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Low Embodied Carbon and Energy Materials in Building Systems: A Case Study of Reinforcing Clay Houses in Desert Regions

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ABSTRACT

Over 40% of the world's energy consumption occurs in the construction sector. However, some countries do not address environmental criteria as design requirements in their construction codes. Accordingly, this research aims to provide a solution that reduces embodied energy and carbon while preserving historical and traditional textures of Iran. The comparison of embodied carbon and energy between new concrete and traditional buildings was performed by calculating the amount of construction materials. By examining both types of buildings, the reduction of embodied carbon and energy in a combined building system was evaluated. In the following, using SWOT analysis, the strategies of this combination were investigated. Clay building has less embodied energy and carbon than concrete one despite containing more mass of materials. According to SWOT analysis, the strategy of integrating clay and concrete systems is presented. The proposed system in compare to the concrete structure resulted in around 40% and 35% reduction in embodied carbon and energy, respectively. Extending this strategy throughout the country saves 13 million tons of embodied carbon and 130 million GJ of embodied energy. Finding a solution based on sustainability considerations to preserve historical texture is one of the basic concerns of countries where these textures form a part of their identity. The presented combined system, while paying attention to sustainable building and urban development, is a desirable solution to reduce buildings' embodied carbon and energy.

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NOMENCLATURE

E_e	Total embodied energy	$c_{p,j}$	Amount of emitted energy intensity for building material j
E_m	Embodied energy of manufacturing construction materials	$e_{p,j}$	Amount of emitted carbon for building material j
E_t	Energy consumption of transporting building materials	$c_{i,j}$	Amount of carbon emitted by producing the building materials j
E_p	Embodied energy related to building productions	$c_{t,l}$	Amount of carbon emission
C_e	Total embodied carbon	$e_{t,l}$	Amount of energy use
C_m	Embodied carbon related to the manufacturing of materials	d_l	Distance of transportation
C_t	Amount of carbon emission of transporting the materials	k	Number of building materials and elements
C_p	Value of embodied carbon emanated from different processes	n	Number of countries which material or element j is imported
$e_{i,j}$	Energy required for manufacturing the materials j in country i	**Greek Symbols**	
$q_{i,j}$	Amount of building materials j imported from the country i	μ_j	Replacement factor for building elements j
$Q_{p,j}$	Amount of building material j	λ_j	Factor for waste materials j

1. INTRODUCTION

Sustainable development is an internationally well-known philosophy defined in “Our Common Future” report published by the World Commission on Environment and Development (WCED), as “the development that meets the needs of the present generation without compromising the ability of future

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generations to meet their own needs" [1]. To achieve sustainable development, economic, social, environmental, and technological aspects are major factors that should be considered [2]. The significance of sustainable development planning causes it to be taken into account in different industries and various aspects of human life. The construction industry as one of the most efficient industries is not an exception to this consideration and sustainability is the major issue in which the construction industry is engaged with it [3, 4]. The relationship between sustainable development and the construction industry is undoubtedly evident [5] and the discourse of construction practitioners and decision-makers worldwide has begun to appreciate and acknowledge the advantages of sustainable building [6]. Sustainable construction was proposed to make the construction processes, activities, and practices more economically, socially, and environmentally responsive [7]. Research shows that among the sustainability dimensions, the main focus is on environmental sustainability [8]. In this regard, the green area is important to balance the ecosystem [9]. To achieve green areas, considerations related to buildings should be taken into account. Buildings, as the main components of cities, have a special and effective role in the emergence of environmental problems [10]. About 40 to 50 percent of the emission of greenhouse gases emanates from the construction industry [11]. In addition, the construction sector is responsible for one third of the global carbon dioxide (CO_2) emissions [12]. A significant amount of natural resources has been consumed by the building industries which is responsible for a noticeable amount of energy usage such that the building operations alone account for 30 to 40 percent of total energy use, globally [11, 12]. The environmental impacts of buildings need mitigation and adaptation strategies [13] and energy efficiency in the construction field needs to be seriously pursued, using approaches ranging from increasing research and development investment to maintaining appliance standards [14].

In order to satisfy sustainability objectives [15], cope with climate change, and reduce greenhouse gas emissions of buildings, the optimization of building design and operation is needed [16]. On the other hand, historical and traditional textures indicate the background and identity of some countries like Iran and are among the factors affecting foreign tourists. While many of the existing buildings in the historical textures are deteriorating and destroyed. Therefore, there is a serious need for solutions to preserve historical textures and maintain their attractiveness for tourists while respecting the technical aspects of construction. Considering that very limited research supports the provision of appropriate solutions to preserve the historical textures while highlighting sustainability considerations in Iran, it is felt necessary to address this issue.

In this regard, the current research, while emphasizing sustainable building and reviewing previous studies on embodied energy and carbon, will examine the life cycle energy assessment of buildings and the waste coefficient and lifespan of materials in the historical and traditional contexts of Iran. Finally, the importance of evaluating embodied carbon and energy in Iran's construction industry will be considered. Then, embodied carbon and energy evaluation has been carried out for both traditional clay houses and conventional concrete buildings. The necessity of modifying the construction codes with the aim of sustainable development in the country was investigated. By comparative studies, the obtained results and measuring the embodied carbon and energy increase after changing the constructional system and materials from traditional to conventional. According to SWOT analysis and the proposed strategies to preserve historical texture, to demonstrate the effect of substituting materials on the amount of energy and embodied carbon, the energy and carbon were analyzed considering a combined building with concrete structure, frame, and joist system, the adobe walls, and the traditional flooring. The presented combined building system, while paying attention to sustainable building with reduced embodied carbon and energy, preserves the structure of historical textures and its attractiveness for tourists.

1. 1. Embodied Energy In the building sector, the energy and the greenhouse emissions embodied in the building materials are becoming dramatically important [17]. Hence, in the past few years, embodied energy (EE) has become a prominent research field. Due to the growing awareness that the energy initially consumed to produce goods and services might prevail in determining the whole amount of life-cycle energy [18]. Accordingly, several studies have focused on reducing greenhouse gas emissions and energy use during a building's life. It is crucial to assess energy requirements to come up with efficient energy-saving solutions [19]. Buildings are reckoned as major consumers of energy. There are various types of energy used during the life cycle of a building including embodied energy, maintenance, operational energies, disposal, and demolition energies. Embodied and operational energies account for a major portion in this regard. Embodied energy (EE) shows the whole energy consumed for the construction of a building, i.e., a sum of embodied energies of building materials, energies related to the transportation of materials, and building construction energy. Embodied energy contributes 10–20% of the lifecycle energy consumption of conventional buildings [20]. The embodied energy of building materials has a noticeable portion of the whole embodied energy in buildings. Hence, it is vital to choose suitable construction materials considering their embodied energy to diminish embodied energy of buildings. High embodied energy in buildings is expected by using energy-intensive construction materials such as steel, brick, glass, and cement [21].

