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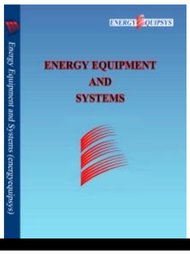

How life cycle assessment is key to reducing carbon emissions in architectural development: Circular economy and regenerative design

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ABSTRACT

In line with the growth of population and construction, the use of natural resources is increasing, which gradually leads to harming nature, increasing greenhouse gas emissions and global warming; this research examines both energy consumption and the environmental impacts in the GWP section; In besides, examining the points related to the architectural development process, it seeks to integrate the relationship between construction and environment through the use of regenerative design. The process involved selecting target buildings, gathering initial data, and 3D modeling (Design Builder). The next step was to conduct a sustainable analysis, including energy analysis and life cycle assessment (One Click LCA). The results showed that the architectural development in buildings has reduced CO2e carbon emissions in the energy sector by 1.3 times. Nevertheless, the sector related to the materials of the modern house is almost 3.5 times more effective on the global warming potentials than the vernacular house. after changing and using low-carbon materials, the impact of the material sector on global warming potential in modern and vernacular houses decreased by 1.8 and 2.6 times, respectively. As a result, although the use of advanced materials has improved its thermal performance, these materials have increased the overall environmental impacts in the global warming potential section by a factor of 2.9.

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1. Introduction

The use of energy resources has increased by about 70% since the 1970s [1]. This has led to rapid environmental degradation; thus to promote sustainable economic growth and environmental sustainability, there seems a need for shifting from non-renewable energy sources, and the implementation of environmental laws and regulations [2]. Climate change is a pressing issue that the world is currently grappling with. It's been caused by the burning of fossil fuels, which results in the release of CO2 emissions and other greenhouse gases into the atmosphere [2], [3]. The changing global climate is causing alterations in the meteorological conditions and climate zones, which in turn affects the construction of buildings in various regions of the world; moreover, it causes alterations in the energy usage of residential buildings. [4]. This is a problem that affects several countries worldwide, including Iran. The energy sector in Iran, including the energy production in some sections as to electricity, transportation and

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buildings, is an important source of greenhouse gas emissions [5]. In this regard, the construction industry is a significant contributor to greenhouse gas emissions, air pollutants, and solid waste [6].

These factors are driving researchers to conduct research using tools such as life cycle assessment (LCA), circular economy (CE), resource management and regenerative design to reduce energy consumption and also to use materials that reduce carbon emissions as much as possible. In addition, as the construction sector increases, research in this area might have a major impact on reducing carbon emissions. In fact, in case greenhouse gas emissions from buildings continue at the current rate, a problematic situation will be created. This sector is responsible for 36% of total carbon emissions [7], as well as acid rain-causing agents [8]. Also, it uses up approximately 40% of the world's natural resources and generates 25% of global waste [9], particularly in urban regions.

The IPCC report of 2007 has shown a strong link between greenhouse gas emissions and global average temperature. It is estimated that the world's urban population will grow to 4.6 billion by 2030 [10]. The rise in population has led to an increased demand for construction, resulting in higher consumption of minerals and energy. This has led to the use of various resources for constructing, operating, maintaining, and demolishing buildings, which in turn, leads to environmental outputs such as greenhouse gas emissions and solid waste [11].

Generally, the construction industry plays a crucial role in creating the physical environment, stimulating economic growth, and generating employment opportunities. However, it also has adverse effects on the environment; effects such as reducing land availability and quality, producing solid waste, emitting dust and gas, and consuming non-renewable resources [12].

It’s believed that construction is a major cause of environmental damage, because it uses up non-renewable resources, contributes to land degradation and depletion, generates solid waste, produces dust and gas emissions, and creates noise pollution [13]. Construction waste refers to the waste materials that result from construction, demolition, and renovation projects [14]. The increasing construction activity associated with urbanization and urban renewal leads to the generation of significant amounts of construction waste [15]. In this regard, the global construction industry due to several significant factors, including the reduction of the depletion of natural aggregate deposits and environmental protection, is driven to recycle waste [16]; because almost half of the construction wastes generated during the end-of-life phase come from construction and demolition (C&D) waste, which is produced throughout the lifespan of buildings [17].

C&D waste disposal is a significant waste of finite natural resources [18]. For example, according to the United States report, approximately 10 billion tons of C&D waste are produced annually on a global scale roughly 700 million tons [19]. However, the makeup of C&D waste might differ among regions because of variations in economic factors, natural surroundings, and construction methods [20]. Typically, the weight of large and heavy materials like concrete and brick makes up around 70 to 80% of the overall waste [21]. Some C&D wastes include dangerous materials like asbestos that might cause serious harm to people, the environment, and society [22]. In this regard, much research has been done to deal with C&D waste [20], [23], [24]. For example, in one study, C&D waste was used as recycled aggregates (RA) in concrete [25]. the other research findings confirm the use of recycled C&D materials in building geosynthetic reinforced structures, that by decreasing the environmental impacts of C&D waste landfilling and natural aggregate extraction, helps the reduction of our carbon footprint [26].

Globally, there is a growing need for construction aggregates [27]. In 2015, the amount of the extracted resources was 13 times greater than that in 1900, rising from 7 Gt to 89 Gt worldwide [28]. Actually, the construction sector follows a linear economic model of "take, make, dispose of", which leads to the extraction of more than 30% of natural resources and the generation of 25% of solid waste worldwide [17]. In this regard, several studies have shown that the linear economy can harm the environment to a great extent [29]–[31]. Thus, the linear economy's depletion-based "produce-consume-dispose" model must be replaced with the CE "reduce-reuse-recovery-recycle-redesign-remake" model to affect a paradigm shift.

The concept of CE was proposed based on the "spaceship theory" by Boulding for the first time(1966). This theory views the earth as a closed system having no exchange of matter with the external environment. The CE model aims to separate global economic growth from the consumption of finite resources [32]; In other words, the concept of CE maximizes the value of building components and resources by keeping them in a continuous cycle of use, reuse, repair, and recycling. This approach helps to minimize waste and to prevent negative impacts like CO2 emissions [33]. From this perspective, the focus is on maximizing the lifespan and utility of buildings and treating them as a repository of materials for the future. As a result, reusing and recycling building materials can lead to the recovery of resources in the future [34].

In recent times, the CE approach has gained growing attention, which involves using strategies such as reuse, repair, refurbishment, recycling, and recovery to slow down, narrow, and close material loops. This approach is being adopted to address the unresolved issues arising from the building industry and minimize their impacts [35]. This strategy aims to achieve a future where there is no production of waste and building debris, and economic activities gradually reduce the consumption of raw resources [36]. In other words, CE models aim to reuse end-of-life building materials by deconstructing their components, creating material banks for new buildings, and maintaining a closed loop of components and materials [37].

Reduction, reuse, and recyclability of materials and components are fundamental concepts of CE. These concepts have been successfully implemented in various industries, such as electrical equipment and textiles. However, their application in the building sector is relatively new and less widespread [38]. CE principles, by decreasing greenhouse gas emissions in supply chains, provide distinct chances for addressing the climate crisis by decreasing greenhouse gas emissions in supply chains [39]. Many researchers emphasize that CE is based on the fundamental principle of "regeneration" [40]–[42].

In this regard, a comprehensive evaluation of the entire life cycle is necessary as the embodied environmental impact accounts for 50% of the total greenhouse gas emissions in energy-efficient residential buildings over a 50-year lifespan [43]. LCA assesses the environmental impact of a product throughout its life cycle [44]. LCA, by evaluating the resources used, outputs generated, and potential environmental consequences throughout its life cycle, involves analyzing the environmental impact of a product system, including its processes and designs [45]. LCA is widely used in the construction industry for improving sustainability and choosing environmentally friendly alternatives [46]. In this regard, many studies have used LCA in the building sector [47]–[49]. For example, according to one study, cob production (cob is an earthen construction material) consumes about 38% of energy and reduces about 82% of global climate change impacts compared to indigenous materials [50]. In another study, the results showed that steel requires more electricity than concrete in every environmental category, while concrete has a higher emission rate [51]. A review of some of the research that has been carried out in line with the current research is presented in Table 1.

In summary, this comprehensive study highlights the importance of considering the environmental impact of buildings throughout their life cycle. Different assessment methods, such as life cycle assessment, energy assessment and carbon emissions assessment, provide valuable insights into these impacts. The results suggest that while certain materials may have higher carbon emissions, their recyclability and other sustainable attributes can help to offset these emissions. It is vital to focus on reducing carbon emissions during both the construction and operational phases of a building. Research highlights the benefits of using sustainable building materials and incorporating energy efficient technologies, such as solar panels on the roof. Prefabrication and Building Information Modelling (BIM) also play an important role in reducing environmental impact. Finally, the study, optimizing manufacturing processes and minimizing land use, highlights the importance of selecting low-carbon materials, optimizing manufacturing processes and minimizing land use to achieve energy efficiency and promote green building design. However, it seems that various researchers have paid less attention to the issue of architectural and construction progress in terms of energy consumption, consumable materials, and carbon emissions, especially when investigating the architectural progress of indigenous houses compared to modern houses.

