Assessment of Alternative Building Materials in the Exterior Walls for Reduction of Operational Energy and CO2 Emissions

(Case study: A typical residential building in Tehran)

Leila Farahzadi, Rosa Urbano Gutierrezi, Alireza Riyahi Bakhtiari, Hamid Reza Azemati, Seyed Bagher Hosseini

Abstract*: *The increase in energy demand which leads to global warming is one of the main environmental issues that drive to detrimental ecological, social and economic impacts. Recently, these impacts are being exposed faster than expected. Since buildings and their materials are one of the major sources of energy consumption and carbon dioxide emissions, environmental assessment of building materials and replacing them with the more environmentally friendly alternatives are increasingly needed to address environmental performance issues. In this study, the operational energy consumption (thermal energy) and carbon dioxide production in a typical building in Tehran is calculated by applying computer simulation –Design Builder software - in two cases of using conventional building materials and alternative ones. The results show a considerable reduction in the operational energy consumption and carbon dioxide emissions in case of applying the alternative-environmentally friendly- building materials.

Index Terms—Alternative Building Materials, Assessment, CO2, Energy.

I. Introduction

In recent years, new requirements caused by environmental issues have turned sustainable architecture into a leading and notable topic. In addition, new technological developments have equipped architects with a range of techniques to move toward this sustainability. Designers have also become more aware of buildings' and structures' role in environmental problems. Each building must be designed in such a way that leads to the minimum use of new resources and also allows the building to be a resource for the construction of other structures at the end of its useful life. Moreover, it is worth mentioning that there are not enough resources to keep constructing new built environments around the world or reconstruct new generations of buildings [1].

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According to the International Energy Agency, the world energy consumption has almost doubled between 1973 and 2007 [2], which itself indicates an exponential growth in extraction, production and consumption of fossil fuels during this period. One percent increase in the intensity of energy consumption leads to an increase of 0.92 percent CO_2 emissions per capita [3]. So, in order to achieve sustainable development in any country, it is critical to reduce the energy consumption.

Global warming as a result of energy consumption is the most important factor in the context of sustainable development. It is estimated that by 2030 the energy demand will increase by 40% and will reach 8.16 billion tons of oil equivalent [4]. Iran has produced 1.2% of the world's greenhouse gas emissions, which has ranked it the thirteenth country in the world in terms of greenhouse gas emissions [5]. The building sector is a major consumer of energy in Iran, and the major producer of carbon dioxide (about 23%) along with transportation sector [6] (Fig.1).

In a standard building, up to 90% of the building environmental impact occurs in the operational stage and mainly due to the heating and cooling procedures. Regulations have made the new strategies for energy efficiency of buildings and as a result, other life cycle stages such as the selection of materials have become more important [7]. Thus, selection of environmentally friendly building materials should be carried out on an appropriate basis of comparing building materials as objectively as possible in a quantitative method [8].

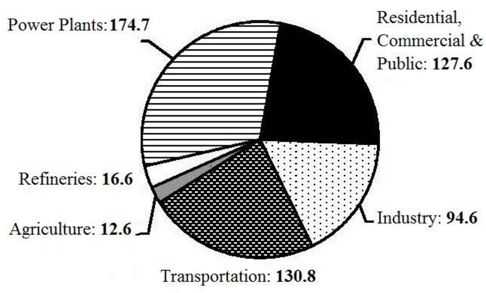

Fig.1. Carbon dioxide emissions in different energy sectors in 2012 [6]

The embodied energy [9] the operational energy (life stage of a building) [10] and the amount of CO_2 emissions [11]-which is the main factor in global warming- are

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considered as important criteria in selecting Environmentally friendly building materials.