Energy consumption in buildings includes two main components: operational and embodied energy. Operational energy is the energy needed for running a building by different operating processes such as cooling, heating, and lighting, whereas embodied energy of a building indicates the energy used by all of the processes associated with the production of the building from the mining and processing of natural resources to manufacturing, transportation, and product delivery. Embodied energy has been defined by different researchers, who have given various nuances to the concept, yet a general consensus exists emphasizing that embodied energy in building materials has increased its importance in a building's life cycle in comparison with operating energy thanks to the better energy performance of the buildings [22]. The consumption of embodied energy is a physical process highly related to material inventory flows which have been determined at the design or pre-construction stage. Dixit et al. [23] presented The first approach to standardization of the embodied energy of various materials. Determining embodied energy is a time-consuming and complex task. Moreover, there is no generally accepted method to accurately and consistently determine the embodied energy; thus, wide variations in measurement figures are inevitable [22]. Several research studies were conducted in the embodied energy field are presented in Table 1. As the table above presents, research on embodied energy has been conducted since 30 years ago in several countries, but Iran is not among them. According to these research projects, a wide range of embodied energy values (25.2 to 27208 MJ/m^2) has been mentioned, which relates to (1) discrepancies in the type of structural systems and materials, (2) differences in the amount of embodied energy of units of different materials in different countries and cities, (3) energy efficiency during operation, (4) building usage type and (5) mass construction. In general, green and wooden buildings possess the lowest embodied energy, while buildings with high energy efficiency during the operation period (low energy, very low energy, net-zero energy consumption, and passive house) have the highest embodied energy values. Some studies have

TABLE 1. Previous studies on embodied energy

Year	Author	Ref.	Building Type	Embodied Energy MJ/m^2	Life Span
1994	Buchanan and Honey	[24]	Conventional Building	5530	-
1995	Debnath et al.	[60]	Conventional Concrete Building	5000	-
1995	Suzuki et al.	[61]	Different houses in Japan	10400,2700	-
1997	Adalberth	[54]	Residential single-unit precast buildings	3014, 3487	50
2002	Thormark	[62]	All three projects with Low energy consumption	7033, 4388, 4079	50
2004	Mithraratne and Vale	[63]	Standard lighting (low energy consumption), Standard concrete (low energy consumption), High insulation (low energy consumption)	4424, 4709, 5088	100
2006	Casals	[64]	Average (Conventional), High Energy efficiency (low energy consumption)	3679.2, 14191.2	30
2007	Nässén, J et al.	[65]	Villa vision, Multi-unit buildings	6200, 5800	-
2008	Huberman, N. and D. Pearlmutter	[66]	Student Dormitory Complex	3280, 4910	-
2009	Utama and Gheewala	[67]	High Rise, Residential Buildings	1666.8, 1470.8	40
2010	Blengini and Carlo	[68]	Standard house (low-energy family house)	7560, 10990	70
2010	Gustavsson and Joelsson	[25]	Low-energy residential buildings	3504	50
2010	Ramesh et al.	[69]	Office and residential buildings	25.2, 385.2	50
2010	Gustavsson and Joelsson	[70]	Eight-story wood-framed apartment	3510	50
2011	Leckner and Zmeureanu	[71]	Conventional, Net Zero Energy House without the solar systems, Net Zero Energy House (NZEH) with solar combisystem	4820.4, 6020.4, 8936.4, 8780.4	40
2012	Dahlstrøm et al.	[72]	Passive house	7516.5, 7590, 7914.5, 7718	50
2013	Paulsen and Sposto	[73]	Social houses (low energy consumption)	7200	50

2013	Paleari et al.	[74]	Zero Energy Residential Buildings	16728	100
2013	Berggren et al.	[75]	Net Zero Energy Buildings	6912, 10584, 8208, 7344, 7344, 9504	60
2014	Stephan and Stephan	[76]	Low-rise residential buildings	27208	50
2017	Dissanayake et al.	[77]	House with recycled expanded polystyrene (EPS) based foam concrete wall panels	3460	-
2018	Vitale et al.	[78]	Residential Prefab LSF, Residential Traditional concrete	9900, 8500	50
2019	Praseeda et al.	[21]	Rural dwellings	2340-2800	50
2019	Tavares et al.	[79]	Prefabricated house with: Steel material, Concrete material, Timber, LSF	5624, 2151, 2335, 2619	100
2019	Thanu et al.	[80]	Conventional residential building	4060	-

recommended the use of wood and soil to diminish embodied energy [24]. For example, in 2010, Gustavsson and Joelsson [25] investigated an 8-story wooden building with a lifespan of 50 years and obtained 3500 MJ per square meter of embodied energy. Some research projects demonstrated the necessity of using local building materials to decrease embodied energy [26]. The traditional buildings in the desert regions of Iran are also made of indigenous materials such as clay and soil. These buildings have also roofs made of wood, and in this respect, they can be classified as low-carbon buildings. But there is a lack of studies in Iran measuring the embodied energy of the aforementioned buildings to compare the amount of energy.

1. 2. Embodied Carbon On a large scale, buildings account for 67% of embodied carbon emissions [27]. The emission of greenhouse gases like carbon dioxide causing climate change plays the most important role in sustainable development. The CO_2 emissions related to energy consumption have risen by 66% to reach a historic high of 33.1 Gt in 2018 compared to 1990 level [28]. Carbon emissions are usually denoted as CO_2 (i.e. CO_2 equivalent), which is a measurement unit according to the relative impact of a given gas on global warming (the so-called global warming potential). For instance, the 100-year global warming potential (GWP) of methane is equal to 25, which means that the effect of 1 kg of methane gas on climate change is equal to the influence of 25 kg of carbon dioxide on that. In other words, 1 kg of methane gas would count as 25 kg of CO_2 equivalent. Table 2 displays typical sources and GWP of various greenhouse gases over 100 years. Through a survey on a building with a lifespan of 40 years in 2009, Shukla et al. [29] concluded that using materials with low embodied energy rather than high embodied energy reduces carbon dioxide emissions to approximately 101 tons per year. In 2010 Ortiz-Rodríguez et al. [30] conducted a simultaneous study in Colombia and Spain on buildings with a lifespan of 50 years, showing that the energy and carbon of the construction period and the operational carbon for the building located in Colombia were, 4940 MJ per square meter, 238 kg carbon equivalent per square meter, and 599 kg per square meter, respectively. For the building located in Spain, these values are 4180 MJ per square meter, 192 kg of carbon equivalent per square meter and 2250 kg of carbon equivalent per square meter [30]. An investigation carried out in Portugal for buildings with a lifespan of 50 years in 2011-2012 revealed that greenhouse gas emissions are 13 kilograms of carbon equivalent per square meter per year [31].

In 2015, Atmaca and Atmaca [32] investigated the carbon content and embodied energy of the construction, operation, and demolition period of two buildings located in the urban and rural areas with a lifespan of 50 years. They obtained the percentage of operational energy as 73% and 76%, construction energy as 24% and 27%, and operational carbon as 59% and 74% [32]. As shown in Table 3, there are some research projects have been conducted in the field of embodied carbon. According to the above table, in a 2007 study of semi-detached houses in Scotland, Asif estimated carbon emissions of 618 kilograms per square meter. The results indicate that 99% of carbon emission is related to mortar and concrete [33]. In 2011, Monahan and Powell [34] investigated a building in which wood was the predominant material, but the most embodied carbon amounts were related to concrete, which indicates the significance of choosing low-carbon materials. In 2016, Luo et al. [35] revealed that as the building height increase, the amount of CO_2 emissions per unit area augments significantly. Also, the amount of CO_2 emissions per unit area of super-high-rise buildings is 1.5 times that of multi-story buildings; the CO_2 emissions in the field of Civil Engineering are responsible for 75% of the total construction materialization stage; and the carbon emissions of steel, concrete, mortar and wall materials account for 80% of the Civil Engineering sector [35]. Therefore, the strategy of preserving the historical texture discussed in this survey, in which buildings have a maximum of two stories, can be effective in reducing embodied carbon. A study by Gan et al. [36] in 2017 demonstrates that 10 to 20% of the reduction of embodied carbon can be fulfilled using cement substitutes. It is also shown that if recycled materials are employed, transportation will account for 20% of embodied carbon [36]. Therefore, the strategy of substituting concrete with low-carbon indigenous materials, used in this research, can be effective in reducing embodied carbon. Using indigenous materials also reduces the embodied carbon of transportation due to distance reduction. Teng's research results revealed that a reduction of wall thickness can diminish embodied carbon (with a 1.9% reduction potential) [37]. This strategy has been employed in the current study to reduce embodied carbon.

