Proposing a Life Cycle Energy Efficiency Index for Comparative Assessment of Insulation Materials' Performance

Hashem Amini Toosi – University of Tehran – HashemAmini@ut.ac.ir
Ali Vakili-Ardebili – University of Tehran – avakiliardebili@ut.ac.ir
Nasim Hasheminejad – Politecnico di Milano –nasim.hasheminejad@mail.polimi.it

Abstract

In this paper, a new method is presented to compare different scenarios of insulation by assigning a Life Cycle Energy Efficiency (LCEE) index, which includes operational energy use and embodied energy of materials. For this purpose, a sensitivity analysis has been performed to determine the relation between insulation thickness and total energy consumption, then the new method to assign the LCEE index has been used and the results have been compared.

Our methodological approach consists of the following steps: (i) Simulate a 27 m^3 cubic simple zone with a double glazed air filled window on south surface in EnergyPlus 8.3 software; (ii) Determine the thermal comfort boundaries for each studied city including Tehran, Bandar Abbas, Tabriz and Kerman; (iii) Vary installation materials and insulation thickness and calculate the total energy demand for heating and cooling in each city that includes 128 insulating scenarios; (iv) Calculate the embodied energy of different insulating alternatives based on LCI databases; (v) Perform a sensitivity analysis for each insulation material in each city to figure out the relationship between thickness of insulation materials and total energy demand in each city; (vi) Use the new method to assign the LCEE index in order to compare different scenarios.

The analysis showed that both operational energy and embodied energy have considerable impacts in decision-making processes in order to select the best insulation type and thickness. Moreover, the new method to assign the LCEE index was used as a useful method to assign a concise comparative index in order to compare different decisions by building designers.

1. Introduction

The building sector is responsible for 40 % of the total energy consumption in Europe. This sector is known as the major contributor to the environmental impact (European Union, 2013; Arena et al, 2003; Iribarren et al, 2015). It is crucial to understand the flow of energy in the buildings life cycle in order to meet global energy efficiency program targets. Energy is consumed in all the life cycle phases of a building, including material production, construction, operation, and demolition. Therefore, it's vital to understand the importance of each phase of a building life cycle. Several studies, showed the growing significance of embodied energy in a building life cycle (British Department for Communities and Local Government, 2007). In the UK, embodied emissions in new construction and renovation each year account for about 10 % of the total CO_2 emissions. Within this, approximately half is used in the extraction of raw materials and manufacture of the materials.

Nowadays in Iran and other developing countries, both the improvement of energy-efficiency standards and the deployment of low-energy buildings typically focus on reducing the operational energy consumption of buildings. Studies on low energy buildings show a reverse relation between operational energy with embodied energy. This means that while utilizing new technologies and high performance materials reduces the operational energy of a building's life cycle, the embodied energy of building is increased and this increase is mainly attributed to energy consumption in high performance material production processes (Keoleian et al., 2001; Yao et al., 2014).

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As a result, it will be increasingly important to consider the primary energy-use for materials in buildings that are designed and constructed to be more energy-efficient (Thormark, 2002; Blengini et al., 2010; Dodoo et al., 2011). In order to optimize the total energy demand in a building's life span, a whole life cycle energy analysis, including all phases of a building's life cycle should be performed. In this paper, the performance of different insulation materials will be compared. For this purpose, a comparative assessment method on building insulation materials will be presented. In this method, the embodied energy and operational energy in a building life cycle are considered in calculations, and the results of each insulation material are compared with other materials.

There are various efforts to define methods with the purpose of calculating the embodied energy of insulation materials that will be reviewed in the next section, but the aim of this paper is to define a clear and concise index that could help the architects understand the differences of insulation material performance.

1.1 Literature Review

Many studies performed in order to assess the environmental impacts of different insulation materials and each study focused on different materials or different environmental targets (Tingley et al., 2015).
Winther and Hestnes (1999) compared total energy use during the life span of buildings, with different insulation scenarios, different ventilation strategies, and different energy saving equipment. Mithraratne et al. (2004) described a method for LCA based on the embodied and operating energy and costs of buildings. Shukla et al. (2009) developed a simple methodology to calculate the embodied energy of an adobe house. Ardente et al. (2008) conducted a life cycle assessment on a kenaf-fiber insulation board in comparison with stone wool, flax, paper wool, PUR, glass wool and mineral wool.
Whilst Shrestha et al. (2014) suggested a protocol to assess the environmental impacts of insulation over their life; La Rosa et al. (2014) performed a comparative LCA of four external wall alternatives with cork insulation and PVC foam. Pargana et al. (2014) conducted an LCA on different types of insulation in Portugal. Bojic et al. (2014) performed an optimization for the entire life cycle of different thermal insulations.

