred to the environmental performance of the building during a 50-year lifespan, including in the assessment of the pre-use, construction, maintenance and operation, and end of life phases.

The Uruguayan building included in this comparison was a COVISA house, a typical three-bedroom concrete masonry Uruguayan house with a 57 m^2 GFA. The environmental assessment considered the performance during its 60-year lifespan and included the entire life cycle except for the use (module B1 of EN 15804), refurbishment (B5), operational water use (B7), and waste processing (C3) modules.

For all analyzed impact categories, the comparison showed that the Saudi Arabian villa has the highest impact because of the impact of the operational stage, even though the

Malaysian and Uruguayan buildings are also highly dependent on the operational stage. The operational stage of the Uruguayan house contributed at least more than 50% to the total building life cycle, whereas building materials production and transport represent around 20% of the impact. The Malaysian case differed as the operational stage was the most significant for GWP and AP, but for ODP, it is the materials stage, and for EP, the end of life.

As observed in Figure 7, the operational stage in the Saudi Arabian villa represents more than 90% of the four impact categories used for the comparison. In this study, the total amount of electricity consumed per year was 121.52 kWh/m^2; this was 59 and 57 kWh/m^2 in Malaysia and Uruguay, respectively. In Malaysia, cooling energy demand represented 47% of the total electricity use, while in Saudi Arabia, it was 62%.

Regarding building materials, the Saudi Arabian residential building had the lowest impact for three of four impact categories. The villa has a larger GFA, which can mean less weight per m^2. Moreover, in the building foundation, a significant difference exists between the amount of concrete, a material that was widely used in the three buildings. For the Saudi Arabian villa, a slab on grade foundation was assumed, which is a method most commonly used in warmer climates where there is no seasonal freezing of the ground.

The comparison shows the results are comparable and confirm that the energy demand hotspot in the residential sector in Saudi Arabia is the operational stage.

3.4. Key Limitations

An LCA reflects the system analyzed and data used, so all limitations concerning data availability and system boundaries need to be considered. The bill of materials was exhaustively analyzed, and different partners were involved in the process, which influence all villa life cycle stages. The most significant stage, the operational stage, was modeled with EnergyPlus according to the characteristics of the villa defined using Revit software, so the limitations of the tools used were assumed when conducting the LCA. Even though secondary datasets were modeled to represent the Saudi Arabia context, the results are also sensitive to the datasets used in the assessment, particularly those describing materials manufacturing. Hence, all used datasets are from the same LCA database, Ecoinvent.

4. Conclusions

The LCA allowed us to analyze the whole life cycle of a typical single-family residential building in Saudi Arabia considering specific construction materials and scenarios of waste management and transport. The results showed that the operational stage has the most impact on energy consumption and the environment in the life cycle of the villa. These results align with previously published life cycle assessments of residential buildings. As indicated in Section 1 and as published in previous studies, the operational stage represents between 40% and 90% of the life cycle energy consumption depending on climatic conditions and usage habits. The operational stage of a typical Saudi Arabian villa represented 95% of the total energy demand, which is above this range. The significant contribution of this stage to the energy demand has implications in terms of environmental impact, which has two main causes. First, the amount of electricity consumed during the use stage is very high (122 kWh/m^2 (GFA) and year) mainly due to climatization requirements and, second, because electricity generation is highly dependent on fossil fuels.

In this study, a sensitivity analysis for the second cause was conducted. Saudi Arabia plans to increase the share of renewable energy sources and reduce the amount of electricity generated from hydrocarbons, which currently represent 46% of the total installed power, by 2032. Compared to the current electricity environmental impact, the CO_2 emission from electricity generation will decrease by 53%, which represents a significant reduction in impact. However, if we analyze how this reduction in environmental impact affects the residential building life cycle, we conclude that it is an impacting factor as a reduction in the impact is obtained, but the main factor is the amount of energy demand during the use stage. Therefore, the results from the sensitivity analysis showed that even with a reduction of 54% in hydrocarbons in electricity generation, the contribution of the operational stage to the total life cycle environmental impact of the villa remained unchanged. For the global warming impact category, its contribution decreases from 93%, with the current electricity mix, to 87% with the increase in renewable sources.

Further research needs to be conducted to identify the main cause of building life cycle environmental impact and energy demand, which is the amount of electricity required during the use stage. Energy efficiency strategies need to be developed and evaluated in the Saudi Arabian context to reduce the electricity demand of residential buildings, which now accounts for 50% of the country's electricity demand. The life cycle approach will allow us to evaluate how the focus on operational energy demand of these strategies affects all building life cycle stages, from building materials manufacturing to the end of life.

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