1. 3. Life Cycle Energy Assessment of Buildings

The interest in Life Cycle Assessment (LCA) has increased dramatically since the 1990s, especially with the advent of scientific publications. LCA is a tool to evaluate the environmental impacts and resources applied during the life cycle of a building, i.e., from the acquisition of raw materials, through the production and use phases, to waste management. The methodological development in LCA has been strong, and it is widely employed in practice. LCA is an exhaustive evaluation considering all attributes or aspects of the natural environment, human health, and resources. The LCA methodological development has been strong over the past decades [38]. Although the focus of LCA can be on social and economic effects, the environmental impacts have been the main focus of LCA. Engineers and designers designing and developing technical systems and products need to be able to study and size up life cycle assessment data about the alternatives they are considering, and the environmental sustainability

TABLE 2. Typical sources and GWP of various greenhouse gases [43]

Greenhouse gas	Chemical formula	GWP	Typical sources
Carbon dioxide	CO_2	1	Energy combustion, biochemical reactions
Nitrous oxide	N_2O	298	Fertilizers, car emissions, manufacturing
Methane	CH_4	25	Decomposition
Perfluorocarbon	PFC	7,390 - 12,200	Aluminum smelting
Hydrofluorocarbon	HFC	124 - 14,800	Refrigerants, industrial gases
Sulfur hexafluoride	SF_6	22,800	Switch gears, substations

TABLE 3. Previous studies on Embodied carbon

Year	Author	Ref.	Building Type	Embodied Carbon kg/m^2	Life Span
2007	Asif et al.	[33]	Semi-detached house	618	-
2008	Hacker et al.	[81]	Semi-detached house	332.70	100
2009	Blengini	[82]	Residential building	8 kgCO2E/m2 year	40
2010	Ortiz et al.	[30]	Dwelling in Colombia Dwelling in Spain	238 192	50
2011	Monahan et al.	[34]	Semi-detached house	405	-
2012	Monteiro	[83]	Single-family house in Portugal	13 kgCO2E/m2 year	50
2013	ChaoMao et al.	[84]	Semi-prefabricated construction conventional construction	336 368	-
2014	Lamnatou et al.	[85]	Building-integrated solar thermal collector	160 kg CO2.eq/m2	30
2015	Galua et al.	[86]	Green building	21000	20
2016	Luo et al.	[35]	78 office buildings	326.75	50
2017	Gan et al.	[36]	High-rise buildings	459 kg CO2-e/m2	30
2018	Kumanayake et al.	[87]	Office building	629.6 kg	_
2019	Teng et al.	[37]	Prefabricated high-rise public residential buildings	561	50
2020	Kayaçetin et al.	[27]	Residential house	409.2 kgCO2-eq/m2	50

specialists among them are also required to carry out the LCA studies [39]. When implementing LCA, the design/development phase is usually excluded, since it is often assumed not to contribute markedly. However, it should be considered that all decisions made in the phase of development/design can greatly affect the environmental impacts in the other life cycle stages. The design of a product can highly predetermine its behavior in the next phases. As a result, this paper focuses on the design stage.

When implementing sustainable development in the building sector, the focus needs to be on the long perspective entailing the significance of considering the whole life cycle of a building [8]. LCA is a strong tool to assess potential environmental influence from the extraction of materials and production, through construction and use or service phase to the waste treatment and end-of-life of the product [40]. Furthermore, LCA is one of the best tools to size up environmental impacts through all phases of the building according to a conclusion drawn and reported by the European Commission [41]. Some of the merits of using LCA assisting in terms of sustainability in the building sector are economic, social, and environmental. Environmental merits are followed by making a comparison between alternative products and providing information about environmental effects helping stakeholders to make informed decisions [42]. Consequently, buildings need to be assessed considering their whole life cycle, which entails both production and end-of-life stages and is not merely based on the energy demand throughout the use stage [17]. Most of the existing literature focused on the analysis of embodied energy of main construction materials such as steel, cement, and glass as the sources of embodied energy, and ignored other equipment inputs and materials [12].

In this regard, life cycle assessment concerning energy and carbon dioxide emission is divided into several categories as follows [43]:

1) Cradle-to-gate carbon emissions: Carbon emissions between the confines of the ‘cradle’ (earth) up to the factory gate of the final processing operation. This consists of mining, raw materials extraction, processing, and manufacturing.
2) Cradle-to-site carbon emissions: Sum of cradle-to-gate emissions and delivery to the installation and construction site.
3) Cradle-to-end of construction: Sum of cradle-to-site and assemblies on-site and construction.
4) Cradle-to-grave carbon emissions: Sum of cradle-to-end of construction and maintenance, renovation, demolition, disposals, and waste treatment.
5) Cradle-to-cradle: Cradle-to-grave emissions plus, converting the components into new components at the end of their life with an equal or lower quality.

Embodied carbon and energy are the emitted carbon and consumed energy measured through one of the above categories. Embodied carbon is usually presented in kilograms of CO_2 per kilogram of material or product, and embodied energy is expressed in megajoule energy per kilogram of material or product. The whole life cycle assessment provides important information, but there are lots of factors introducing more complexity to LCA in the building industries [44]. For example, the expected lifetime of buildings is usually more than 50 years which is a long lifetime, therefore, accurate prediction of all lifetime behavior of the project from cradle-to-grave is very difficult [45, 46]. There has been much research conducted on the life cycle energy assessment (LCEA) of buildings. Some important ones are presented in Table 4. The life cycle energy assessment is an exhaustive task, and cannot be fulfilled without calculating the embodied energy. Hence, to complete the life cycle analysis, there have been several studies calculating the amount of embodied energy around the world, as shown in Table 1, but Iran is not among them. Therefore, conducting such studies in Iran is of special necessity.

1. 4. Waste Coefficient and Lifespan of Materials

The construction industry produces nearly 35% of waste in landfills across the globe [47]. One of the most voluminous and heaviest waste streams produced in the European Union (EU) is construction and demolition waste (C&DW). It accounts for nearly a third of the waste produced which is more than 850 million tons [48]. In the UK, 44% of waste in 2013, was due to the construction sectsor [49]. Also, in 2014, the amount of C&DW generated by the UK was equal to 58 million tons [50]. The rate of C&DW generation (kg per capita per day) in Iran is six times more than that of the USA [51]. While the average of C&DW generated in the United States is 0.77 kg per capita per day, that average is equal to 4.64 kg per capita per day in Iran, according to reported data by Tehran Municipality Waste Management [52].

The definition of waste is important since the classification of substances as waste is the basis for the formulation of waste management policy and the application of regulatory controls to protect the environment as well as human health [53]. According to the EU Waste Framework Directive (European Community 1991), waste is defined as any substance or object that the holder discards or intends to discard or has to discard. The materials are considered waste under one of the following circumstances [53]:

- If the objects or substances have been discarded.
- If the objects or substances cannot be utilized anymore for their original design objective or elsewhere with the same design objectives.
- If the objects or substances are produced more than required.

TABLE 4. Previous studies on Life Cycle Energy Assessment (LCEA)

Year	Author	Ref.	Building Type	50 years Life Cycle Energy (GJ/m^2)	Energy Contribution
1997	Adalberth	[54]	Residential single-unit precast buildings	27.4, 31.7	Embodied energy: 11-12%, Renovation energy: 4-5%, Operational energy: 84%, Destruction energy: 0.3-0.5%
2002	Thormark	[62]	20 apartments	15.24	Embodied energy: 46%
2004	Mithraratne and Vale	[63]	Three residential concrete buildings with high insulation	17.02, 16.24, 11.83 (for 100 years)	Operational energy: in order 74%, 71%, 57%
2007	Citherlet and Defaux	[88]	Three variants of a family house	10-29	_
2007	Sartori and Hestnes	[89]	Conventional and low-energy buildings		Embodied energy: (Conventional) 2-38% (Low-energy) 9-46 %
2008	Utama and Gheewala	[90]	Houses made of clay bricks and concrete blocks	12.56, 13.24	Operational energy: in order 6.7 %, 6.2%
2009	Utama and Gheewala	[67]	Residential high-rise buildings with a double and single wall system	3.33, 5.41	Operational energy: in order 28%, 16%
2010	Ramesh et al.	[69]	Office and residential buildings	118.8-1404 kWh/m^2	Embodied energy: 7-107 kWh/m^2 Operational energy: 0-330 kWh/m^2 (about 80 to 90 %)
2010	Gustavsson and Joelsson	[70]	Eight-story wood-framed apartment building	1800-3672 kWh/m^2	Embodied energy: 45-60 %
2017	Ma et al.	[12]	Office building	345 *kWh/m2/year*	Embodied energy: 20 % Operational energy: 73 %
2019	Praseeda et al.	[21]	Rural dwellings	0.77-4.05	Embodied energy: 69 %, Operational energy: 0-2 %
2019	Petrovic et al.	[91]	Wooden single-family house	30.16 (for 100 years)	Operational energy: 64 %
2019	Hernandez et al.	[92]	Residential block	3.85	-
2019	Tettey et al.	[93]	Multi-story residential building with different materials	4060-11700 kWh/m^2 (for 80 years)	-

- If some of the materials and equipment remain and cannot be returned to the seller or sold to another person.
- If the materials or equipment cannot be operated after construction and installation.
- If the substances are discarded owing to rework, demolition during construction, low quality of the final product, modification of work, work changes, executive orders of principals, regulations, time delays, planning problems, budgeting and financing problems, productivity, and the quality of human resource and other such things.