Ogunkah & Yang [12] have discussed the definition of appropriate criteria and also the use of Analytic Hierarchy Process (AHP) method for the selection of materials. In another study, they have presented a model consists of different criteria and have used it along AHP method to select the right flooring materials for residential buildings [13]. Henrickson [14] has assessed the criteria related to evaluating the performance of buildings in terms of environmental and sustainability issues to develop relevant and measurable criteria for green building programs. The environmental characteristics of materials used in the construction of two residential buildings have been compared in order to develop a construction system that would be friendly to future environment [15]. A model for selecting sustainable materials has been proposed in structural elements in Sri Lanka with the approach of life cycle assessment (LCA) and with regard to the social, economic and environmental issues [16]. Seo et al. [17] have used the LCA design tool with methodological approach to select sustainable materials for a building. Asif et al. [18] have performed a comparative study on some window frame materials in terms of their production, energy consumption and environmental impact through their life cycle.

Comparing the similar buildings with different materials and systems and evaluating the environmental impact of each of those factors is a major step towards identifying and selecting environmentally friendly materials as well as identifying possible improvements. Ghorbani et al. [19] have analyzed the environmental properties of concrete and Ahmadi [20] has studied the performance of concrete structures towards environmental sustainability. In other studies two medical building with similar structures in America (through using GaBi software) [21] and also office buildings in Thailand have been compared based on certain environmental criteria [22].

There are no binding regulations or guidelines in Iran respecting proper selection of Building materials, particularly those materials with the lowest energy consumption and the carbon dioxide emissions, so conducting studies on the evaluation and comparison of building materials in terms of their environmental impact and providing a proper model for selecting materials seems essential. This study will attempt to use a quantitative method and a building modeling by using the DesignBuilder software to compare conventionally used materials with the proposed ones that can be as an alternative for the exterior walls of residential building in Tehran. The analysis will focus on thermal energy consumption and carbon dioxide emissions in the operational stage of the building. The selection of alternative building materials is based on a former research conducted by the authors [23].

II. Materials and Methods

A. Type of building materials used

Standard bricks, polystyrene thermal insulation, oil-based paint, aluminum frames and air-filled double glazed windows are used in the exterior walls of the conventional building in Tehran. Clay blocks, glass wool thermal insulation, acrylic paint, and wooden frames, and argon-filled double glazed windows are proposed to be applied in the exterior walls of the alternative building (Table I). The alternative building materials have been studied as more environmentally compatible ones based on a former research carried out by the authors by applying certain environmental criteria (better indoor air quality, less embodied energy, heat transition, CO_2, VOC emissions, and toxic content) for building materials selection [23].

B. Properties and characteristics of the used materials

In general, each material has different mechanical, physical and environmental properties. Some of these properties are illustrated in Table II.

C. Importance of simulation

Simulation is an accurate tool to make an interrelation between the design of a building and its performance parameters such as energy efficiency, comfort levels, air quality, etc. Thus it helps to identify potential problem areas, check diagnostic evaluations and appraise and test suitable design modifications.

In this study, simulation contributes to the optimization of the design process and selection of building materials in a way that leads to create a proper environmental basis for the process of construction [28].

A. Software used in the study

In this study, the DesignBuilder software has been chosen to obtain **the** annual thermal energy consumption and carbon dioxide emissions for a typical residential building in Tehran.

Table I. Conventional and alternative building materials used in the walls

Conventional materials	Alternative materials
Brick	Clay block
Petrochemical insulation (polystyrene)	Mineral based insulation (glass wool)
Synthetic and petrochemical paints (oil-based paints)	Natural paints (acrylic)
Aluminum window frames	Wooden window frames
Double glazed windows 6mm spacing (air filled)	Double glazed windows 6mm spacing (argon filled)

The Design Builder software can be used to model buildings in various aspects such as building HVAC, energy efficiency, lighting systems, day lighting, comfort performance, etc.

The Design Builder modeling software uses customized profiles for the climates of various cities in Iran to perform the related calculations of energy consumption and waste precisely based on the climatic conditions the building (http://www.designbuilder.co.uk/).

