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**Article**

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Energy Reports

**Provided in Cooperation with:**

Elsevier

*Suggested Citation:* Raouf, Ayman M.; Al-Ghamdi, Sami G. (2020) : Effect of R-values changes in the baseline codes: Embodied energy and environmental life cycle impacts of building envelopes, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 6, Iss. 1, pp. 554-560, <https://doi.org/10.1016/j.egyr.2019.09.025>

This Version is available at:

<https://hdl.handle.net/10419/243787>

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6th International Conference on Energy and Environment Research, ICEER 2019, 22–25 July,  
University of Aveiro, Portugal

# Effect of R-values changes in the baseline codes: Embodied energy and environmental life cycle impacts of building envelopes

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Received 24 July 2019; accepted 12 September 2019

Available online 24 September 2019

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## Abstract

The major environmental and economic burdens occurring from the high-energy consumption of buildings led to energy performance being a critical aspect for green building rating systems. Building energy codes play an important role for such performances through establishing the baseline requirements to meet the rating system needs. Building information modeling (BIM) was used to model a concrete masonry unit (CMU) block wall with various insulation thicknesses assigned various insulation layer thicknesses depending on the insulation material property. Multiple scenarios were created in compliance with several energy codes and its different versions. The scenarios modeled were then analyzed using Life Cycle Assessment (LCA) to calibrate environmental performance of different energy codes used as baseline codes for different green building rating systems. The results indicate the differences between the various green building rating systems according to respective energy baseline codes and their versions adopted. Tendencies towards more efficient with less environmentally harmful buildings were observed. Comparing the different codes with the direct impact on the green building rating systems shows that rapid development in energy codes surpassed the impact resulted from adopting the green building rating systems. The amount of reduction in environmental impact was significantly and tangible due to change in the energy code.

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Peer-review under responsibility of the scientific committee of the 6th International Conference on Energy and Environment Research, ICEER 2019.

*Keywords:* Green buildings; R-values; ASHRAE; Energy; Life cycle assessment; Building envelope; LEED

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## 1. Introduction

There is a growing impetus towards transitioning into a more sustainable building sector that is responsible for more than one-third of the global energy consumption that is used for heating and cooling, and a significant contributor to the global carbon dioxide (CO<sub>2</sub>) emissions [1,2]. The International Energy Agency (IEA) highlighted the importance of designing building envelopes to reduce energy loads for heating and cooling the building [1]. A governing criterion in the building envelope design is the R-value, a performance metric that is used to gauge the

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<https://doi.org/10.1016/j.egy.2019.09.025>

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ability of the thermal insulation to resist heat traveling through it. Building codes have geared towards increasing the R-values over the years to gain better energy efficiency performance. In saying this, there is a potential that the enhanced insulation configuration may have environmental implications, not to mention the greater economic costs associated. In addition, an increased insulation thickness for higher R-values may be perceived with an increase in embodied energy, which holistically may offset the operational energy savings purpose, thus becoming counterproductive.

### *1.1. Building rating systems and baseline codes*

Building rating systems evaluate the sustainability aspects of a building using categories such as energy consumption, water use, and materials to rate a building, with slight variations in the categories from one rating system to another. A building must meet the prerequisites of each category in a rating system to be certified. Parts of such prerequisites are meeting baseline requirements stipulated by building codes and further enhancement in the building performance would yield higher ratings. There are many green building rating systems in the world with each uniquely set and weigh categories that address its country's specific characteristics and needs [3]. An example is the United States' Leadership in Energy and Environmental Design (LEED) building rating system developed by the U.S. Green Building Council (USGBC). One of the six building assessment categories is Energy and Atmosphere (EA) that covers 30% of the total credits and stipulates a baseline requirement to meet the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 90.1–2010 requirements.

Commensurate to ASHRAE with slight deviations in setting energy baseline requirements is the International Energy Conservation Code (IECC). These codes have evolved with time and have impacted the minimum requirements for the building rating evaluations. Examples of ASHRAE are ASHRAE 90.1 is the “Energy Standard for Buildings Except Low-Rise Residential Buildings” which is the allocated benchmark for commercial building codes in the United States and stipulates the minimum energy efficiency requirements for the design and construction of the new buildings and their systems. Also, ASHRAE 189.1 (189.1) is the “Standard for the Design of High-Performance Green Buildings” which, in its sole 2009 version, sets the minimum requirement to construct and operate green buildings. Other adopting authorities opt for the IECC instead of ASHRAE 90.1. There are slight deviations with the inclusion of residential requirements included in the IECC. The IECC was established in 2000, and had newer versions released in 2003, 2006, 2009 2012 and 2015.