The more waste a building has, the more amount of embodied carbon and energy it has. In the current study, the waste coefficient of the most widely used materials in Iran is obtained from questionnaires and interviews with professionals and is shown in Table 5. The lifespan of different materials is presented in Table 6 [54, 55].

1. 5. The Importance of Investigation on Embodied Carbon and Energy in Iran's Construction Industry

There are some research projects conducted on embodied carbon and energy evaluation per unit of various materials. But for reasons such as different energy efficiency, export, import,

TABLE 5. Waste coefficient of materials in Iran

Material	Waste coefficient	Material	Waste coefficient
Concrete	0.063	Polystyrene	0.0407
Steel	0.0645	Mosaic	0.0593
Cement- Slurry	0.1005	Stone	0.0959
Brick	0.0896	Cupper	0.0709
Coating	0.119	Mortar	0.1023
Ceramic tiles	0.0775	Aggregate	0.0468
Aluminum	0.0208	Glass	0.0329
Paint	0.0521	Bitumen	0.0903
Plastic	0.0078	Asphalt	0.0806

TABLE 6. The lifespan of materials

Material	Life Span	Material	Life Span
Cement	50	Iron	50
Concrete	50	Aluminum	30
Concrete – Cement replacement with fly ash (0-30)%	50	Bronze	30
Concrete – Cement replacement with furnace slag (0-30)%	50	Mosaic	40
Floor carpet - nylon	50	Ceramic	14
Vinyl flooring	50	Brick	50
Sealants and adhesives	50	Lead	50
Plastic - UPVC - Window	30	Copper	50
Aggregate	50	Brass	30
Sand	50	Wood	30
Soil	50	Linoleum	50
Clay	50	Isolation	50
Lime	50	Rubber	40
Asphalt	50	Coating	50
Bitumen	50	Glass	30
Facade Stone	50	Paint	10
Steel	50		

industrial and environmental conditions; these values vary for different countries and even different parts of a country. Few studies in Iran have investigated embodied carbon and energy while life cycle assessment accomplishment is impossible without considering this issue. Construction codes in Iran merely consider operational energy standards and embodied carbon and energy have not been regarded yet. Statistics show an increase in carbon emissions from 2003 to 2014 in Iran which will continue if not controlled [56]. Countries with high CO_2 emissions aim to reduce emissions by at least 25% until 2030; unfortunately, Iran is not among them [57]. Consumption of energy and waste of energy in Iran is higher than the world's average, and the contribution to air pollution is higher than expected as well. Based on statistics, China, the USA, India, Russia, Japan, Germany, South Korea, Iran, Saudi Arabia, and Indonesia are the top ten CO_2 emitters among all countries in the world according to their emission trends throughout the 1991–2015 period [57].

Therefore, Iran is among the top ten countries in the world with high CO_2 emissions. Using an annual increase of 5% as an assumption, the total amount of CO_2 emissions in Iran is predicted, by Mousavi et al. [56] to reach 985 million tons in 2025. Concerning the percentage change in CO_2 emissions, India, Indonesia, and Saudi Arabia without doubt are at the top of the increase in carbon emissions list (the percentage growth of their CO_2 emissions is either greater than or equal to 100%), followed by China, Iran, and South Korea. Although Saudi Arabia and Iran have not been committed to any Intended Nationally Determined Contribution (INDC) goals that would bring about international attention and discussion in the future, the situation of carbon reduction is grim in these countries. An adjustment in the structure of energy consumption is an urgent and inevitable requirement to reach the win-win combination of economic growth and CO_2 reduction, especially for countries such as Saudi Arabia and Iran which are petroleum-rich countries [57].

Although the building industry accounts for a considerable amount of carbon emission and energy consumption and the life cycle assessment in terms of energy and carbon is not fulfilled without considering embodied energy and carbon, the studies on embodied energy and carbon are very limited in Iran, and researchers merely focus on the operational energy standards, and embodied energy is not considered in energy codes. Therefore, in this paper, embodied carbon and energy evaluation has been carried out for both traditional clay houses and conventional concrete buildings, and the necessity of modifying the construction codes with the aim of sustainable development in the country was investigated by comparing the obtained results and measuring the embodied carbon and energy increase after changing the constructional system and materials from traditional to conventional. Figure 1 indicates a flow chart in which the research process of this article is illustrated.

2. METHODOLOGY

This research project aims to study the observance of environmental issues in Iran's desert regions by comparing the amount of energy consumption and carbon emission of concrete and traditional buildings and providing energy and carbon reduction strategies. In this survey, the positive effects of using optimal structural systems and materials concerning reducing carbon emission and energy consumption, and the amount of this reduction will be dealt with. The research flowsheet is shown in Figure 1. To achieve the above-mentioned objective, first, a traditional house was selected as a case study, and then a concrete building with a plan similar to that of a traditional building was designed using ETABS and SAFE software keeping the spaces as it was.

The case study is a clay house with a lime concrete foundation located in Yazd city, with a coordinate of 31°54'09"N, 54°22'02"E, and an altitude of 1212 meters above sea level. This house with an area of 383 square meters relates to 200 years ago in the Qajar period and is registered in the name of "Ehramianpour House" in the

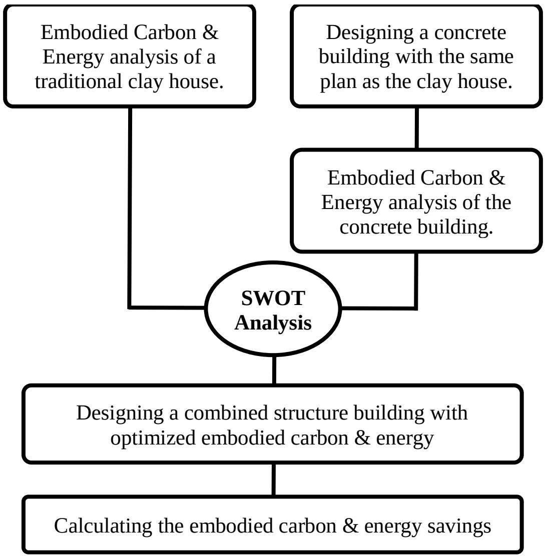

Figure 1. Research process flow chart

Cultural Heritage Organization of Iran. The pictures, plans, and sections of this building are illustrated in Figures 2 to 4. A view of designing the concrete building with ETABS software is indicated in Figure 5. After choosing the case study and designing the concrete building, according to executive details, the types and weights of each material used were obtained. According to the weight amounts obtained, energy and embodied carbon analyses were performed. Analyzing embodied energy and carbon in this paper is based on a model presented by Chen in 2001 [55]. Embodied energy and carbon per mass unit of each material are also taken from a database (inventory of carbon & energy (ICE) Version 2.0) prepared by the University of Bath UK [58] presented in a supplementary file. To calculate the amount of energy and embodied carbon, a program was created using Excel software based on the aforementioned model and database. The concrete building uses materials with a large amount of energy and embodied carbon per mass unit and in the traditional building, due to the high thickness of the clay walls which usually reach 50cm, much more materials have been utilized. Therefore, drawing a comparison of energy and embodied carbon between these two buildings is a challenging task. Thanks to the existing limitations, including the University of Bath database version 2, which published life cycle information based on the cradle-to-gate stage, life cycle analysis in this paper is bound to that stage.