2. Materials and Methods

Life Cycle Energy Analysis (LCEA) is a simplified version of life cycle assessment, which only focuses on the evaluation of energy inputs in different phases of the life cycle (Chau et al., 2015).
Our methodological approach consists in the following steps: (i) Simulate a 27 m^3 cubic simple zone with a double glazed air filled window on south surface in EnergyPlus 8.3 software; (ii) Determine the thermal comfort boundaries for each studied city including Tehran, Bandar Abbas, Tabriz and Kerman; (iii) Vary installation materials and insulation thickness and calculate the total energy demand for heating and cooling in each city; (iv) Calculate the embodied energy of different insulating alternatives based on LCI databases; (v) Perform a sensitivity analysis for each insulation material in each city to figure out the relationship between thickness of insulation materials and the total operating energy demand in each city; (vi) Use the new method to assign the Life Cycle Energy Efficiency index (LCEE) in order to compare different scenarios.
To calculate the total embodied and operational energy demand of different insulating scenarios during the 30 years of life span, the Equation 1 will be used.

$$LCE_j = \Sigma_{i=1,12} (n\ OE_i + V\ EE_j) \qquad (1)$$

where:
LCE_j : the total operating and embodied energy in 30 years life span for j(th) scenario
OE_i: heating and cooling operating energy demand of each month in a year
n: life span of insulation materials (years), (in this case study, n = 30 years)
V: the total volume of insulation materials
EE_j: embodied energy of the insulation material for j(th) scenario
To assign the LCEE index, equation 2 will be used. The mathematical meaning of this equation is a

comparative index that helps the architects find the best insulation scenario in technical design phases. By dividing the LCE of a single scenario by the sum of the LCE for all the considered scenarios according to this equation, a clear and concise index between 0 and 100 will be obtained which could help the architect understand the differences between insulation materials' performance quickly and easily.

$$\text{LCEE index}_j = (1 - \text{LCE}_j/\Sigma_{j=1,n}\ \text{LCE}_j) \qquad (2)$$

Where:
LCCE index$_j$: for j(th) scenario
LCE$_j$: the total operating and embodied energy in a 30-year life span for j(th) scenario
N: the all insulating scenarios

Fig. 1 and Table 1 show the thermal zone and thermal specifications of materials and construction assemblies, modeled in EnergyPlus 8.3. The values in Table 1 are the average values of Iran's building technology industry.

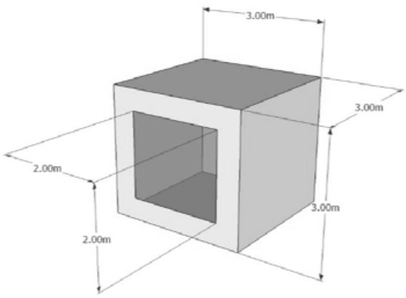

Fig. 1 – The thermal zone which is modeled in EnergyPlus 8.3

Table 1 – Thermal specification of materials (an average based on common construction materials in Iran)

Assembly	Thick ness (m)	Density (kg/m^3)	Thermal conductivity (W/(m K))
Wall (Brick)	0.1	1800	0.9
Roof (Lightweight concrete)	0.1	1400	0.5
Floor (Lightweight concrete)	0.1	1400	0.5
Insulation (External insulating for walls, roof and floor)	Variable	Variable	Variable
Window (double glazed, air filled)	-----	----------	0.15 (equivalent thermal conductivity)

2.1 Life Cycle Inventory and Weather Data

Life cycle inventory has a high importance in any LCA analysis process, because the quality and reliability of the results in a life cycle assessment process completely depend on the quality of LCI data (SAIC, 2006). Table 2 presents the physical properties and embodied energy of the studied insulation materials.