### *1.2. Life cycle assessment on buildings*

The life cycle assessment (LCA) concept emerged to answer issues on which life cycle phases shared the greater environmental burden. It is a standardized procedure to calculate the environmental burdens of a product from raw material acquisition, manufacturing, transportation through to end of life. It is an effective decision-making support tool on tackling which product to adopt or finding ways to minimize the environmental impacts. LEED v4 explicitly recommends adopting LCA techniques for a building as a whole and in one of the options for the health care sector in evaluating Environmental Product Declaration (EPD) forms [4]. There are also studies dedicated to LCA adopted into the LEED rating system [5] and [6].

### *1.3. Insulation materials for building envelopes*

Insulation materials constitute an integral component of the building envelope and reduce the energy demand in buildings [7,8] during both winter heating and summer cooling. [9] claims that 60% of the European market is dominated by inorganic fibrous materials such as stone wool (RW) and glass wool (GW) whereas oil derived organic foamy materials dominate 30% of the market. These include extruded polystyrene (XPS), expanded polystyrene (EPS) and Polyurethane (PUR). Such results corroborated well with the report issued by (10) on a global scale. [10] also highlighted the market size of Polyisocyanurate (PIR) in the US. Cellulose fiber insulation (CFI), although a less commonly used insulation, is increasing in popularity as a result of its thermal properties and the recycled paper fiber usage.

Information is provided on [Table 1](#) on the thermal conductivity and Specific heat range sourced from [11]. Rock Wool (RW) is made from basalt rock, blast furnace slag and other raw materials [12] which undergo melting in

**Table 1.** Insulation thicknesses adopted in complying with baseline code R-values.

Insulation type	Thermal conductivity $\lambda$	Specific heat range kJ/kg K	ASHRAE 90.1 2004 R-value sum: 2.01 W/m <sup>2</sup> K		ASHRAE 90.1 2007 & 2010 R-value sum: 2.64 W/m <sup>2</sup> K		ASHRAE 189.1 R-value sum: 3.52 W/m <sup>2</sup> K	
			Thickness t (mm)	R-value $t/\lambda$	Thickness t (mm)	R-value $t/\lambda$	Thickness t (mm)	R-value $t/\lambda$
CFI	0.042	1.3–1.6	22	0.52	50	1.19	85	2.02
EPS	0.035	1.25	18	0.439	40	0.95	70.5	1.68
RW	0.034	0.8–1.0	17.5	0.42	39	0.93	68.5	1.63
GW	0.019	0.9–1.0	10	0.24	31	0.74	38.4	0.91
PUR	0.02	1.3–1.45	14.3	0.34	33	0.79	59.5	1.42
XPS	0.019	1.45–1.7	13.8	0.33	31	0.74	54.5	1.3
PIR	0.02	1.4–1.5	10.2	0.24	23	0.55	40.4	0.96

a furnace at high temperatures of 1300–1500 °C [11,12]. Glass Wool (GW) has a similar furnace manufacturing process as RW only that the raw materials are silica sand, recycled glass, limestone and soda ash. Expanded 0.8–1.0 Polystyrene (EPS) is made from small solid sphere beads of polystyrene are expanded by heating with water vapor and addition of pentane C<sub>6</sub>H<sub>12</sub> expansion agent [12]. Extruded Polystyrene (XPS) involves a polystyrene mass undergoing an extrusion process (the production of objects with a fixed cross-sectional profile). Polyurethane (PUR) are carboxylic acid derivatives of repeating urethane groups. Polyisocyanurate (PIR) produced by the reaction of a polyester-derived liquid polyol with methylene diphenyl di-isocyanate (MDI) in the presence of a blowing agent and other additives. Finally, Cellulose Fiber Insulation (CFI) exhibits consistency similar to that of cotton wool [13], and is made up of shredded recycled paper and wood fiber [14].

#### 1.4. Motivation and purpose

Increasing the R-value to attain an enhanced insulation would minimize the energy loads needed for heating and cooling but the economic extent is unknown. The economic outlook will be assessed based on the energy efficiency attained in the building overall by considering the embodied and operational energy savings. It is worth examining whether the environmental implications resulting from the improved R-value requirements does not compromise the overall benefits reaped from the enhanced insulation. Green buildings face criticism in conflicting objectives in energy reduction and environmental conservation so it is worthwhile to investigate building envelopes more carefully in a parallel manner [15,16].