We expanded Chen's model to embodied carbon in which total embodied energy and carbon can be obtained using the following equations:

$$E_e = E_m + E_t + E_p \tag{1}$$

$$C_e = C_m + C_t + C_p \tag{2}$$

where E_e, E_m, E_t, and E_p stands for the total embodied energy, the embodied energy of manufacturing construction materials, the energy consumption of

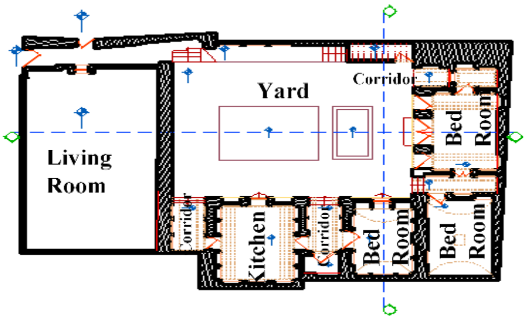

Figure 2. Clay building plan map

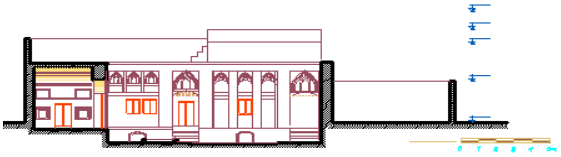

Figure 3. Clay building section

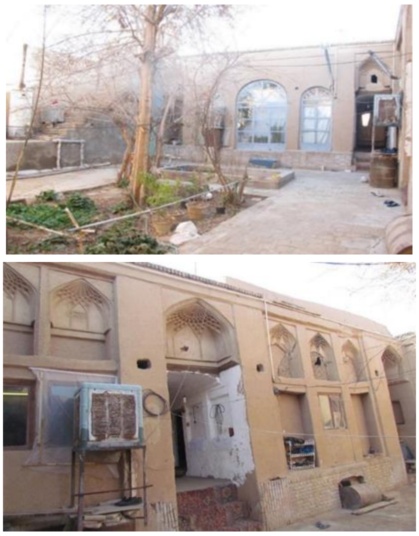

Figure 4. Clay building picture

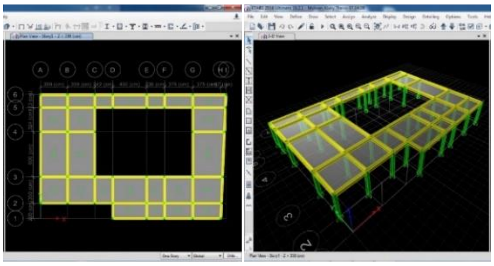

Figure 5. Designing the concrete building using ETABS

transporting building materials from and to the construction site, and embodied energy related to various processes throughout building productions, respectively. Moreover, C_e, C_m, C_t, and C_p represent the total embodied carbon, the value of embodied carbon related to the manufacturing of building materials, the amount of carbon emission of transporting the construction materials and building components, and the value of embodied carbon emanated from different processes, i.e. smoothing of soil and crane lifting, during building productions, respectively. E_m and C_m can be calculated using the following equations:

$$E_m = \sum_{j=1}^{k}(1+\lambda_j)\,\mu_j\left[\sum_{i=1}^{n} q_{i,j} e_{i,j}\right] \tag{3}$$

$$C_m = \sum_{j=1}^{k}(1+\lambda_j)\,\mu_j\left[\sum_{i=1}^{n} q_{i,j} c_{i,j}\right] \tag{4}$$

where k, $e_{i,j}$, $q_{i,j}$, and $c_{i,j}$ represent the number of building materials and elements, the energy required for manufacturing the building materials j in country i in MJ/kg, the amount of building materials j imported from the country i in kg, and the amount of carbon emitted by producing the building materials j in country i in MJ/kg, respectively. Also, n, μ_j, and λ_j denote the number of countries from which building material or element j is imported, the replacement factor for building elements j throughout the whole lifespan of a structure, and the factor for waste materials j produced during the implementation of the structure, respectively. It should be stated that μ_j must be higher than or equal 1, and (μ_j-1) stands for the factor for the recurring embodied energy of building material j. Some building components such as damaged doors and windows might be partially supplanted throughout the buildings' lifespan, while others, such as ceilings, walls, and floor finishes, might be required to be completely replaced every time. The replacement factor can be determined as follows:

$$\mu_j = L_b / l_j \tag{5}$$

The difference between Equations (5) and (6) yields the maintenance factor.

$$\mu_j = \lceil L_b / l_j \rceil \tag{6}$$

where L_b, l_j, are the buildings' lifespan, the mean value of lifespan of building components or materials j, and the mathematical operator that gives the least integer which is equal to or higher than a real number within.

E_t and C_t can be calculated using the following equations:

$$E_t = \sum_{j=1}^{k}(1+\lambda_j)\mu_j Q_j(\bar{e}_{t,j} + e_d) \tag{7}$$

$$C_t = \sum_{j=1}^{k}(1+\lambda_j)\mu_j Q_j(\bar{c}_{t,j} + c_d) \tag{8}$$

where E_t and Q_j are the amounts of energy needed for transportation of the building elements and materials in MJ/(kg. km) and the amount of building material j in kg, respectively. In addition, e_d and c_d indicate the amount of energy consumed and the amount of carbon emitted through demolishing the buildings and transporting the components of demolished buildings from the building site to the landfill, respectively. Subscripts t, $\bar{e}$, and $\bar{c}$ refer to transportation, the mean energy use and carbon emission for transportation of material to the building site in MJ/kg, which might be calculated by:

$$\bar{e}_{t,j} = \sum_{i=1}^{n} \frac{q_{i,j}}{Q_j}\left[\sum_l e_{t,l} d_l\right] \tag{9}$$

$$\bar{c}_{t,j} = \sum_{i=1}^{n} \frac{q_{i,j}}{Q_j}\left[\sum_l c_{t,l} d_l\right] \tag{10}$$

where $e_{t,l}$ and $c_{t,l}$ represent the amount of energy use and carbon emission related to the transportation of building materials by means of conveyance l in MJ/(kg·km). Also, d_l denotes the distance of transportation by the conveyance l in km. The required energy and carbon emitted for different processes throughout demolishing and producing the buildings can be calculated by:

$$E_p = \sum_{i=1}^{k} Q_{p,j}\, e_{p.j} \tag{11}$$

$$C_p = \sum_{i=1}^{k} Q_{p,j}\, c_{p.j} \tag{12}$$

where $Q_{p,j}$ indicates the amount of building material j dealt with in a process throughout demolishing and producing the building in kg, m^3, or MJ/m^2. $c_{p,j}$, and $e_{p,j}$ stands for the amount of emitted carbon and required energy intensity for this process and building material j in MJ/kg, MJ/m^3, or MJ/m^2 usable floor area. In the next step, the traditional and concrete structural systems were analyzed using the SWOT analysis method, and a solution for optimizing embodied carbon and energy was provided considering the preservation of historical texture. Developing ideas exploring emerging opportunities, and guarding against threats while keeping the weaknesses and strengths of the organization in mind is the goal of this analysis [59]. Finally, by surveying the statistics of clay houses in the country, the effects of implementing the strategy of combining traditional and modern building systems in saving embodied energy and carbon were expressed.

3. RESULTS AND DISCUSSION

To obtain the amount of materials utilized in the building understudy, quantity surveying and estimating of this building was performed and the obtained results are presented in Table 7.