Table 1. An overview of some of the research done in line with the present research

No.	Research title	Building type	Location	Software	Conclusion	Refrences
1	Analyze Differences in Carbon Emissions from Traditional and Prefabricated Buildings Combining the Life Cycle	Traditional and Prefabricated Buildings	China	One click LCA	Prefabricated buildings offer significant carbon emission reductions compared to cast-in-situ buildings, with the highest emissions occurring during the field installation.	[52]
2	A Comparative Study on the Life Cycle Assessment of New Zealand Residential Buildings	Residential buildings	New Zealand	One click LCA	The light steel house had 12.3% more carbon emissions compared to the light timber house. However, the extra carbon emitted by the light steel house can possibly be balanced out because steel is recyclable.	[53]
3	Comparative life cycle assessment of a reinforced concrete residential building with equivalent cross-laminated timber alternatives in China	Residential buildings	China	Revit, DesignBuilder 4.6, One click LCA	The use of cross-laminated timber (CLT) and hybrid CLT buildings leads to reduced greenhouse gas emissions throughout their life cycle, particularly in the product and construction stages, making them more sustainable compared to reinforced concrete(RC) buildings.	[54]
4	Life cycle assessment for carbon emission impact analysis for the renovation of old residential areas	Old residential buildings	China	---	When the impact of embodied carbon is not taken into account, the estimates for carbon reduction are inflated by 5.54%; Furthermore, Incorporating rooftop solar panels is the most effective measure to reduce carbon emissions, and can serve as a guide for low-carbon renovations in older residential areas, benefiting energy saving and emission reduction in cities.	[55]
5	Comparative Life Cycle Assessment of Mass Timber and Concrete Residential Buildings: A Case Study in China	Residential buildings	China	One click LCA, Carbon Designer	The timber building, highlighting its environmental benefits, demonstrated an impressive decrease of 25% in the global warming potential compared to its concrete counterpart. To enhance the sustainability of timber buildings, focusing on local sourcing, improved logistics, and manufacturing optimizations is crucial.	[56]
6	Assessing the embodied carbon reduction potential of straw bale rural houses by hybrid life cycle assessment: A four-case study	rural houses	China	One click LCA	The materialization stage is the primary contributor to carbon emissions in building construction, indicating the need for sustainable material choices. Wood and light-steel structures offer significant reductions in carbon emissions for rural houses, emphasizing the importance of selecting low-carbon materials.	[57]
7	Assessing the effect of structural parameters and building site in achieving low carbon building materialization using a life-cycle assessment approach	Residential buildings	---	---	The research findings highlight the significant carbon reduction potential achieved by replacing steel structures with concrete structures and relocating structures to different soil sites.	[58]
8	A quantitative study of life cycle carbon emissions from 7 timber buildings in China	timber buildings	China	One click LCA	Timber buildings play a role in decarbonization specifically during the production stage, resulting in an approximately 11.0% reduction of potential carbon emissions. On the other hand, upgrading energy efficiency to ultra-low-energy buildings can lead to even greater carbon emissions savings, with a potential reduction of approximately 32.7%.	[59]
9	Embodied energy and CO2 emissions of life cycle assessment (LCA) in the traditional and contemporary Iranian construction systems	Green Guesthouse	Iran	One click LCA	The study concludes that the use of Traditional Techniques and Materials can have a substantial effect on the overall life cycle energy and carbon emissions in Iran's short-lived buildings.	[60]
10	Carbon emission reduction in prefabrication construction during materialization stage: A BIM-based life-cycle assessment approach	Residential buildings	China	One click LCA, BIM	The study, highlighting the benefits of BIM and prefabrication in reducing environmental impact, emphasizes the importance of a potential 15% reduction in emissions by utilizing prefabricated components.	[61]

No.	Research title	Building type	Location	Software	Conclusion	Refrences
11	Comparative Whole Building Life Cycle Assessment of Energy Saving and Carbon Reduction Performance of Reinforced Concrete and Timber Stadiums—A Case Study in China	Stadiums	China	Integrated Environmental Solutions software	Based on life cycle assessment, timber stadiums in China show greater potential for energy conservation and carbon reduction compared to reinforced concrete stadiums.	[62]
12	Comparative Life-Cycle Assessment of a High-Rise Mass Timber Building with an Equivalent Reinforced Concrete Alternative Using the Athena Impact Estimator for Buildings	high-rise MT building	United States	LEVER Architecture, One click LCA	The cross-laminated timber building emits 70% less CO2 eq than the reinforced concrete building, while storing 1.84 × 106 kg of CO2 eq in its wood material during its lifetime; therefore, choosing sustainable building materials is crucial for mitigating global climate change.	[63]
13	A review of life cycle assessment of buildings using a systematic approach	---	---	---	For a more effective building LCA process, a multi-objective assessment with other tools is necessary. Additionally, BIM-based LCA saves time and effort.	[44]
14	Development of a Carbon Emissions Analysis Framework Using Building Information Modeling and Life Cycle Assessment for the Construction of Hospital Projects	Hospital	China	Revit, GTJ2018, Green Building Studio, One click LCA	During the construction phase, the largest portion (around 49.64%) of carbon emissions is attributed to reinforced concrete engineering, whereas HVAC systems (heating, ventilation, and air conditioning) account for the highest proportion (approximately 53.63%) during the operational phase.	[64]
15	A hybrid life cycle assessment of embodied energy and carbon emissions from conventional and industrialized building systems in Malaysia	conventional and industrialized building	Malaysia	One click LCA	The hybrid LCA model enhanced the accuracy of energy and carbon inventory data compared to other models. By utilizing low-energy and carbon-intensity materials, products, or components, a significant reduction in energy and carbon emissions was achieved, which demonstrates the practicality of this methodology in assisting designers during the early stages of construction in Malaysia.	[65]
16	Life cycle assessment and cost analysis of residential buildings in southeast of Turkey: part 1—review and methodology	Residential buildings	Turkey	review and methodology	The study emphasizes the importance of considering environmental impacts throughout the life cycle of a building, and highlights energy, material, and land use minimization as fundamental steps to achieve energy efficiency and eco-friendliness in building design.	[66]
17	A review of Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings	---	---	---	The study found that Life Cycle Assessment, Life Cycle Energy Assessment, and Life Cycle Carbon Emissions Assessment have a similar goal of evaluating the environmental impacts of building construction throughout its entire life cycle.	[67]
18	Life-cycle assessment and control measures for carbon emissions of typical buildings in China	residential and office buildings	China	One click LCA	Buildings constructed with a reinforced concrete block masonry structure have the potential to significantly reduce carbon emissions by 38-112 kgCO2/m2 compared to buildings constructed with either a reinforced concrete or brick masonry structure.	[68]
19	Scope-based carbon footprint analysis of U.S. residential and commercial buildings: An input–output hybrid life cycle assessment approach	Residential buildings	United States	---	The study reveals that the highest carbon footprint in U.S. buildings is attributed to direct purchases of electricity, accounting for 48% of emissions. Additionally, the construction supply chain plays a significant role, contributing 6% to the building's carbon footprint.	[69]
20	Evaluation of whole life cycle assessment for heritage buildings in Australia	residential heritage buildings	Australia	One click LCA	The research discovered that simply reducing life cycle primary energy consumption does not necessarily result in a corresponding decrease in carbon emissions.	[70]

To be considered sustainable, a city must ensure that its residents' quality of life is maintained at a desirable level for an extended period of time. This involves upholding integrity, self-sufficiency, natural performance, quality assurance, and adaptability [71]. As a result, regenerative design has been suggested as a way to create a system that has a beneficial effect on the environment [72]. Regenerative processes are those that replenish the resources required for their operation. Regenerative design is based on holistic thinking, where the combination of human and non-human systems enhances resilience [73].

The review of the literature indicates that architecture has progressed towards energy optimization, but new constructions will deplete resources and increase environmental impact. This article investigates the energy consumption and environmental repercussions in the (GWP) region. The regenerative design approach will be considered to achieve the maximum environmental impacts. In this respect, low-carbon and environmentally compatible materials are used. In addition, an analytical model is needed to plan the development of the 6Rs (reuse, recovery, recycling, recovery, redesign, remanufacture) in the building sector. The present study advocates for the conservation of rural homes and proposes the use of eco-friendly modern materials that manage resource depletion not only to minimize harm to the environment but also to enhance the ecosystem's quality. In addition, the present study has evaluated the approach of creating a balance between the use of low-carbon materials along with energy consumption optimization.

In general, the innovation of this article can be expressed as follows:

- To study simultaneously the amount of energy consumption and the amount of carbon emissions of materials in order to reduce the effects of carbon emissions on GWP.
- Investigate the impact of architectural development on reducing energy consumption and carbon emissions.
- Integrate the relationship between construction and the environment through the use of regenerative design, which has been less explored.