Table 2 – LCI data of insulation materials (Hegner, 2007)

Insulation material	Thermal conductivity (W/(m K)	Density (kg/m^3)	Embodied Energy (MJ/m^3)
XPS	0.03	50	2823
GMW	0.035	20	505
PU	0.026	31	2880
Foam Glass	0.041	117	197
GMW unforced rolled	0.032	32.5	538
Wood fiber	0.044	210	1362
EPS	0.035	30	3057
Cork Slab	0.044	120	3156

Iran is located in West Asia and borders the Caspian Sea, the Persian Gulf, and the Gulf of Oman in the region known as the Middle East. It lies between latitudes 24° and 40° N, and longitudes 44° and 64° E. Iran has a variable climate. In the northwest, winters are cold with heavy snowfalls and subfreezing temperatures in December and January. Spring and fall are relatively mild, while summers are dry and hot. In the south, winters are mild and the summers are very hot with virtually continuous sunshine, the daily average temperatures in July exceed 38 °C (Bagheri et al, 2013).

In the present paper, Tehran, Kerman, Bandar Abbas, and Tabriz have been selected for the mild, warm–dry, warm–humid, and cold regions respectively. According to the National Center of Climatology of Iran, the climatic characteristics of each of the selected cities are presented in Table 3.

Table 3 – Climatic characteristic of studied cities

City	Latitude	Longitude	Elevation
Tehran	35.68 ° N	51.30° E	1219 m
Kerman	30.29° N	57.06° E	1755 m
Bandarabbas	27.20° N	56.15° E	10 m
Tabriz	37.80° N	46.25° E	1365 m

Table 4 presents the average temperature of the warm and cold months of each studied city, also the maximum and minimum comfort temperature boundaries are presented.

Table 4 represents the maximum and minimum comfort temperature based on a research that was performed in Iran according to the adaptive theory described in EN 15251.

Table 4 – Thermal comfort boundaries (Max CT, Min CT) for studied cities and the average of warm and cold months temperatures (WMT, CMT) (Heidari, 2014)

City	WMT (°C)	CMT (°C)	Humidity (%)	Max CT (°C)	Min CT (°C)
Tehran	28.4	21.1	44	30.1	20.9
Bandar Abbas	29.3	22	66	31.3	18.3
Kerman	30.0	22.7	37.6	27.3	14.7
Tabriz	26.3	18.5	54	30.7	16.5

3. Result and Discussion

The following figures, present the sensitivity analysis of insulation thickness to total embodied and operating energy demand over a 30-year life span in each studied city. Fig. 2 presents the sensitivity analysis of insulation thickness in Tehran, and shows different rates of upward trends for different insulation materials. As these results are shown in this figure, extruded polystyrene, polyurethane, expanded polystyrene, wood fiber panels, and cork slab have a rising trend in results, and there is a direct relation between the thickness of insulation and total energy demand.

The reason for a direct relation between insulation thickness and total energy demand is the fact that infiltration is not taken into account in this study. Therefore, by increasing the thickness of insulation, the thermal resistance of walls, roof, and floor will be increased, naturally the conductive heat loss (which is the only way of natural cooling) and the rate of cooling will be decreased, as a result the cooling energy demand in warm months (dominant energy demand in Iran) will be increased.

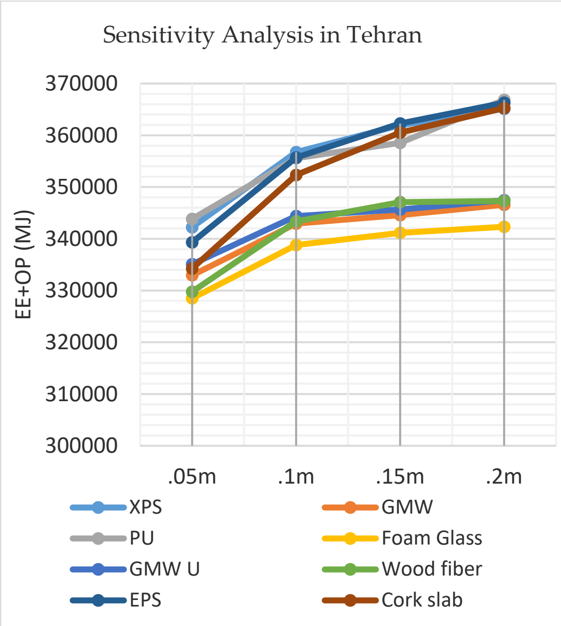

Fig. 2 – Sensitivity analysis of insulation thickness and total energy demand in Tehran