Next, the weights, as well as weight percentages of the materials, are presented from the highest to the lowest volume of materials used in the traditional building in Table 8 and Figure 6. Subsequently, ten materials with the most energy and embodied carbon can be observed in Table 9. The structure of this building has been made of adobe and mud mortar and its lining is made of cob. The soil has been utilized to prepare all of them. Expectedly,

TABLE 7. The outcomes obtained from quantity surveying and estimating of the traditional building

Material	Unit	Quantity
Mud-lime mortar	m^3	3.59
Wood	m^3	3.91
Glass	m^2	9.17
PVC water pipe	m	71
PVC Sewage Pipe	m	40
Power Cable	m	1000
Valves(brass)	kg	10
Mosaic	m^3	126.29
Plaster	m^3	12.28
Sun-dried brick	m^3	592.17
Mud mortar	m^3	252.37
Soil	m^3	145.82
Plaster of clay and straw	m^3	88.76
Lime mortar	m^3	58.22
Brick	n	59361
Soil plaster	m^3	29.1
Cement sand mortar	m^3	19.14

TABLE 8. The mass and percentage of materials used in traditional buildings

Material	Density kg/m^3	Weight kg (max to min)	Weight percentage
Sun-dried brick	1920	1136966.4	47.34890893
Mud mortar	2000	504740	21.01987208
Soil	2000	291640	12.14533323
Plaster of clay and straw	1600	142016	5.914249225
Lime mortar	1850	107707	4.485452634
Brick	1700	100913.7	4.202545995
Soil plaster	1600	46560	1.938988874
Cement sand mortar	2100	40194	1.673877122
Plaster	1300	15964	0.664819982
Mosaic	55 kg/m^2	6945.95	0.289263741
Mud-lime mortar	1300	4667	0.194356982
Wood	650	2541.5	0.105840641
Glass	25 kg/m^2	229.25	0.009547105
PVC plastic	-	134.23	0.005590002
Copper	0.0225 kg/m	22.5	0.000937011
Brass	-	10	0.00041645
Sum	-	2401251.53	100

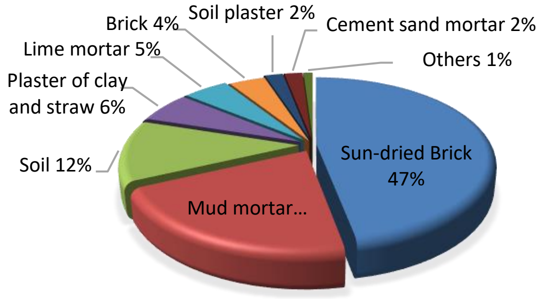

Figure 6. Pie chart of the weight percentage of materials used in traditional building

the soil has the most energy and embodied Carbon in the ranking table. For the accurate comparison between the two types of modern and traditional buildings; the structure and foundation of a one-story concrete house were designed and modeled exactly according to the plan of the traditional house keeping the existing spaces by Etabs and Safe Software with ACI 318-14 regulations.

TABLE 9. The rankings of the materials in terms of energy embodied carbon and equivalent carbon for the traditional building

Rank	Traditional building					
	Material	EE - MJ	Material	EC - kgCO2	Material	EC - kgCO2e
1	Soil	839852.6976	Soil	42925.80454	Soil	44792.14387
2	Brick	329863.3848	Brick	25289.52617	Brick	26389.07079
3	Plaster	90771.2423	Lime	11955.7044	Lime	12270.3282
4	Lime	83375.307	Cement	6468.82236	Cement	6911.892385
5	Wood	74909.86533	Plaster	5790.903386	Plaster	6334.264981
6	Cement	42977.79239	Wood	4915.959913	Wood	5009.597244
7	Sand	21610.29458	Sand	1280.610049	Sand	1360.648177
8	Mosaic	15611.18926	Mosaic	1199.238813	Mosaic	1271.193142
9	Plastic	10784.10075	Plastic	364.5920073	Plastic	433.0403152
10	Glass	5920.067209	Glass	339.4171866	Glass	359.150744

Then, it was analyzed concerning the amount and type of consumed materials. The dimensions of the cross-section of the columns and beams in the design were 30*30 cm and 35*30 cm, respectively. The roof type was selected as a joist system. The foundation of this building was designed as a strip footing with a width of 1 meter, and to control the punching shear, the depth of the foundation was designed to be 90 cm. Concerning the details obtained, the quantity surveying and estimating of the concrete building was carried out and the results are summarized in Table 10. Next, the weights and weight percentages of the materials are presented from the highest to the lowest volume of materials used in the concrete building in Table 11 and Figure 7.

TABLE 10. Results obtained from the concrete building quantity surveying and estimating

Material	Unit	Quantity
Concrete C25	m^3	206.04
Rock	m^3	148.35
Concrete C20	m^3	85.44
Cement Sand Mortar	m^3	61.84
Brick	m^3	76.30
Soil	m^3	42.39
Cement Block	n	2167.31
Soil Plaster	m^3	15.39
Deformed Bar	kg	21289.56
Granite	m^2	620.14
Clinker	m^3	28.02
Plaster	m^3	7.71
Bituminous Felt	m^2	377.47
Mosaic	m^2	88.48
Ceramic	m^2	230
Paint	m^3	0.0385
Tile	m^2	110.30
Wood	m^3	3.05
Glass	m^2	9.17
PVC Plastic	kg	134.23
Power Cable	m	1000
Valves (Brass)	kg	10
Nylon	m^2	83.15

Ten materials with the highest amounts of energy and embodied carbon in the concrete building are observed in Table 12.

Since the skeleton and the foundation of the building are made of reinforced concrete and its walls are made of pressed bricks, steel, concrete, and brick are at the top of the ranking table with the most energy and embodied carbon. Based on the data collected, the total equivalent of carbon and embodied energy, as well as the weight of the materials used, including the wastes, were compared in both traditional and concrete buildings in Table 13. As shown in Table 13, the weight of a concrete building is 1480 tons and the weight of its adobe counterpart is 2488 tons, which is about 1.7 times heavier. It is due to the high thickness of the adobe building walls, which sometimes reach 50 cm, and the use of materials with more mass in the adobe building as well. However, the results of carbon and embodied energy analysis show an increase of 1.73 times in the embodied energy, 2.28 times in the embodied carbon, and 2.33 times in the equivalent embodied carbon, with the change of system structure from traditional to concrete.

In other words, despite the lower mass of materials used in concrete buildings, the amount of carbon and embodied energy is markedly more compared to adobe buildings. It is because of using materials with energy, embodied carbon, and more units of mass.

As a result, establishing conventional concrete buildings instead of adobe buildings leads to increased carbon and embodied energy and a loss of historical context. It is also known that traditional houses such as ordinary rural buildings, need seismic retrofitting to become more resistant to earthquakes. This seismic retrofitting needs to be done in the context of sustainable development so as not to increase carbon emissions and energy consumption indiscriminately. Therefore, to choose the optimal method of strengthening these historical monuments, the right decision needs to be made, and in this regard, the SWOT technique will be employed. SWOT analysis is a systematic analysis seeking to provide a list of capabilities, weaknesses, opportunities, and threats, so the organizations can use these findings to find a strategy that fits their situation. From this model's viewpoint, a proper strategy maximizes the strengths and opportunities and minimizes weaknesses and threats.

TABLE 11. The mass and percentage of materials utilized in the concrete building

Material	Density (kg/m^3)	kg (max to min)	Weight percent	Material	Density (kg/m^3)	kg (max to min)	Weight percent
Concrete C25	2400	494496	35.5553378	Plaster	1300	10023	0.720675497
Rock	1400	207690	14.93336267	Bituminous Felt	15 kg/m^2	5662.05	0.407113709

Concrete C20	2390	204201.6	14.68253913	Mosaic	55 kg/m^2	4866.4	0.349904743
Cement Sand Mortar	2100	129864	9.337504021	Ceramic	21 kg/m^2	4830	0.347287504
Brick	1700	129710	9.326431086	Tile	20 kg/m^2	2206	0.158616197
Soil	2000	84780	6.095866375	Wood	650	1982.5	0.142546061
Cement Block	13.25 kg/n	28716.8575	2.064804506	Glass	25 kg/m^2	229.25	0.016483574
Soil Plaster	1600	24624	1.770519151	Plastic	-	134.23	0.009651429
Deformed Bar	7850	21289.56	1.530765663	Paint	1310	50.43	0.003632833
Granite	2800	17363.92	1.24850361	Copper	0.0225 kg/m	22.5	0.001617799
Clinker	550	15411	1.108084415	Brass	-	10	0.000719022
				Nylon	0.11 kg/m^2	9.15	0.000657905
				Sum	-	1388172.44	100