Nomenclature

AP	acidification
BC	building circularity
BCI	building circularity index
BIM	building information modeling
C&D	construction and demolition
CDW	construction and demolition waste
CE	circular economy
CO2e	carbon dioxide equivalent
EPD	environmental product declarations
EP	eutrophication potential
FU	functional unit
GWP	global warming potential
HVAC	heating, ventilation, and air conditioning
ISO	international organization for standardization
LCA	life-cycle assessment
ODP	ozone depletion potential
POCP	formation of ozone in the lower atmosphere
SWM	solid waste management
6R	reuse, recovery, recycling, recover, redesign, remanufacture

2. Material and methods

The implementation of the CE principle in the construction sector encourages the utilization of eco-friendly materials, minimization of waste generation, and maximization of material recovery while avoiding landfill disposal [74]. In this research, the focus has been on achieving maximum resource utilization by studying the changes required in the building's CE perspective.

The construction industry heavily relies on minerals and energy, leading to a scarcity of resources. As a result, the way resources are used and recycled should change. This shift towards CE, while minimizing environmental damage, aims to increase resource utilization. This was done through the regenerative design approach in the final step.

The process involved selecting target buildings, gathering initial data, and studying BIM and 3D modeling. The next step was to conduct a sustainable analysis, including energy analysis and LCA. Also, the study included analyzing the energy losses and gains of various building components such as walls. In addition, the thermal loads of houses were examined. In the second step, LCA tools were used to assess the stability components of the building. Furthermore, as shown in Fig. 1, this study has focused on developing zero-emission structures by selecting biocompatible materials for regenerative models. Finally, to create a balance between the use of alternative low-carbon materials and energy consumption, energy optimization was performed.

2.1 Step 1: Energy simulation software

The need for dependable energy demand forecast models has risen due to the environmental impact of the escalating global building energy demand [75]. As a result, to achieve intelligent and sustainable designs, it would be essential to utilize building energy consumption modeling and forecasting as a crucial tool [76].

Various studies have utilized different software for building energy simulation, including DesignBuilder [77], Rhinoceros 3D (Honeybee, Ladybug) [78], and TRNSYS [79]. But, based on the research conducted by Vitor Pereira [80], it has been shown that EnergyPlus has been used the most for energy analysis; Therefore, in the current research, the DesignBuilder software, which uses the EnergyPlus engine, has been utilized. Another reason for choosing DesignBuilder software for simulating building energy would be the possibility of determining the building materials and connecting them to One Click LCA software through the relevant plug-ins, which are used in this research.

2.2 Step 2: LCA of buildings

To assess the life cycle of the target buildings, the second step involves the evaluation of various modules from A1 to C4, as shown in Fig. 2. Additionally, Module D transforms the building's life cycle information into a cradle-to-cradle life cycle.

The LCA studies involve normalizing inputs and outputs, which are defined as vernacular and new residential buildings in Kang, Iran in the cold climate. Various research studies have utilized different software for the LCA of buildings, including ATHENA [81], Gabi [82], Open LCA [83], and SimaPro [84]. However, in this research, One Click LCA software, due to its numerous capabilities, such as integration with modeling software and the ability to analyze carbon design, was used. LCA measures the environmental impacts and economic costs of building products. The EN-15978 standard was also used to analyze material and energy changes, focusing on life cycle stages.

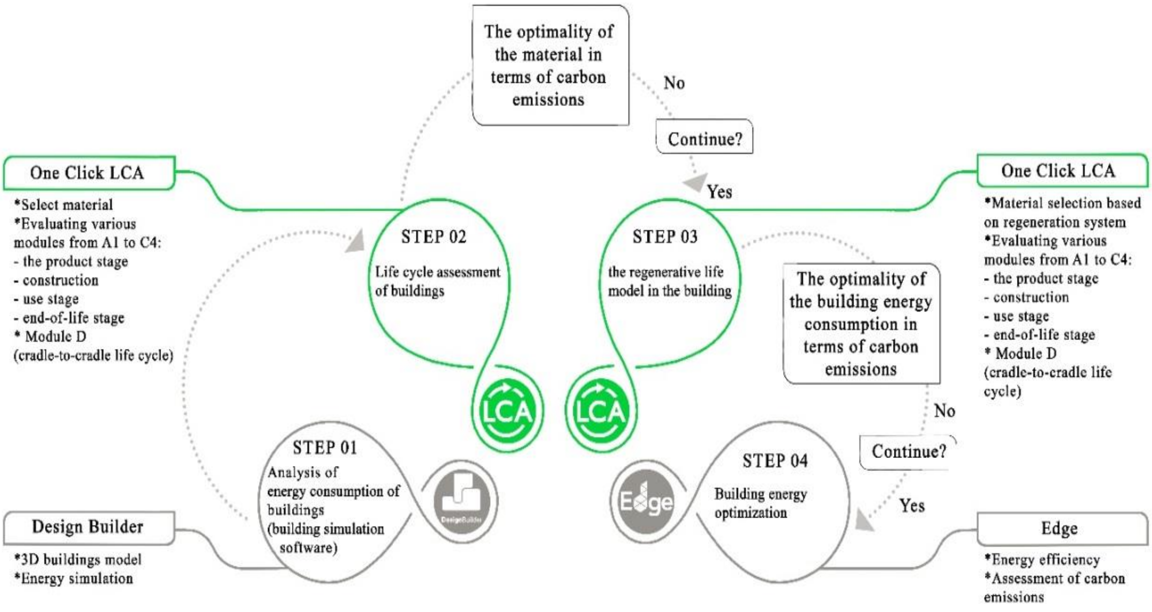


Fig. 1. Applied process of research

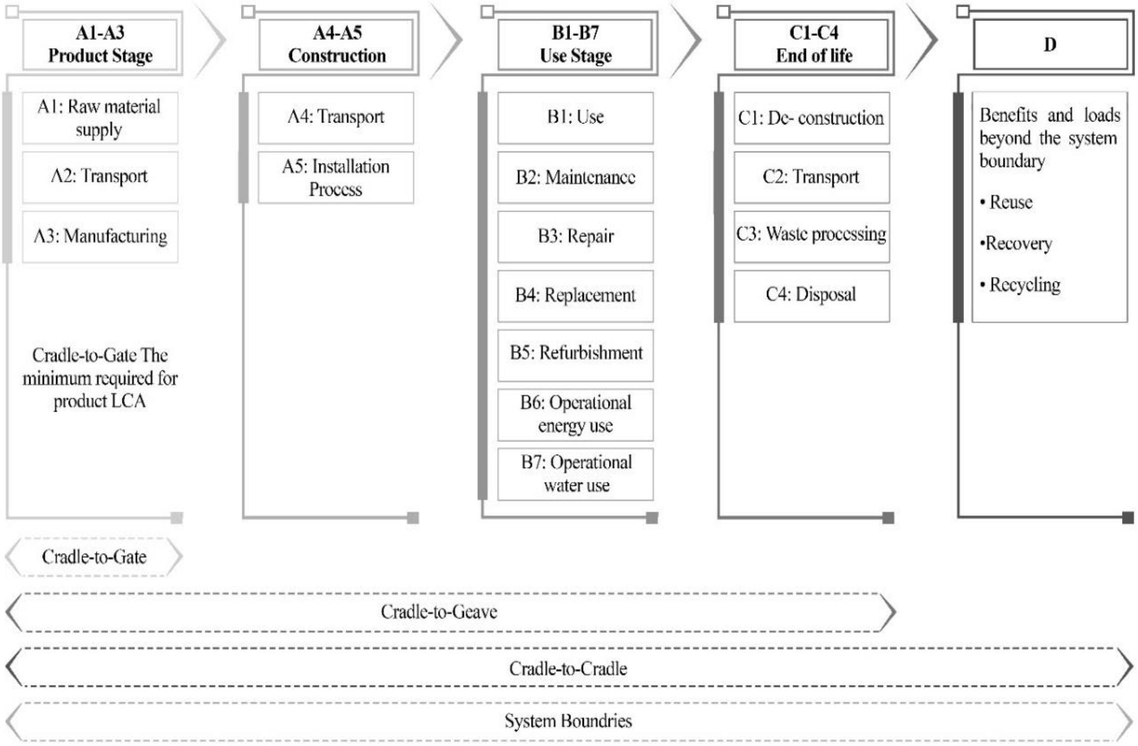


Fig. 2. Life cycle stages

Table 2. Classification of carbon emissions of materials (One Click LCA software)

Carbon Emission	1 CO2	2 CO2	3 CO2	4 CO2	5 CO2
Rank Rate	Very Low	Low	Average	High	Very High

2.3 Step 3: The regenerative life model

Eco-friendly products can be used as valuable natural materials. So, the regenerative approach although managing resource depletion, focuses on improving the ecosystem's quality [85]. The One Click LCA database categorizes materials based on their group and subgroup, in which carbon emissions are compared to others in the same group. The groups are shown in Table 2. Materials with the lowest carbon emissions, in the top 20%, are marked as 'very low' in dark green, while those with the highest carbon emissions, in the bottom 20%, are marked as 'very high' in dark red. In this study, a building model is developed using a range of materials that have varying levels of carbon emissions. However, the final design adopts a regenerative approach and uses materials with low carbon emissions. This ensures that zero-emission and regenerative buildings can be designed using selected materials.