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Table II. The properties and characteristics of the used materials

Type of materials	**Description**
Brick	They are mainly composed of aluminum silicates and are produced in the forms of solid, perforated, or hollow rectangular cube or thin piece. They are biodegradable thermal masses with low embodied energy [24].
Clay blocks	Clay block is produced by processing clay, shale or other suitable materials at the temperatures above 930°C. They are good biodegradable thermal masses with very low embodied energy [25].
Petrochemical thermal insulation	They are obtained from fossilized materials. Polystyrene is a good example. They are non-biodegradable with high embodied energy and CO^2 emissions [24].
Natural and mineral-based Thermal Insulation	They are organic thermal insulations that are manufactured from natural materials (such as cellulose, cork, sheep wool, wood), and also natural insulators that are made of minerals (such as glass wool, mineral wool). They are biodegradable with relatively low embodied energy [24].
Synthetic petrochemical paints	They are made of non-renewable resources, have a lot of latent energy and release volatile organic compounds. They are non-biodegradable [24].
Natural and mineral paints	They are made of renewable sources. They are non-toxic and biodegradable and have a low latent energy [24].
Aluminum frame	Aluminum is a soft, light metal with silver color, metallic luster, and high formability; it is extracted through electrolysis from bauxite, which is a sedimentary rock. Thy have high embodied energy content and are high Global warming potentials [26].
Wooden frame	Wood is an organic cellulose tissue composed of 50% carbon, 40% oxygen, 6% hydrogen and 1%, nitrogen and minerals. Wood is one of the oldest building materials. They have Low embodied energy with good thermal performance [27].
Glass	The raw materials of soda-lime-silica glass used for window glaze include: Silica sand, soda and lime fluxes. They are thermal weak links [27].

A. Case Study

The study is conducted on a typical 4-storey residential building in the city of Tehran with a total area of 94.2 square meters on each floor (Fig.2-Typical plan and Fig.3-Elevations).