TABLE 12. The ranking of materials in terms of energy and embodied carbon and the equivalent carbon for concrete building

Rank	**Concrete building**					
	Material	**EE - MJ**	**Material**	**EC - kgCO2**	**Material**	**EC - kgCO2e**
1	Steel	661722.1039	Concrete	64892.07616	Concrete	69523.6485
2	Concrete	489895.8448	Steel	58693.84415	Steel	62772.95301
3	Brick	423991.7836	Brick	32506.03674	Brick	33919.34268
4	Ceramic	324901.8109	Cement Mortar	20900.31216	Cement Mortar	22331.84039
5	Stone	209318.4877	Ceramic	20035.61167	Ceramic	21118.61771
6	Bituminous Felt	180884.9125	Stone	12178.53019	Stone	13320.2674
7	Cement Mortar	138858.2383	Bituminous Felt	9415.145287	Bituminous Felt	9980.054004
8	Plaster	51188.74447	Plaster	3274.806625	Plaster	3579.854989
9	Wood	48075.94458	Wood	2529.644845	Wood	3182.71135
10	Soil	39295.53	Soil	2008.4382	Soil	2095.7616

TABLE 13. The total equivalent of embodied energy and carbon as well as the weight of materials used, including the construction waste

Comparison Criteria	**Traditional Building**		**Concrete Building**	
	Total	**per sqm**	**Total**	**per sqm**
EE - MJ	1521527.328	3972.656	2634913.490	6879.670
EC - kgCO$_2$	100888.823	263.417	229776.491	599.939
EC - kgCO$_2$e	105514.025	275.494	245546.029	641.112
Material weight including waste (kg)	2488035.475	6496.18	1480248.721	3864.88

Table 14 shows the SWOT analysis for concrete buildings with ordinary materials. Table 15 shows the SWOT analysis for traditional buildings with adobe materials. Therefore, according to the SWOT table and the proposed strategies to preserve historical texture and tourists attraction, and to show the effect of substituting materials on the amount of energy and embodied carbon, the energy and carbon were analyzed considering a combined building with concrete structure, frame and the joist system, the adobe walls, and the traditional flooring. Based on the analyzed information, the amount of embodied energy and carbon equivalent to total as well as the weight of materials used, including construction wastes in this combined building, and its difference from the conventional concrete building are presented in Table 16. The case-by-case comparison of saved weights, energy, and embodied carbon was performed and the percentage of savings for each material is separately shown in Table 17.

TABLE 14. SWOT analysis for concrete structures with the common materials

	Strengths (S)	**Weaknesses (W)**
SWOT analysis for concrete structures with the common materials	• High seismic retrofitting • High safety and security • High durability • Low maintenance costs	• High embodied energy (1.73 times higher than that of a traditional building according to the analysis) • A great amount of embodied carbon (2.28 times greater than that of a traditional building according to the analysis) • A great amount of construction waste • Lack of originality and non-observance of the tradition of Islamic Iranian architecture in such buildings
Opportunities (O)	**Strategies (SO)**	**Strategies (WO)**
• Familiarizing the executives and engineers with such materials, and how to implement them • The number of experts familiar with this structural system • Providing equipment for the implementation of such structures • Possessing a bylaw to match design issues	• Using concrete structures in dilapidated and historical textures to diminish financial as well as human losses • The combined use of concrete structures so as to maintain and renovate historical structures for greater durability	• Combining the technology of concrete frame construction with traditional facade rather than stone, traditional plan, and materials by the native architecture of each area • Creating new job opportunities by investing in line with the development of regulations, embodied energy, and carbon standards and monitoring their compliance • Informing engineers and project managers about the issue of embodied energy and compliance with standards
Threats (T)	**Strategies (ST)**	**Strategies (WT)**
• Not using indigenous materials • Non-compliance with environmental issues as well as the sustainable development model • Lack of attraction for tourists • The difficulty of construction waste recycling these materials	• Raising the awareness of the community, bringing the culture and a sense of trust in meeting energy and embodied carbon standards, and preserving the environment • Providing government funding, attracting private investment, and allocating funds to implement energy and carbon regulations • Development and the attraction of tourists by combining modern and traditional structures with Iranian architecture and preserving the historical texture in line with sustainable urban development	• Labeling all building materials in terms of energy and embodied carbon in factories for designer use • Replacing the common materials with the indigenous ones with less energy and carbon per unit of mass and easier recycling capability

TABLE 15. SWOT table for traditional structures with adobe materials

	Strengths (S)	**Weaknesses (W)**
SWOT analysis for traditional structures with adobe materials	• Low embodied energy (according to the analysis performed) • Low embodied carbon (according to the analysis performed) • Low construction waste and adaptation to climate • Possessing the originality and observance of the tradition of Iranian Islamic architecture in such buildings	• Low seismic retrofitting, high casualties during the natural catastrophe, and low safety Foundation • heavy roof • Lack of dry walls, lack of integrity, long and uncontrolled lengths, and long walls
Opportunities (O)	**Strategies (SO)**	**Strategies (WO)**
• Inexpensive and available indigenous materials Attract tourists	• Preserving historical and traditional textures and restoring them to preserve the originality of Iranian architecture and attract tourists	• Fixing major weaknesses in the structural system by combining concrete frame

• Materials are easily recycled • The necessity of considering environmental issues, following the model of sustainable development, and high executive potential	• Using indigenous materials due to the ease of access and coordination with the rural economy	construction technology with traditional adobe and finishing • Reduced construction waste in the construction sector using traditional architecture and materials in line with sustainable development
Threats (T)	**Strategies (ST)**	**Strategies (WT)**
• Lack of skilled experts familiar with this structural system • Modernism and forgetting the originality of architecture • No regulations to match the design issues of these structures • Ignorance from officials and the media regarding the culture of sustainable energy development and environmental issues	• Culturalization of preserving the originality of Iranian architecture and creating a sense of trust in this style of architecture by using modern technologies and standards • Training experts to use materials compatible with the climate of each region to create thermal and cooling insulation to save energy	• Encouraging engineers and allocating funds for research on seismic retrofitting of adobe buildings and improving the quality of rural life • Making regulations and implementing a plan to improve traditional buildings and reduce casualties due to natural catastrophes due to the impossibility of removing this system in rural areas that are far from facilities

TABLE 16. Energy and embodied carbon equivalent to total and the weight of materials used in the combined building compared to the conventional concrete building

Comparison Criteria	Combined Building		Combined building savings compare to concrete building		
	Total	per sqm	Total	per sqm	percentage
EE - MJ	1705856.092	4453.932	929057.398	2425.7	35.26%
EC - kgCO2	139289.164	363.679	90487.327	236.3	39.38%
Material weight including waste (kg)	2133260.538	5569.87	-653011.817	-1705.0	-44.12%

TABLE 17. Saved weight, energy, and embodied carbon in materials

Material	The amount of savings			The percentage of savings		
	Weight (kg)	Embodied Energy (MJ)	Embodied Carbon ($kgCO_2$)	Weight	Embodied Energy	Embodied Carbon
Concrete	63083.2	39742.4	5299.0	8.16%	8.11%	8.17%
Steel	1055.1	285767.3	30389.2	4.66%	43.19%	51.78%
Brick	133439.79	400319.37	30691.15	94.42%	94.42%	94.42%
Coating	13731.8	14456.4	887.8	35.42%	28.24%	27.11%
Ceramics and Tiles	6367.82	272906.44	16829.23	84.00%	84.00%	84.00%
Paint	53.06	18570.50	642.009	100.00%	100.00%	100.00%
Mosaic	-8262.49	-14459.4	-1218.7	0.00%	0.00%	0.00%
Stone	19028.95	209318.49	12178.53	100.00%	100.00%	100.00%
Mortar	112642.57	109263.29	16445.82	78.69%	78.69%	78.69%

Correspondingly, if the project is divided into three sections: skeleton frame, framework, and finishing, the skeleton frame includes concrete, steel, polystyrene, and aggregate; the framework includes pressed and clay brick, lining, plastics other than polystyrene, mortar except for slurry and bitumen, and the finishing includes cement-slurry, ceramic and tile, aluminum, paint, mosaic, stone, glass, and asphalt. Energy percentage and the embodied carbon and the weight of the materials in each of the work sections in the concrete building and the amount of savings in each section are presented in Table 18 and the diagrams in Figures 8 to 10.