2.4 Step 4: Building energy optimization

The sector related to energy consumption in buildings, which has been addressed in LCA and in stage B6, can have a significant impact on GWP. Even considering the best materials for buildings, energy optimization in buildings is still needed, because a major part of the impacts related to GWP is due to high energy consumption. As a result, after stage 3 and replacing materials with low carbon emissions, there would be a need for optimization of the building's energy consumption.

However, for the energy optimization process, the Edge software was used this time. as this software can express the amount of energy consumption and carbon produced according to the input data in the fastest possible way than the other software. besides, this software makes the optimization of energy consumption possible by providing options. In fact, EDGE makes it easy to design and certify resource-efficient and zero-carbon buildings of any type, anywhere. The free EDGE software offers a measurable way to cut back on the resource intensity of your building design. This part of the present study has been added to the research as a complement to the main objective of the research, so as to create a balance between energy consumption optimization and optimizing the materials used in buildings in terms of reducing carbon emissions.

3. Results and discussion.

3.1 Study area

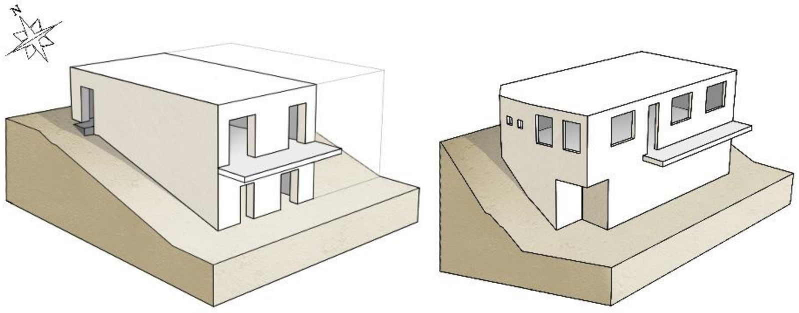
Kang village is situated in Razavi Khorasan province, Iran, at a longitude of 59°13' and a latitude of 36°19'. The village has a stepped architecture, where the roofs of lower buildings serve as courtyards for upper buildings (Fig. 3). Due to the presence of high mountains, trees, and cool winds, the village has a moderate climate in hot seasons, but a cold mountainous climate in cold seasons.

3.2 Case studies

This research examines two residential buildings (one vernacular and one modern) located in the cold climate of Kang Village (Figure 4). Table 3, provides general information about both buildings. The study aims to compare the two buildings and their architectural features.

As the aim of the present study is to assess the variations in energy consumption and to compare the LCA on the impact of architectural advances, these two models were chosen. These two houses were chosen for the present study because of their similarity in area, orientation, materials, number of floors, and use. The vernacular house is characterized by its wooden frame, thatch, and stone, with a wall thickness of 60 cm that has been designed for increasing the efficiency of thermal energy in the Kang region. In contrast, the modern house has a metal frame and uses bricks in its construction. Both of these houses have floors that are used for residential purposes and lower floors that are not used and are empty of habitation. Table 4 shows the other building materials used for both houses.

Fig. 3. Kang village, Iran



Vernacular House

Modern House

Fig. 4. Vernacular and modern houses 3D model

Table 3. General specifications of the two vernacular and modern buildings

	Vernacular building	modern building
Location	Razavi Khorasan, kang, Iran	Razavi Khorasan, kang, Iran
Type	Residential	Residential
Building elongation	north-south	East-west
Area	105	103
floors	2	2
Structure type	Thatch with a wooden frame	Steel structure

Table 4. Building materials available in the selected research buildings

Vernacular House

CO2 - Bricks, 226x104x60, 226x85x60 mm

CO2 - Precast concrete cover slab, Thickness 50-80 mm, 2.4x7.4 m

CO2 - Clay bricks

CO2 - Flooring/decking, composite wood, French average, ép. 34mm

CO2 - Precast concrete blocks (CMU), 105.7 units/m3, 10.5 m2/m3, 1950 kg/m3, 440 x 100 x 215 mm

CO2 - XPS insulation panels, L=0.033 W/mK, R=1.2 m2K/W, 40 mm, 1.25 kg/m2, 31.25 kg/m3, compressive strength 300 kPa, 40% recycled polystyrene, CO2 blowing agent, Lambda=0.033 W/(m.K)

CO2 - Floor screed mortar, cement screed, 1500 kg/m3

CO2 - Gypsum plaster, 1100 kg/m3

CO2 - Gypsum plasterboard, 6,5 - 18 mm; 5,5-18 kg/m2

CO2 - Urea formaldehyde resin in-situ foam, L = 0.0259 W/mK, 10 kg/m3

CO2 - Clay soil, compacted dry density, 1600 kg/m3

CO2 - Sawn timber, 489 kg/m3

CO2 - Gypsum plasterboard, 12.5 mm, 8.985 kg/m2

Modern House

CO2 - Filler mortar for repairing concrete structures, 1536 kg/m3

CO2 - Bitumen-polymer membrane roofing

CO2 - Bricks, 226x104x60, 226x85x60 mm

CO2 - Ready-mix concrete

CO2 - Bitumen sheets for waterproofing of underground walls and foundations, French average

CO2 - Floor levelling screed, cement based, 10-100 mm

CO2 - Bubbledeck concrete, T: 200 - 600 mm, C20/25 to C45/55 with Bst 500, 2400 kg/m3, 2.3 W/(mk)

CO2 - Leveling compound, cement based, fibre-reinforced, 10-60 mm, 1.7 kg/l, C25

CO2 - Float glass, single pane, 3-12 mm

CO2 - Render mortar, normal render, high-grade render, 1550 kg/m3

CO2 - XPS insulation panels, L=0.033 W/mK, R=1.2 m2K/W, 40 mm, 1.25 kg/m2, 31.25 kg/m3, compressive strength 300 kPa, 40% recycled polystyrene, CO2 blowing agent

CO2 - Drainage floor underlay from EPS, ép.25 mm

CO2 - Gypsum plasterboard, with square edges, 9.5/12.5 mm, 668 kg/m3, 10µ water vapour resistance

CO2 - Gypsum fibreboard, 12.5 mm, 1180 kg/m3

CO2 - Glue laminated wood, oak, 750 kg/m3

CO2 - Gypsum plaster, 1100 kg/m3

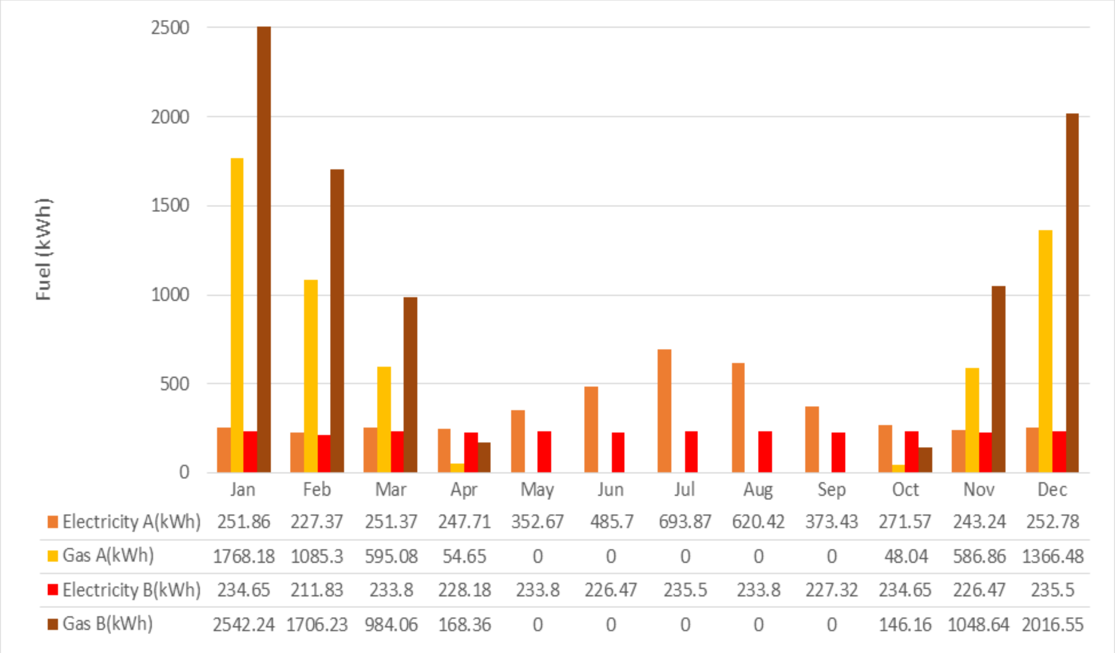
CO2 - Polyethylene foam, L = 0.050 W/mK, 30 kg/m3

3.3 Analysis of simulation results

After performing the building simulation process, the obtained results were examined. The modern house uses active air conditioning, heating and lighting equipment along with a passive ventilation system, so in the simulation of this house, normal HVAC systems specific to the cold climate were used. The vernacular house also uses active heating and lighting equipment but does not have an active air conditioning system.