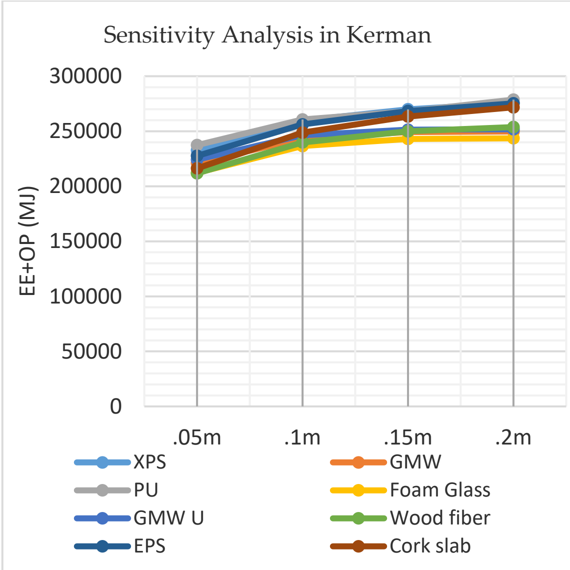

Fig. 4 – Sensitivity analysis of insulation thickness and total energy demand in Kerman

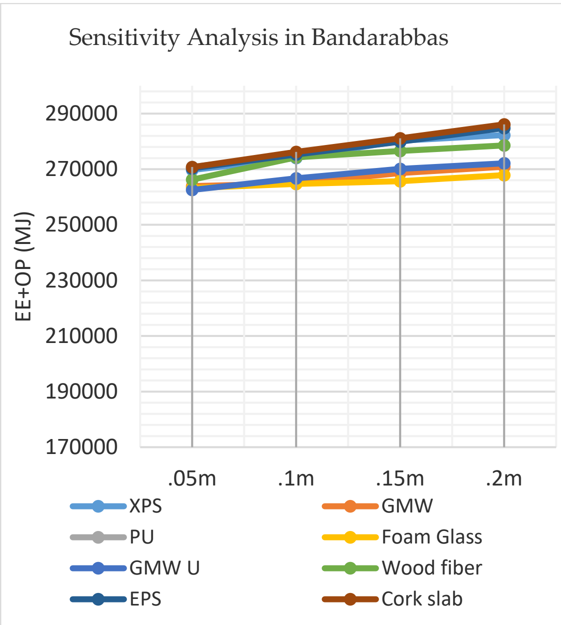

Fig. 3 – Sensitivity analysis of insulation thickness and total energy demand in Bandar Abbas

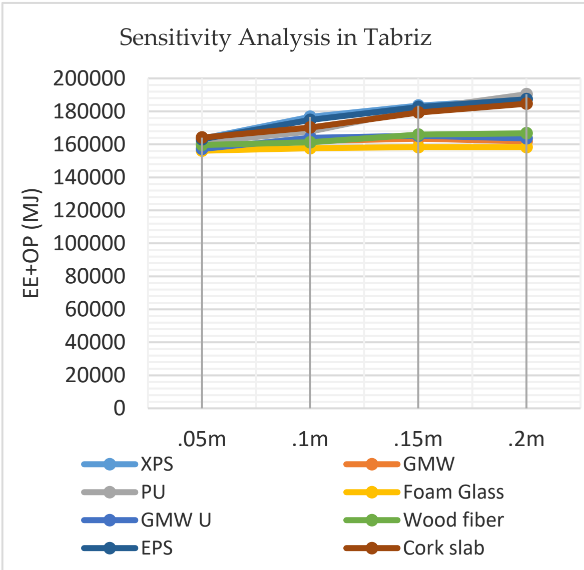

Fig. 5 – Sensitivity analysis of insulation thickness and total energy demand in Tabriz

Also unforced glass mineral wool, foam glass, and glass mineral wool represent different results, and show two different trends that indicate the importance of these simulation and sensitivity analyses to find the optimum thickness of the insulation materials.

Fig. 3 shows a weak relation between the thickness of insulation and the total embodied and operating energy demand in Bandar Abbas.

This can be attributed to an equivalence of increasing in embodied energy and decreasing in operating energy demand by increasing the thickness of insulation in Bandar Abbas.

Fig. 4 shows a direct relation in the total energy demand and thickness of insulation material for all studied insulation materials in Kerman, the increase in operating energy demand because of a decreasing natural cooling rate and increasing the embodied energy due to the increase of the volume of insulation materials are the reasons of this trend in the diagram

From Fig.s 5 and 3, we can understand that the sensitivity analysis results in Tabriz and Bandar Abbas are almost similar. The direct relation in the increase of insulation thickness and total energy demand for extruded polystyrene, polyurethane, expanded polystyrene, wood fiber panels, and cork slab are similar to the results of Tehran, but with a difference in the rate of the increase. Also a weak direct relation between energy demand and insulation thickness is found for unforced rolled glass mineral wool, glass mineral wool, and foam glass, this relative independence can also be attributed to the equivalence of an increase in embodied energy and decrease in operating energy demand by increasing the thickness of insulation.