TABLE 18. Saved weight, energy, and embodied carbon for each work section separately

Work sections	Concrete Building			The amount of savings			Percentage of weight saved
	Weight 1000ton	Embodied Energy 1000GJ	Embodied Carbon 1000 ton CO2	Weight 1000 ton	Embodied Energy 1000 GJ	Embodied Carbon 1000ton CO2	
Skeleton frame	0.96	1.18	0.125	0.06	0.33	0.04	6.71%
Framework	0.29	0.62	0.057	0.26	0.52	0.05	88.30%
Finishing	0.03	0.56	0.033	0.02	0.49	0.03	69.64%

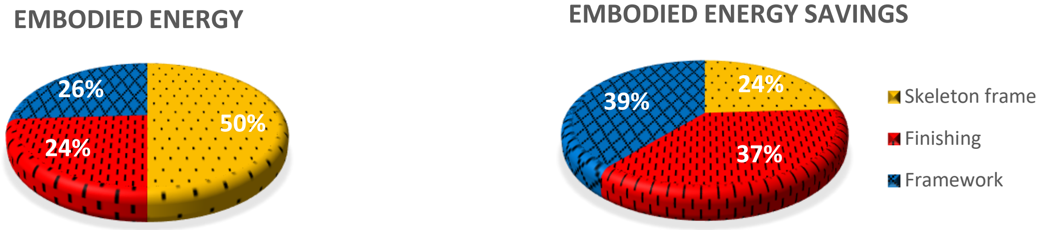

Figure 8. The embodied energy and its saving amount for each work section separately

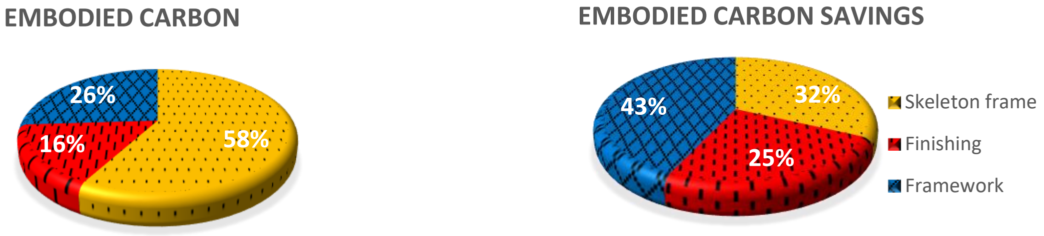

Figure 9. The embodied carbon and its saving amount for each work section separately

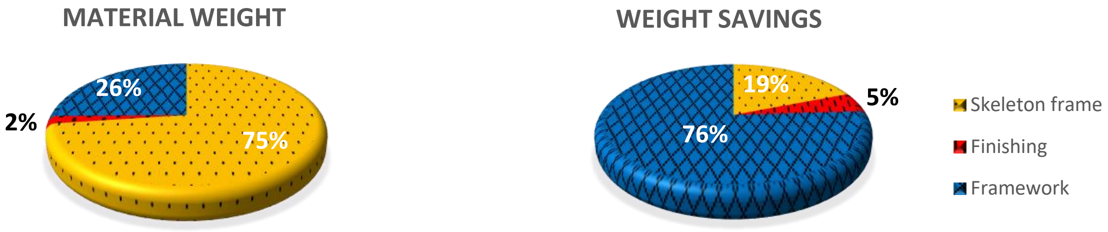

Figure 10. Material weight and its saved mount for each work section separately

4. CONCLUSION

Over time, the structural system of buildings has changed. This change caused an increase in energy and carbon dioxide. However, research in Iran has focused less on the necessity and importance of reforming this process. In this respect, a Microsoft Excel program was provided to determine embodied energy and carbon for all types of buildings, the results of which were validated in the selected case sample by manual calculations.

According to the strategy explained for historical and derelict buildings in Yazd and after SWOT analysis, the skeleton frame and roof of the concrete structure were combined with a framework and finishing to achieve the goals of reducing embodied energy and carbon (by removing and replacing materials such as bricks). Preserving the texture of the area is in line with sustainable urban development and maintaining the attractiveness of this texture for tourists. Because the frames of this combined structure are made of concrete, there is no need to implement thick load-bearing walls, moreover, the wall thickness is reduced to a minimum of 25 cm (a row of adobe considering the thickness of finishing with plaster of clay and straw).

According to Table 16, the weight of materials employed in the combined building has finally decreased by 14% compared to the traditional building. Observing the results of embodied energy and carbon analysis for the modified building indicates 39.38% savings in carbon and 35.26% in embodied energy. Consistent with the latest census of the Statistics Center of Iran in 2016, the number of residential units in which adobe is used is 10.54% of the total rural houses. It reveals that about 53.73 million square meters go to adobe houses. Considering the amount of energy and carbon saved in the combined plan, it is possible to reduce 13.66 million tons of carbon equivalent to 1.96 million tons of energy and store 130.34 million gigajoules of energy by developing this plan for the adobe texture in the country.

To show the effect of implementing the results of the current research project, it can be pointed out that the amount of energy saved in the proposed strategy is equivalent to the production of electric energy from Iran's largest power plant ‘Damavand Power Plant’ (Pakdasht Martyrs) with a capacity of 2868 MW in 2 years and 4 months. To develop the present study, the following suggestions are presented to researchers who intend to conduct additional research in this field:

- Investigating the effect of increasing the lifespan of building and durability of materials to reduce the replacement coefficient to save embodied energy and carbon.
- Calculate the amount of embodied carbon and energy of wooden houses and examine the possibility of replacing this structural system with current systems according to the climate.
- Investigating the role of advanced technologies in embodied energy and carbon optimization.

Comparison of steel and concrete structures concerning embodied energy and carbon.

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Persian Abstract

چکیده

بیش از 40 درصد انرژی مصرفی جهان در بخش ساخت و ساز مصروف می گردد. با این حال، برخی از کشورها معیارهای زیست محیطی را به عنوان الزامات طراحی در کدهای ساخت و ساز خود در نظر نمی گیرند. بر این اساس، هدف این تحقیق ارائه راهکاری است که با حفظ بافت‌های تاریخی و سنتی ایران، انرژی و کربن نهفته را کاهش دهد. لذا مقایسه کربن و انرژی نهفته بین ساختمان‌های بتنی جدید و ساختمان های سنتی با محاسبه میزان مصالح ساختمانی انجام شد. ضمن بررسی هر دو نوع ساختمان، کاهش کربن و انرژی نهفته در یک سیستم ساختمان ترکیبی مورد ارزیابی قرار گرفت. در ادامه با استفاده از تحلیل SWOT راهبردهای این ترکیب بررسی شد. ساختمان سنتی گِلی علیرغم داشتن جرم بیشتر مواد، انرژی و کربن نهفته کمتری نسبت به ساختمان بتنی دارد. با توجه به تحلیل SWOT، استراتژی یکپارچه سازی سیستم های ساختمانی سنتی گِلی و جدید بتنی ارائه شد. سیستم پیشنهادی به ترتیب حدود 40٪ و 35٪ کاهش کربن و انرژی نهفته را در مقایسه با سازه بتنی ایجاد می‌کند. گسترش این استراتژی در سراسر کشور باعث صرفه جویی 13 میلیون تن کربن و 130 میلیون گیگاژول انرژی نهفته می شود. یافتن راه حلی مبتنی بر ملاحظات پایداری برای حفظ بافت تاریخی یکی از دغدغه های اساسی کشورهایی است که این بافت ها بخشی از هویت آنها را تشکیل می دهند. در همین راستا سیستم ترکیبی ارائه شده، ضمن توجه به ساختمان پایدار و توسعه شهری، راه حلی مطلوب برای کاهش کربن و انرژی نهفته ساختمان است.