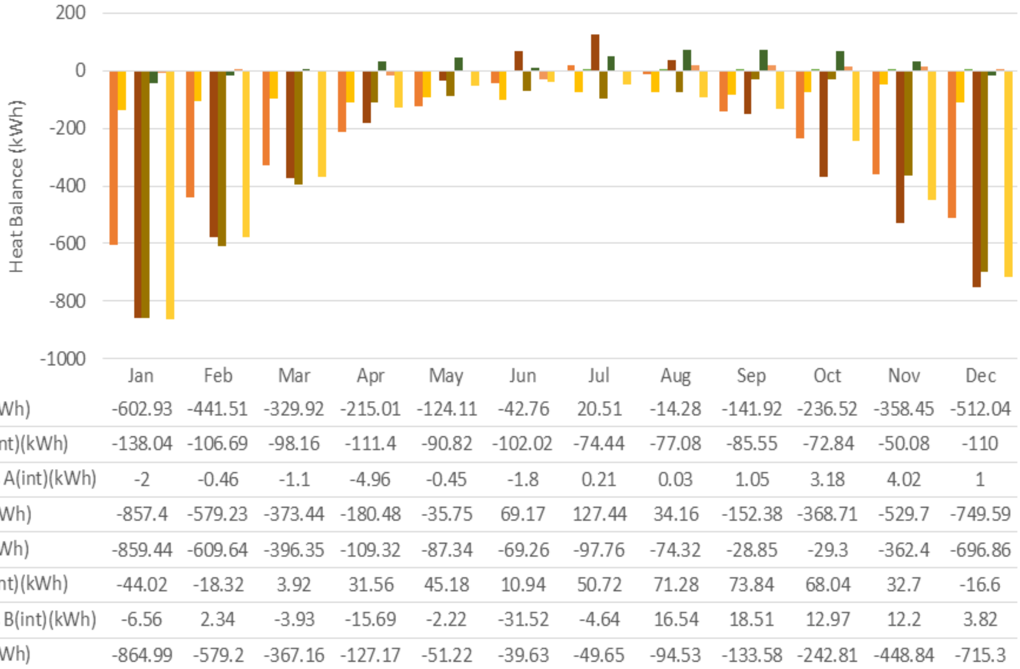
The results showed that the maximum natural gas consumed in the vernacular and modern houses was 2542.24 and 1768.18 kWh respectively (in December). The analyses also showed that the Vernacular house, with the use of thick walls and a passive air conditioning system, was able to achieve a better performance compared to the modern house in terms of electricity consumption. On an annual basis, modern homes outperform indigenous homes in terms of natural gas consumption, and vernacular homes use 1.5 times less electricity than modern homes.

The maximum energy consumption for both the modern and vernacular houses occurred in December. The walls of a vernacular house lose energy 1.4 times more than the walls of a modern house, according to the analyses of the house's components. The energy loss in the roofs of both buildings is almost similar, while on the floor area the modern house loses energy 3.1 times more than the vernacular house. In both houses, the lowest level of thermal behavior during the year was related to the floors of the houses' in the modern house, the highest amount of heat absorption was related to the roof of the house and particularly in August, but in the vernacular house, the highest amount of heat absorption was related to the floor of the house and in September. Overall, the annual thermal behavior of the modern building indicates a 7% reduction in energy waste compared to the vernacular house. This indicates the improved thermal performance in the architectural development process (Fig. 6), which may be due to the use of new building materials in different parts of the building.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
■ Electricity A(kWh)	251.86	227.37	251.37	247.71	352.67	485.7	693.87	620.42	373.43	271.57	243.24	252.78
■ Gas A(kWh)	1768.18	1085.3	595.08	54.65	0	0	0	0	0	48.04	586.86	1366.48
■ Electricity B(kWh)	234.65	211.83	233.8	228.18	233.8	226.47	235.5	233.8	227.32	234.65	226.47	235.5
■ Gas B(kWh)	2542.24	1706.23	984.06	168.36	0	0	0	0	0	146.16	1048.64	2016.55

Fig. 5. Fuel and electricity consumption for two modern (A) and vernacular (B) houses based on the months of the year



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
🟧 Walls A(kWh)	-602.93	-441.51	-329.92	-215.01	-124.11	-42.76	20.51	-14.28	-141.92	-236.52	-358.45	-512.04
🟨 Floors A(int)(kWh)	-138.04	-106.69	-98.16	-111.4	-90.82	-102.02	-74.44	-77.08	-85.55	-72.84	-50.08	-110
🟩 partitions A(int)(kWh)	-2	-0.46	-1.1	-4.96	-0.45	-1.8	0.21	0.03	1.05	3.18	4.02	1
🟫 Roofs A(kWh)	-857.4	-579.23	-373.44	-180.48	-35.75	69.17	127.44	34.16	-152.38	-368.71	-529.7	-749.59
🟫 Walls B(kWh)	-859.44	-609.64	-396.35	-109.32	-87.34	-69.26	-97.76	-74.32	-28.85	-29.3	-362.4	-696.86
🟩 Floors B(int)(kWh)	-44.02	-18.32	3.92	31.56	45.18	10.94	50.72	71.28	73.84	68.04	32.7	-16.6
🟧 partitions B(int)(kWh)	-6.56	2.34	-3.93	-15.69	-2.22	-31.52	-4.64	16.54	18.51	12.97	12.2	3.82
🟨 Roofs B(kWh)	-864.99	-579.2	-367.16	-127.17	-51.22	-39.63	-49.65	-94.53	-133.58	-242.81	-448.84	-715.3

Fig. 6. Heat exchange from the elements of the house on a monthly basis for modern (A) and vernacular (B) houses

3.4 LCA of buildings

The LCA results of the present research have been presented using the One Click LCA software. Also, in this research, to prevent distortion in the results, due to the distance of Iran from other countries, the option of material transfer was considered to be ineffective. It should be noted that the vernacular house is a building that is as old as several hundred years and only the interior and exterior walls have been repaired over the years. Therefore, in the LCA, the transportation distance has not been considered for parts of this building that have not been rebuilt.

3.4.1 life cycle stages

to reduce the GWP of vernacular houses, it would be essential to prioritize the energy sector, as it has a much larger impact (94.4%) compared to the other factors. Fig. 7 illustrates the share of GWP impacts in the different life cycle stages in modern and vernacular houses. This ratio is the same for the modern house, but it has decreased significantly and the energy sector has taken 75.4%. the part related to the material of the modern house shows a percentage that is almost 3.5 times more than the vernacular house. This shows that the architectural changes and development in buildings, from the past to the present, have reduced CO2e carbon emissions in the energy sector by 1.3 times. though, the architectural development in the material part of buildings has significantly increased its impact on global warming and environmental effects (Fig. 8).

Regardless of the classification of the environmental effects, in vernacular and modern houses, the energy consumption sector has affected the environment by approximately 95% and 75%, respectively. After energy consumption, the greatest effects are related to the materials (Fig. 9). This means that the negative impact of using non-renewable resources and materials has been exacerbated by the development of architecture.

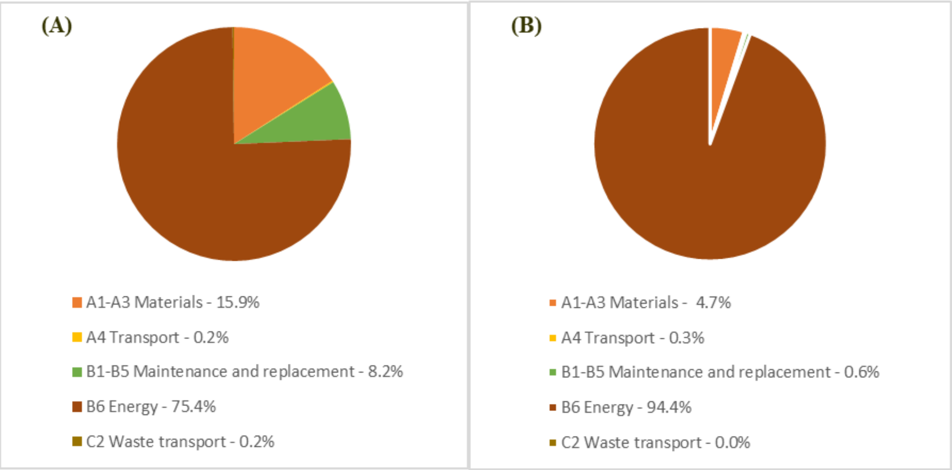


Fig. 7. Distribution of GWP in different life cycle stages in modern (A) and vernacular (B) houses