## 2. Methods and procedures

This paper evaluates the environmental impacts of a building insulation materials in fulfilling the requirements of various energy codes. In doing so, a concrete masonry unit (CMU) block was duplicated and assigned various insulation layer thicknesses depending on the insulation material property. The study deals with assessing embodied environmental impacts of various insulation materials when attaining three benchmark R values of 2.02, 2.64 and 3.52 W/m<sup>2</sup> K for an above grade wall. The functional unit is defined as a 100 m<sup>2</sup> usable floor space. The datasets for inflow and outflow of materials was from Gabi6 and Ecoinvent databases. The program used, Tally, provides characterization factors of Tools for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) characterization scheme.

### 2.1. Isolated prototype wall studies

A 40 m × 6 m wall was modeled using Autodesk® Revit® BIM software using the built-in Brick on CMU. A total of 7 wall duplicates were created with each containing an insulation layer type. The reference R-value to attain in each scenario is 2.29 W/m<sup>2</sup> K. Insulation layer thicknesses were modified for each scenario to obtain the benchmark R-value, while the thicknesses for the Brick (70 mm), Air (30 mm), Damp-proofing (negligible), CMU (190 mm), Metal Furring (42 mm) and Gypsum Wall Board (16 mm) were kept constant. Revit automatically calculates the

R-value as a sum of the contribution of all the layers. Further material properties of each layer that impact the R-value other than thickness are Thermal Conductivity  $\lambda$  (W/m K), Specific Heat  $c$  (J/g °C) and  $\rho$  (kg/m<sup>3</sup>). The air void is also treated as an insulation layer material with thermal conductivity of 0.025 W/m K. Once the models were carried out, Revit's add-in software called Tally<sup>®</sup> was used to conduct the environmental assessment. Tally is a convenient tool as it is made for green building rating systems evaluation. As a Revit application add-in, it can be easily implemented on the Revit model to conduct LCA on the building materials to find out the embodied environmental impact. All the processes within the cradle-to-grave (C2G) lifecycle (i.e. raw material, manufacturing, operation and disposal) are as per the EN 15804 standard. The climate condition is based on Qatar's local climate in the period of January at 18.5 °C with relative humidity of 58.5%.

### 3. Results and discussions

#### 3.1. Insulation wall thicknesses for benchmark R-values

Table 1 shows the insulation thicknesses for the various insulation materials in each ASHRAE code scenario. All the scenarios share the same hierarchy in the insulation material thicknesses. Such differences are visually displayed in Fig. 1 along with the R-value contribution to the total sum R-value prescribed by the baseline standard.

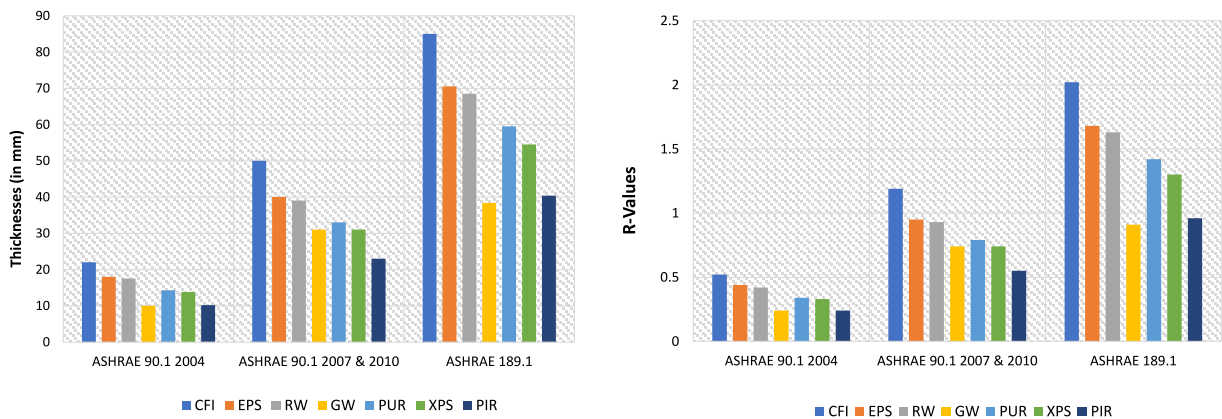


Fig. 1. The insulation thicknesses and R-values adopted in complying with different codes.