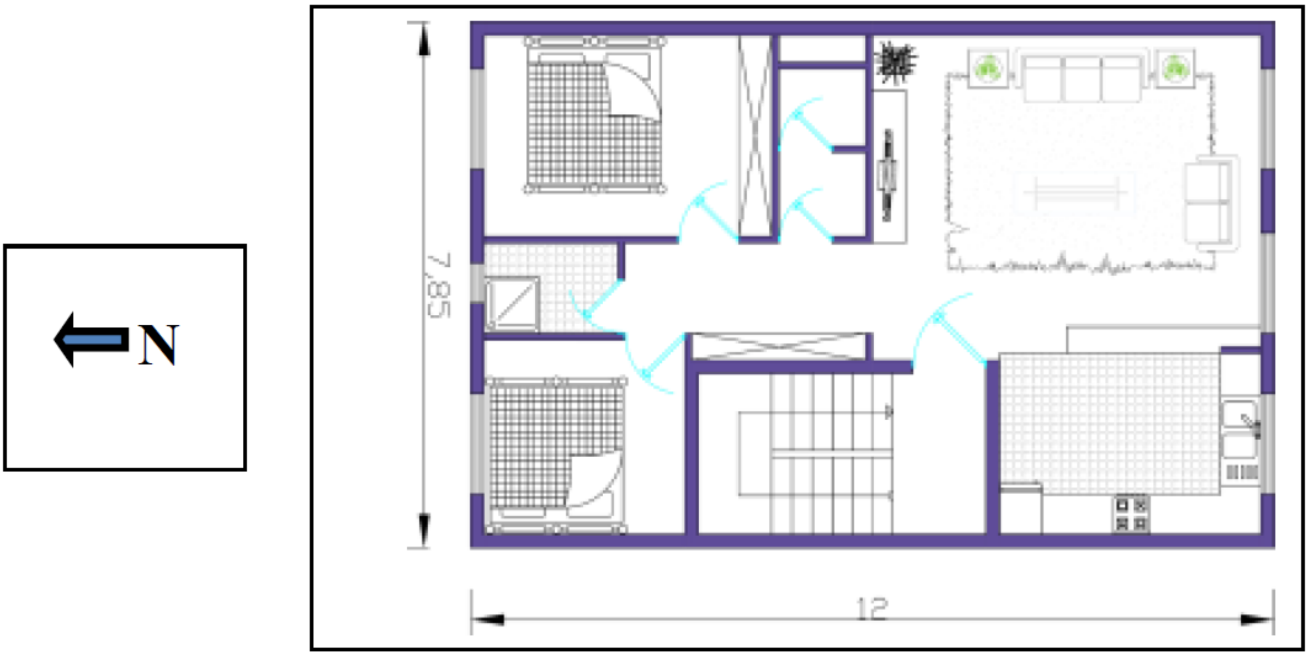

Fig.2.Typical floor plan of the case study

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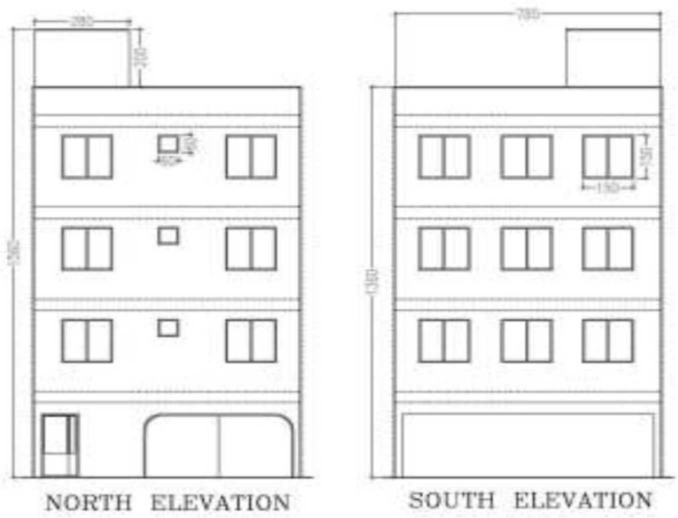

Fig.3.Typical floor Elevations

Basic characteristics of the model building are illustrated in table III.

Table III. Basic characteristics of the model building

Location	**Tehran, Iran (35.68° N, 51.38° E)**
Type of building	residential
No. of floors	Ground floor + 3
Total Building area (m^2)	376.8
Number of bedrooms/bathrooms (each floor)	2/1
Height of Building (m)	15.60
Structural system	reinforced concrete system
Partitions	built in-situ
Window area (m^2)	57.79
Wall area (m^2)	732.93
Window to wall ratio (WWR)	7.8%

A. Conceptual Model

The conceptual model of this investigation is shown in Fig4.

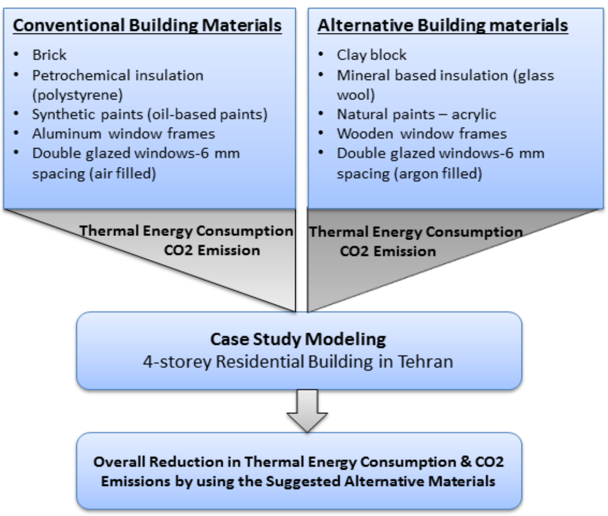

Fig.4. Conceptual model of the research methodology

III. Results and Discussion

It should be noted that, the rate of heat loss and optimization of consumption were only calculated for hydrocarbon fuels used in the building sector, which mainly include diesel or natural gas. Electrical power uses impact is considered on CO_2 emissions.