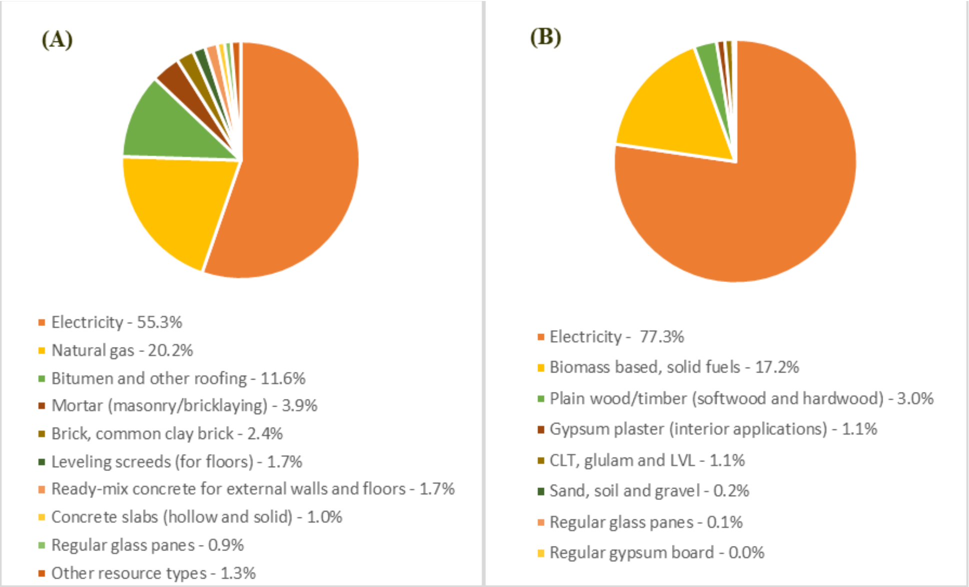


Fig. 8. Distribution of GWP in different types of sources in modern (A) and vernacular (B) houses

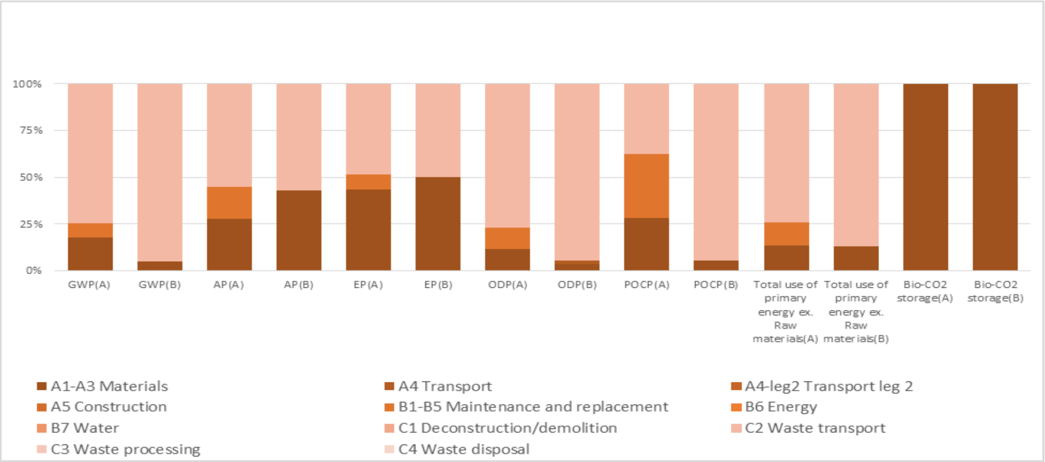


Fig. 9. Modern house (A) and vernacular house (B): distribution of environmental impacts in different life cycle stages

3.4.2 The impact of building elements on GWP

A wider range of materials have been used in the modern house compared to the vernacular house. so it’s been predicted that the modern house would have a greater impact on GWP. Among the components, the roof and floor play a major role in heating the earth in both houses, about 68% in the vernacular house and 80% in the modern house (Fig. 10). One of the reasons is the use of thatch as the main material of the vernacular house.

Section B6 of the study reveals that the impact ratio of the energy sector to produce phase impact on GWP is considerably higher for the vernacular house (20 times) compared to the modern house (4.7 times). This data is presented in Fig. 11. As a result, a detailed analysis done in terms of the amount of carbon produced in the LCA has shown that the modern house produces 3.1 times more carbon in the production phase than the vernacular house.

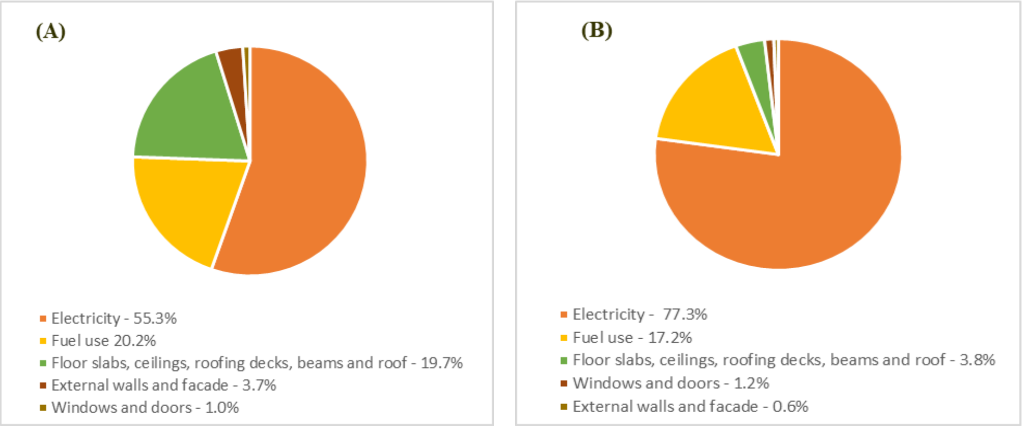


Fig. 10. GWP distribution when classifying building elements in modern (A) and vernacular (B) houses

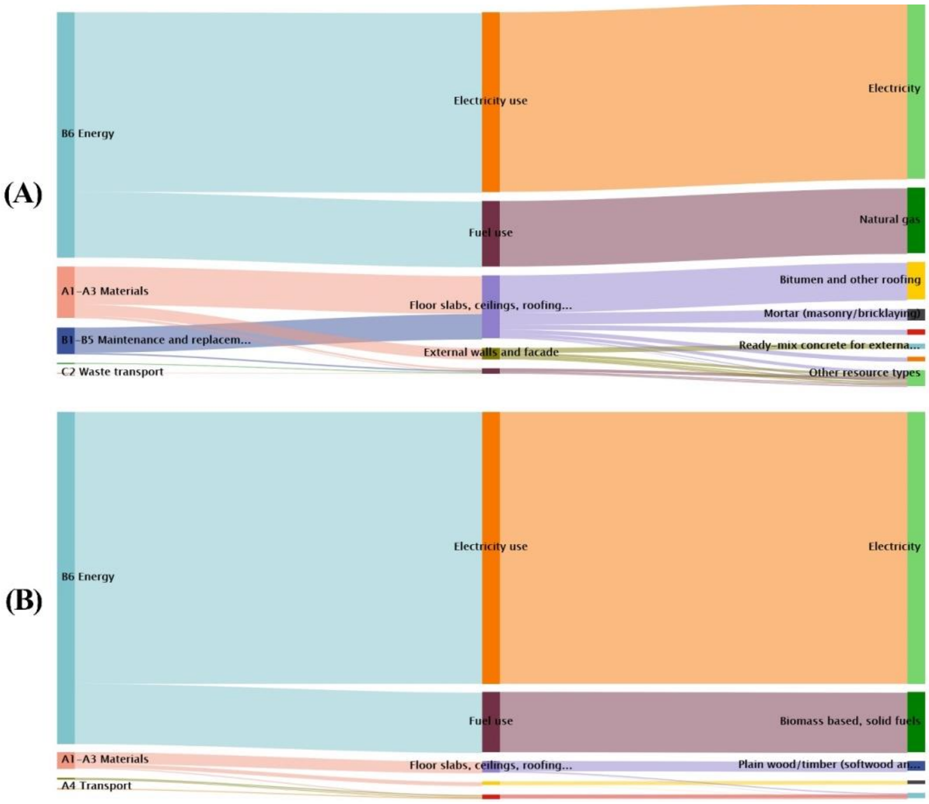


Fig. 11. Embodied carbon of the building components, in modern (A) and vernacular (B) houses

3.4.3 Analysis of the regenerative design model

To create a regenerative design, materials with lower carbon emissions have been replaced with available materials in the One Click LCA software (Table 5). These materials are environmentally friendly and biocompatible. In this section, some materials have not changed because no better substitute was found for them. however, some materials have not changed due to their very low impact in the carbon production section.

Stage D in LCA includes part 6R (reuse, recovery, recycling, recovery, redesign, remanufacture), which actually refers to the regenerative design part. Due to the large number of materials used in the modern building, in this section only the changes in stage D have been stated in relation to the modern building. Before changing the material, the modern building in stage D showed the number -2.21E3; But after changing the building material, part D in the modern building showed the number -1.56E3. This means that changing the material has created 1.5 times better performance in stage D in the modern building. As a result, the regenerative design, by creating a circular system for the building, can increase resource efficiency and reduce harm to nature, resources and humans.