The thickness percentage increases for the various insulation layers between ASHRAE 189.1–2009 and ASHRAE 90.1–2004 in meeting the respective 2.02 and 3.52 W/m<sup>2</sup> K R-values. PUR experienced the greatest relative increase in thickness (316%), followed by PIR (296%), XPS (295%), EPS (292%), RW (291%), CFI (286%) and GW (284%). If a decision was to be made based solely on thickness, GW becomes most effective in meeting the enhanced R-value requirements at an optimized thickness increase.

#### 3.2. Environmental impact assessment results

The results of ASHRAE 90.1 2007/2010 are displayed in Fig. 2 to highlight the environmental impact assessment performance of the various insulation materials. The ranks of the material performances of the baseline code is identical to the other codes. RW demonstrated to have the highest Acidification Potential (AP) (42.43 kgSO<sub>2</sub> eq.), Global Warming Potential (GWP) (6221 kgCO<sub>2</sub> eq.) and Oxidation Potential (OP) ( $1.58 \times 10^{-4}$  CFC-11 eq.) but a much lower EP (0.9967 kgN eq.) compared to the other insulation materials. RW also exhibited the third SF rank (207 O<sub>3</sub> eq.) from the highest exhibited by the CFI counterpart (316.5 O<sub>3</sub> eq.) CFI, however, stood second in GWP (5902 kgCO<sub>2</sub> eq.), AP (32.02 kgSO<sub>2</sub> eq.) and third at EP (14.94 kgN eq.). This emphasizes that contrary to the perception that CFI is an eco-friendly insulation, it demonstrated relatively heavy environmental effects. However, CFI being biodegradable undergoes biochemical processes in decomposition compared to the rest of the insulation materials which remain inert in a landfill site. GW scored the lowest environmental impact effects compared to the rest of the insulation materials with exception to ODP ( $5.023 \times 10^{-5}$  CFC-11 eq.). Fig. 2 shows a trend of

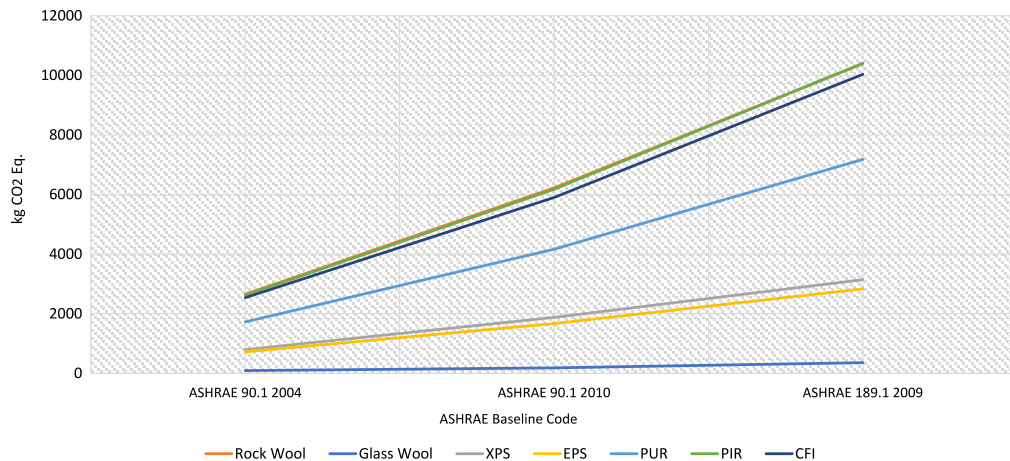


Fig. 2. Various LCA variable impacts and insulation materials.

GWP impact across the baseline codes in which the change of impacts was at varying extents with RW, PIR and PUR had a 5-fold increase in GWP and XPS, EPS and MW was a 3-fold increase. [9]’s results corroborated with this in that RW had appreciably greater environmental impacts with 30% in almost all impact categories and the least impactful being GW which contributed 4%–14% of the global impact. Subsequent to GW were EPS, PU and EPS although PIR and CFI were not considered in their study. [15] pertained results that deviated from this study’s results in that CFI needed the lowest thickness whereas GW required the highest thickness for roof insulation. In all other insulations, EPS had the lowest thicknesses. The following study’s results demonstrated otherwise in that CFI demanded the highest thickness and GW the lowest according to Revit’s built-in thermal conductivities of GW and CFI being 0.019 and 0.042 W/m<sup>2</sup>. Such thermal conductivities were in the range dictated from literature [12,13]. However, [15] are reflecting what is stipulated in the Swedish Passivhouse and BBR building codes. There was no indication of the thermal conductivity to CFI.