By using Equation 2, the LCEE index has been assigned to each insulation scenario in different climatic conditions. The LCEE index indicates the life cycle energy efficiency in each insulating scenario. The higher index means the higher efficiency and vice versa.

Different trends and results have been observed in each city. In Tehran the highest Index is assigned to Foam glass and Wood fiber, and the lowest Index is assigned to PU, XPS and EPS. In Bandar Abbas there is not much difference between the insulation materials, but the lowest index is assigned to PU.

Fig. 6 – Life cycle energy efficiency index for different insulation scenarios in Tehran

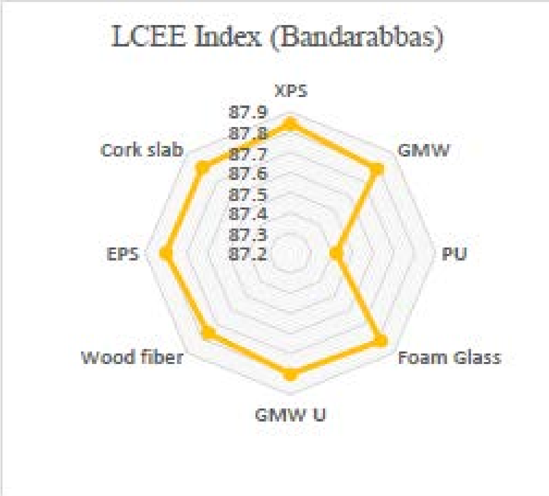

Fig. 7 – Life cycle energy efficiency index for different insulation scenarios in Bandar Abbas

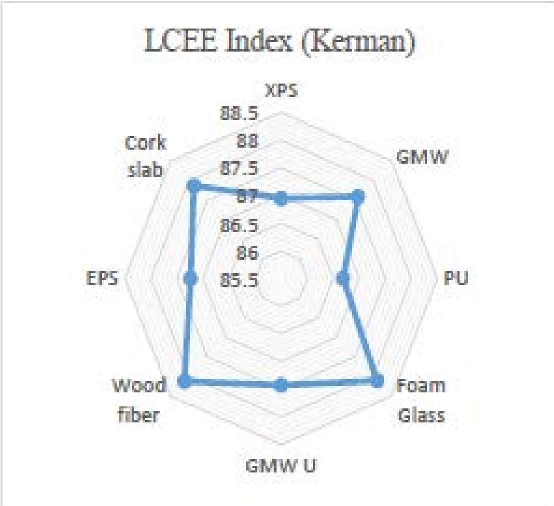

Fig. 8 – Life cycle energy efficiency index for different insulation scenarios in Kerman

Fig. 9 – Life cycle energy efficiency index for different insulation scenarios in Tabriz

Analysis in Kerman shows that the lowest index is assigned to PU and the highest index is assigned to foam glass and wood fiber. Also analysis in Tabriz shows similar results to Bandar Abbas.

By considering the results in Fig.s 2 to 9, we can conclude that insulating materials behave in different ways in each studied city. As these cities are located in different climatic conditions and the thermal comfort boundaries are not similar (according to a research based on adaptive theory). This fact (different behavior of insulation materials) can be attributed to differences in total operating energy demand for providing thermal comfort in each climate, and also to different humidity in each city that can affect the performance of the insulating materials.

4. Conclusion

The main aim of this study was to present a new method to comparative life cycle energy analysis for insulation scenarios under different climatic conditions. By this method the operational energy and embodied energy of each insulation scenario were considered in calculations. The analysis showed that both operational energy and embodied energy have a considerable impact on decision-making processes in order to select the best insulation type and thickness. Moreover, the new method to assign the LCEE index was used as a useful method to assign a concise comparative index in order for building designers to easily compare different options. The differences in analysis and results for each scenario can be attributed to the embodied energy of the insulation materials, the thermal performance of the insulation materials, and the differences in climatic conditions and energy demand.

In addition, this is recommended to consider the effect of different fuels used in energy systems in future studies. It is expected that the embodied energy of the energy systems has also considerable effects on the whole life cycle energy demand of a building.

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