Monthly thermal energy consumption (kWh) and carbon dioxide emissions (kg) of the building during one year were measured by the software. Table IV shows the monthly thermal energy consumption (kWh) and carbon dioxide emissions (kg) for the building constructed with conventional building materials and Table V the same parameters for the building with the alternative ones.

Table IV. Monthly thermal energy consumption and CO_2 emissions for the building with conventional materials

Month	**Thermal Energy Consumption (Gas-kWh)**	**CO_2 Emissions (kg)**
January	4262.62	1906.73
February	2882.08	1532.93
March	788.77	1225.95
April	124.87	1282.52
May	0	1924.11
June	0	3314.19
July	0	3786.78
August	0	3939.24
September	0	3129.66
October	4.92	1637.93
November	417.08	1191.35
December	3215.89	1706.59

Table V. Monthly thermal energy consumption and CO_2 emissions for the building with alternative materials

Month	**Thermal Energy Consumption (Gas-kWh)**	**CO_2 Emissions (kg)**
January	4071.02	1672.04
February	2927.54	1354.11
March	731.58	1158.67
April	105.64	1322.84
May	0	2022.31
June	0	3238.98
July	0	3658.95
August	0	3786.10
September	0	3118.61
October	4.51	1788.20
November	375.83	1216.03
December	3060.57	1510.08

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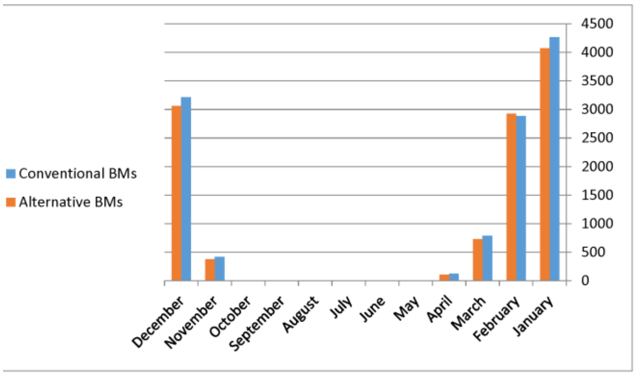

Fig.5.Comparison of monthly thermal energy consumption

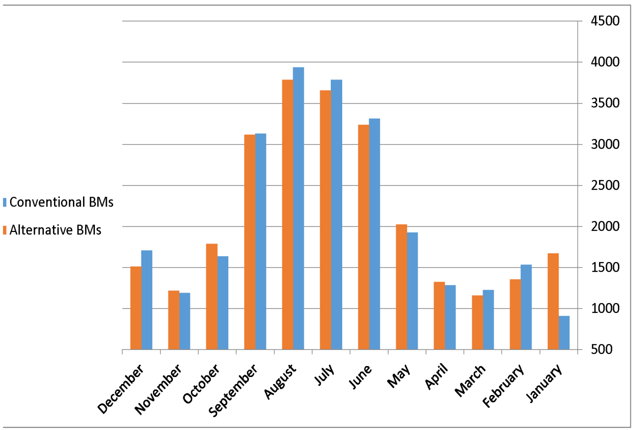

Fig.6.Comparison of monthly CO2 emissions

The monthly energy consumption and CO_2 emissions for a building with alternative building materials is significantly less than the building with conventional ones (Table IV & V). Some investigations have studied and measured the reduction amounts in energy consumption/CO2 emissions while using alternative building materials. Cui et al. [29] have assessed the reduction of more than 30% in CO2 emissions in case of using the proposed building materials for whole building. Gonza´lez & Navarro [30] have reached to a similar appraisal.

Table 6 shows that the annual thermal energy consumption in the building constructed with conventional materials (brick wall, synthetic insulation- polystyrene, petrochemical paint-oil based paint, aluminum window frames, air-filled double pane glass) is 12099.49 kWh, while by using alternative materials (clay blocks, natural insulation - glass wool, natural paint, wooden window frames, argon-filled double pane glass) the value would be decreased by 9.5 percent (to 11078.70 kWh). Reddy & Jagadish [31] have shown that total embodied energy of load bearing masonry buildings can be reduced by 50% when energy efficient/alternative building materials are used.