### 3.3. Embodied energy evaluation

Under ASHRAE 90.1 2007/2010, GW scored the lowest in primary energy demand consumption of 3591 MJ, which was 19-fold less than the highest embodied energy of PIR of 137,260 MJ. CFI had the greatest renewable embodied energy proportion (40% of the 108,765 MJ total embodied energy) compared to the rest of the insulation materials. Fig. 3 displays the results breakdown by renewable and non-renewable embodied energy for various insulation materials.

A study by [17] demonstrated different results from the current study in that EPS (158.8 MJ/kg) had an approximately five fold higher PED than RW (22.1 MJ/kg). The study results suggest otherwise in that RW (6134 MJ) had a greater total embodied energy compared to EPS (4095 MJ). [18] conducted a study in integrating the energy and environmental analysis for various building envelope scenarios to enable the design phase to have more environmentally informed decisions when allocating a certain configuration. It is worthwhile to integrate energy and environmental analysis for more informed decisions, and thus a Spearman’s Rank test was conducted for investigating such associations in Table 2.

Table 2. Spearman’s rank association test: Embodied energy and other environmental impacts.

Association type	Association description
<b>EE and GWP</b>	<b>Positive association (<math>\rho = 0.678</math>)</b>
EE and EP	Strong positive association ( $\rho = 0.857$ )
<b>EE and AP</b>	<b>Positive association (<math>\rho = 0.571</math>)</b>
EE and ODP	Negative association ( $\rho = 0.535$ )
<b>EE and SF</b>	<b>Strong positive association (<math>\rho = 0.71</math>)</b>

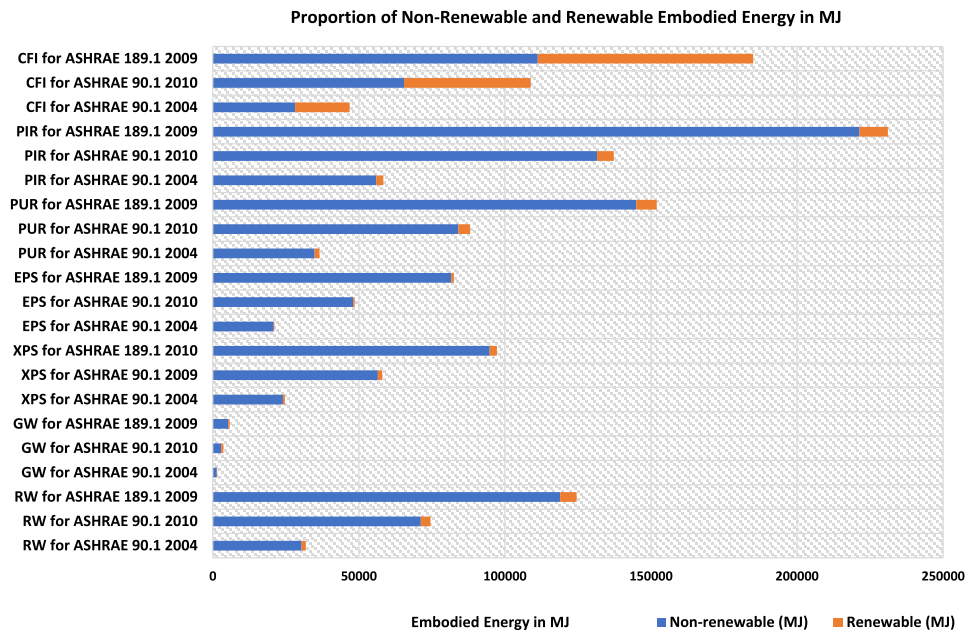


Fig. 3. Renewable and non-renewable embodied energy analysis in MJ.

#### 4. Conclusion

The research has investigated the environmental impacts and embodied energy associated with the different insulation materials in meeting the LEED rating system baseline codes ASHRAE 90.1–2004, 90.1–2007 and 2010 and 189.1–2009. The insulation materials assessed were cellulose, mineral and polymer-based to capture differences in the environmental impacts and associated embodied energy. GW exhibited the minimum insulation thickness required for the R-value benchmarks and had the minimum overall environmental impact. However, the majority of its embodied energy comes from non-renewable sources. The study highlights the importance of integrating environmental impacts and energy analysis together to help decision-makers make more informed decisions on the choice of material type and policymakers on more details than just R-value stipulations for a more environmentally consolidated decision with the energy consumption.

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