Table 5. Selection and change of building materials of the two studied houses based on CE

	Vernacular House		**Modern House**
CO2	- Finger jointed structural timber, 439,8 kg/m3	CO2	- Clay bricks
CO2	- Gypsum plasterboard, 6,5-18 mm; 5,5-18 kg/m2	CO2	- Hollow core concrete slabs (300 kg/m3)
CO2	- Clay soil, 1280 kg/m3	CO2	- Polyethylene vapor barrier membrane, UV resistant, 0.2 mm, 0.185 kg/m2
CO2	- Gypsum plaster for internal walls and ceilings, average	CO2	- Mastic asphalt, 2400 kg/m3
CO2	- Sawn timber, 489 kg/m3	CO2	- Lime cement mortar, 1800 kg/m3
CO2	- Gypsum plasterboard, 12.5 mm, 8.985 kg/m2	CO2	- Lime cement render, 1 mm, 1.6 kg/m2
		CO2	- Precast concrete blocks (CMU), 105.7 units/m3, 10.5 m2/m3, 1950 kg/m3, 440 x 100 x 215 mm
		CO2	- Glass, clear, float, 3 mm, LT 90.8%, RLE 8.2%, SF 0.89, 7.5 kg/m2
		CO2	- Concrete block, masonry, B40, 200x500x200/250 mm
		CO2	- Render mortar, normal render, high-grade render, 1550 kg/m3
		CO2	- XPS insulation panels, 40 mm, 1.25 kg/m2, 31.25 kg/m3, compressive strength 300 kPa
		CO2	- Gypsum fibreboard, 12.5 mm, 1180 kg/m3
		CO2	- Gypsum plasterboard, 12.5 mm, 8.985 kg/m2
		CO2	- EPS insulation panels, graphite, L= 0.037 W/mK, R= 2.7 m2K/W, 100 mm, 1.5 kg/m2, 15 kg/m3, compressive strength 85kPa
		CO2	- Gypsum plasterboard, 6,5 - 18 mm; 5,5 - 18 kg/m2
		CO2	- Multi layer waterproofing system with flexible sheets for roofing, fully torched, European average, 3.8 (top) + 3.1 (bottom) mm, 4.8 (top) + 3.9 (bottom) kg/m2
		CO2	- Fresh sawn timber, biogenic CO2 not substracted, wood moisture at delivery 70 %, 740 kg/m3

In fact, the main focus of this research was on the amount of carbon emissions and its impact on GWP in the material and energy consumption sections. The results have shown that the use of low-carbon materials, compared to the initial state of the materials used in both studied buildings, making the most changes in EP, AP and GWP, has had a profound impact on each of the environmental outcomes, (Fig. 12). In Fig. 13, the life cycle stages after selecting alternative materials have been studied in the GWP section. The product phase, due to the maximum use of virgin materials has had the greatest impact on GWP after the energy sector (stage B6). Before changing the materials of both modern and vernacular houses, the material part of the modern house had an impact on GWP approximately 3.5 times more than the vernacular house. However, after changing and using low-carbon materials, the impact of the material part on GWP in the modern and vernacular houses decreased by 1.8 and 2.6 times, respectively. Although this amount has decreased significantly for both houses, even under these conditions, the modern house affects GWP approximately 5 times more than the vernacular house in the material part.

The categories shown in Fig. 14, have been obtained using the embodied carbon benchmark of the One Click LCA software; in such a way that the carbon embodied in the vernacular and modern houses, along with more than a thousand buildings in different countries have been tested. Before the main material of both houses was changed, the traditional house was in class A with 71 CO2e/m2 and the modern house was in class G with 919 CO2e/m2. However, after the change and use of low-carbon materials, the vernacular house with a 1.5 times reduction in carbon production remained in grade A, and the modern house with a 2.5 times reduction in carbon production moved to grade C. In general, by using environmentally friendly materials, the carbon footprint of the entire building can be minimized. It is crucial to consider these factors in the early stages of design so as to ensure that the building is constructed using bio-compatible materials and alternative solutions.

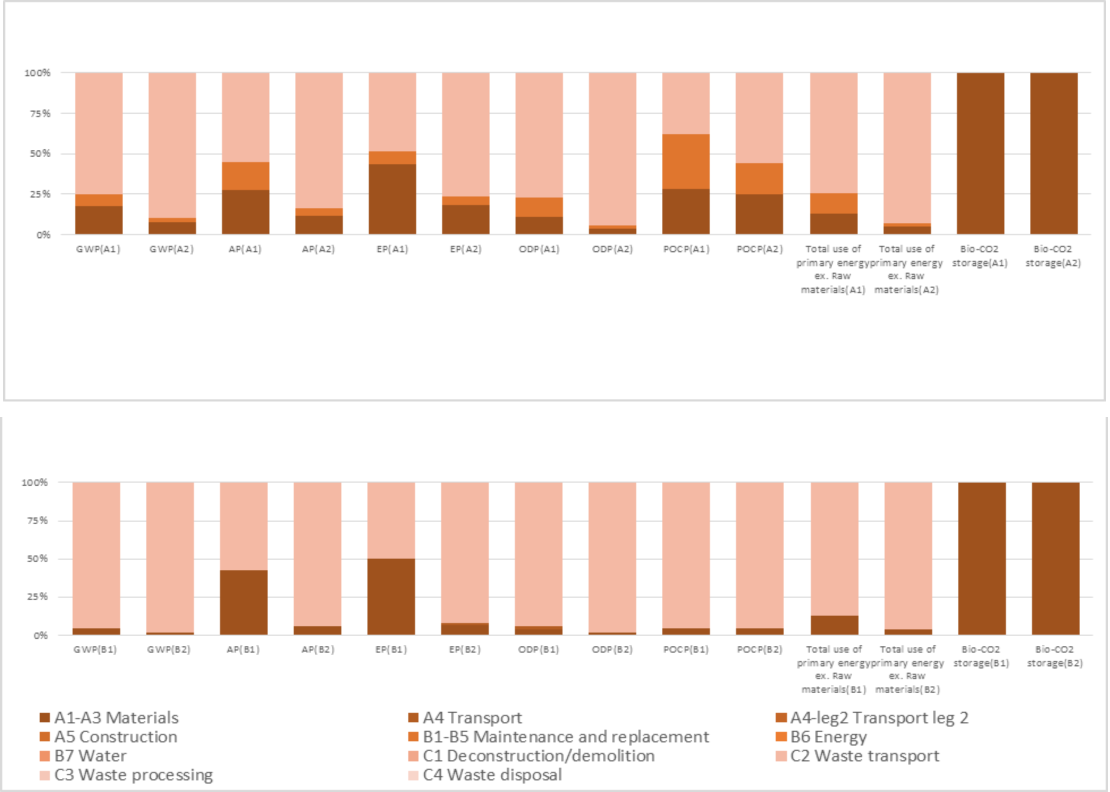


Fig. 12. Comparison of the environmental effects distribution during various stages of the life cycle concerning the initial state of materials utilized in modern (A1) and vernacular (B1) houses, with altered materials in modern (A2) and vernacular (B2) houses

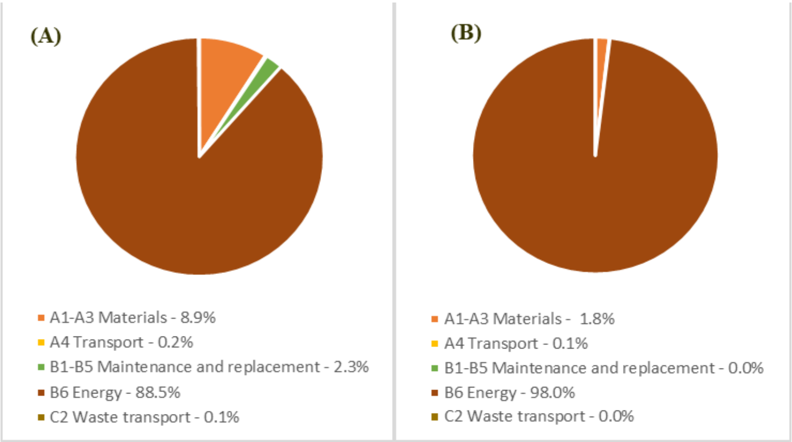


Fig. 13. Comparison of life cycle stages after choosing alternative materials, in GWP section, in modern (A) and vernacular (B) houses

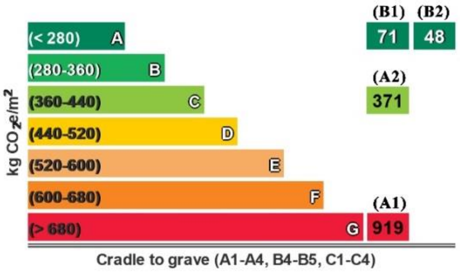


Fig. 14. Embodied carbon benchmark in modern (A1) and vernacular (A2) houses before changing the material and in the modern (B1) and vernacular (B2) houses after changing the material

Comparing the energy consumption and LCA of modern buildings with those of vernacular buildings, it would be clear that while architectural progress has led to a reduction in energy consumption, the use of new materials has resulted in a 3.5-fold increase in the impact on Global Warming Potential (GWP) and environmental outcomes. In fact, despite measurements for reducing energy consumption in new buildings, the ecological ramifications such as carbon emissions and their consequences have been ignored. As a result, the architectural development has performed disappointingly in terms of reducing carbon production and environmental impacts.