Table VI. Thermal energy consumption and carbon dioxide emissions in a one year period

Building Type	Thermal Energy Consumption (Gas- kWh)	CO_2 Emissions (kg)
Building with Conventional BMs	12099.49	26600.79
Building with Alternative BMs	11078.70	25846.93

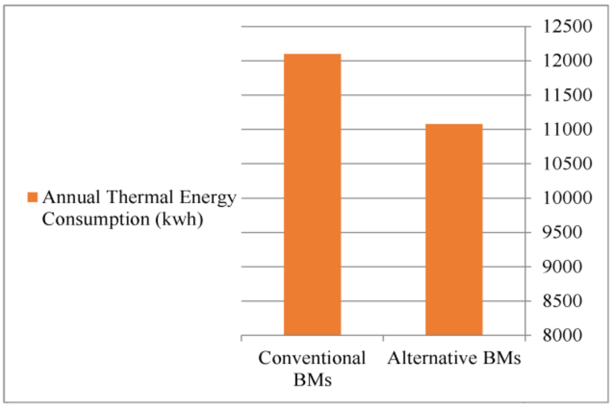

Fig.7.Comparison of annual thermal energy consumption

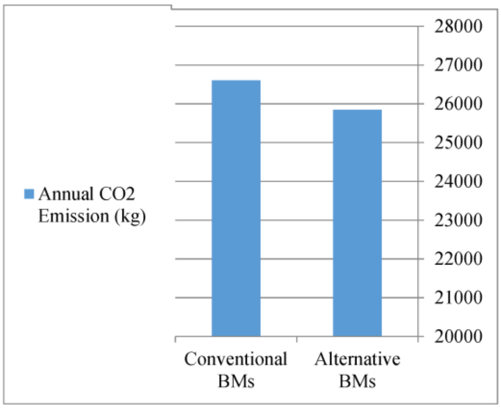

Fig.8.Comparison of annual CO2 emissions

The amount of annual carbon dioxide emissions (kg) in the building constructed with conventional materials is 26600.79 kg, while by using alternative materials this value would be decreased by about 3 percent (to 25846.93 kg). It should be noted that CO_2 emissions in hot months increase due to the growth in electricity power use (Fig. 6).

IV. SUGGESTIONS AND SOLUTIONS FOR ARCHITECTURAL DESIGN

1) Using petrochemical insulations such as polystyrene, epoxy, and polyurethane is needed to be reduced, because they are non-biodegradable, leave hazardous wastes and increase carbon dioxide emissions.
2) Synthetic and petrochemical paints are made from non-renewable resources, increase carbon dioxide emissions and also create volatile organic compounds (VOCs), are potentially toxic, and besides having

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adverse environmental effects, endanger the health of residents by affecting the air inside the building. Using natural and water-based paints is recommended.

3) The minimal heat transfer coefficient can be reduced by using argon-filled double or triple glazed glass.
4) Thermal conductivity of aluminum is high and heat easily passes through it. It is better to use wooden frames for windows.
5) Using clay blocks instead of bricks reduces the heat transfer to the outside in the winter and reduces the energy dissipation. In addition, it decreases the weight of building structure.

V. CONCLUSION

This study shows that the idea of substituting conventionally used building materials in the exterior walls with the proposed environmentally friendly building materials has the satisfactory result of decreasing the functional (thermal) energy consumption of building by 9.5% and reduction in the carbon dioxide emissions by 3%. This result encourages the advantageous idea of using environmentally compatible and friendly building materials in all the building's components. This study presents a simple model based on reality to promote greater use of alternative, environmentally friendly building materials in residential buildings. Energy consumption and carbon dioxide emissions can be reduced even further by integrated environmental solutions and replacing the materials of all components of building (wall, roof, ceiling, windows, etc.) with the alternative ones which can be the basis for future researches in this field.

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