Therefore, it can be said that architectural development and building construction is currently moving towards environmental damage, and is based on a linear economy. As a result, to create sustainable development and to reduce environmental effects arising from carbon production, the present research has proposed the use of a regenerative design model strategy.

3.4.4 Optimization of energy consumption and analysis of carbon emissions

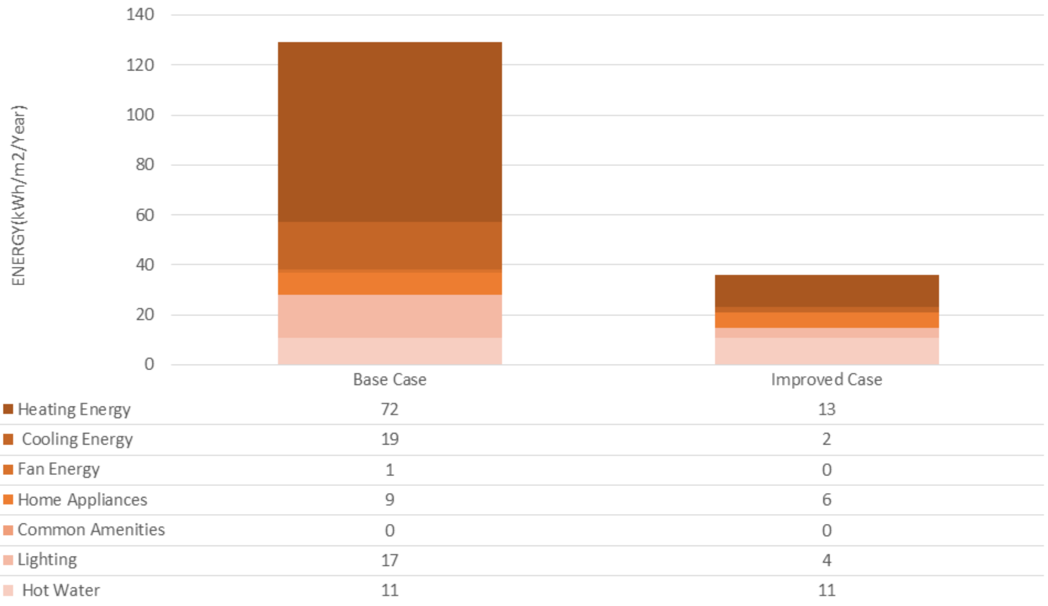
After replacing materials with low carbon emissions instead of the main material of the studied buildings, it was shown that the negative effect of this phase in relation to GWP can be greatly reduced in the production phase in LCA. But still, the energy consumption section has a major share of the negative effects of carbon emissions on GWP. As a result, the optimization related to the building material section must be followed by energy consumption optimization. In addition to considering the impact of materials on GWP, the impact of energy consumption on this part is optimized. Given that an emphasis on preserving the type of vernacular housing in villages has been made for preserving the heritage of housing and maintaining the integrity of the village appearance, modern housing in villages is still progressing, this part of the research has only been considered for the modern house study sample.

In this regard, Edge software was used. In this section, the initial characteristics of the modern building were first entered into the software and after obtaining information about the building's energy consumption and carbon emissions, energy consumption optimization was performed. then the results related to energy consumption and carbon emissions were compared with their initial state. To avoid the effect of possible differences between the numerical results of Design Builder and Edge software, the results of this optimization are only stated in the form of progress percentage, because the Design Builder results have not been optimized with Edge. As a result, this part of the research merely addresses the possibility of progress in energy optimization and reducing carbon emissions related to energy consumption.

After entering the information related to the modern house, energy consumption optimization was performed. The options considered for optimization are shown in Table 6. By activating these options, the results showed that energy consumption can be saved by 40%, which in turn can reduce carbon production by 2.4 times. In Fig. 15, the percentage of impact of different energy-consuming parts of the building in the optimized state compared to the initial state is shown. As a result, it can be said that although architectural development has reduced energy consumption, the energy consumption section according to Fig. 13, is yet at the most effective level in GWP in LCA, beside using low-carbon materials, the issue of energy consumption optimization must still be considered and balanced for being created in the selection of materials and energy consumption.

Table 6. Options considered for creating energy consumption optimization in the modern building in the Edge software.

Options to optimize energy in edge software
- WWR (15%)
- Insulation - Roof (U-value: 0.34)
- Insulation - External Walls (U-value: 0.34)
- Low-E Coated Glass : (U-value: 3)
- Higher Thermal Performance Glass (U-value: 1.9)
- Natural Ventilation
- Energy Saving (Light Bulbs and Internal Spaces)
- Solar Photovoltaics (25% of Total Energy Use)



	Base Case	Improved Case
■ Heating Energy	72	13
■ Cooling Energy	19	2
■ Fan Energy	1	0
■ Home Appliances	9	6
■ Common Amenities	0	0
■ Lighting	17	4
■ Hot Water	11	11

Fig. 15. The percentage of impact of different energy-consuming parts in the building in the optimized state compared to the initial state

4. Conclusion

The aim of this research was to review the transformations of architectural development in rural buildings in terms of the environmental effects and CE in building construction, from the past to the present. While there has been extensive research on reducing carbon emissions by optimizing building materials and energy efficiency, the continued growth of new construction in the future would deplete primary resources and contribute to global warming. Therefore, this article focuses on analyzing both energy consumption and the environmental impacts in terms of GWP. Also, it examines aspects of the architectural development process and aims to integrate the link between construction and the environment by exploring regenerative design approaches, an area that has received less attention. In this regard, two residential houses (a vernacular house and a conventional modern house) were studied in the cold climate of Iran.

In general, modern construction techniques result in showing a better thermal performance than in the vernacular houses. In annual electricity consumption, the vernacular house consumed 2761.95 kilowatt-hours, but this amount in the modern house was 4271.99 kilowatt-hours (due to the high thickness of the walls of the vernacular house and non-use of active cooling systems); nevertheless, the modern house compared to the vernacular house showed 7% more optimized performance in terms of annual energy consumption. However, the LCA results showed that the vernacular house outperformed the modern house in terms of carbon emissions and its impact on GWP.

Although the modern house uses advanced materials that have improved thermal performance, the LCA analysis of the two houses has shown that the production phase has had a greater impact on GWP than the energy consumption phase. These materials increased the environmental impact in the GWP section by a total of 2.9 times.

The study showed that recyclability is crucial in reducing the use of materials, especially since the LCA of the two houses showed that the production phase's environmental impact has been highest after energy consumption. Also, as construction activity increases, the consumption of virgin materials increases either. To address this issue, this article, proposing to replace the existing building materials with those that have low carbon emissions, evaluates the energy and environmental performance of two case studies. This approach will help in reassessing the environmental impact of buildings through LCA.

After conducting an LCA study on the two houses, a regenerative design solution was formulated. This involved the replacement of high-emission materials with those that emit low carbon, and optimization of energy consumption through architectural development; because after substituting low-carbon materials, the results showed that the GWP impact of the Modern House and the vernacular House decreased by a factor of 1.8 and 2.6 respectively, leading to an increasing positive impact on the environment through regenerative design.

Considering that presently energy consumption optimization has received much attention, in the LCA analysis section, the current research showed that a major part of the effects related to GWP is still related to the energy consumption of buildings, which after replacing materials with low carbon emissions lead to the energy efficiency of the modern and vernacular houses by 88.5% and 98%, respectively. This indicates that, despite the better performance of the vernacular house compared to the modern house in terms of reducing the impact of the production phase, the energy consumption part still needs more attention and optimization.

Finally, to determine the impact of energy consumption optimization on both energy use and carbon emissions, an analysis was carried out using Edge software. The results showed that by energy consumption optimization in a way that energy consumption can be reduced by 40%, carbon production can be decreased by 2.4 times. Ultimately, the construction industry can effectively reduce its environmental impact by striking a harmonious balance between energy consumption and the use of low-carbon materials. This can be achieved by limiting the use of virgin resources and reducing energy consumption.

Since the use of materials with low carbon emissions can somewhat increase energy consumption, and since the results in the energy consumption optimization section showed that the environmental impacts of the construction industry can be significantly reduced, future researchers have been recommended to study the conditions proper for creating a balance between the use of materials with low carbon emissions, along with energy consumption optimization through an accurate assessment.

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