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Research Article

Heat Transfer, Environmental Benefits, and Social Cost Analysis of Different Insulation Methods by Considering Insulation Disadvantages

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ABSTRACT

In this paper, the thermal performance of four common insulators in two internal and external insulation systems is investigated for the ASHRAE setpoint range by applying detailed numerical simulation and Anti-Insulation phenomenon. Anti-Insulation phenomenon and consequent extra load on the HVAC system can occur following the thermal insulation of a building if proper temperature setpoint is not selected. In the next step, the proper setpoint is analyzed under simulated building conditions, and all related criteria are studied for this temperature. Also, continuous and intermittent operations of the air conditioning system are investigated. Moreover, the assessment of the environmental benefit of wall insulation is performed by evaluating greenhouse gasses emission payback period and social cost saving. A residential building is simulated in the EnergyPlus software for the case study. Results show that Anti-Insulation occurs approximately at 22 ºC. Both external and internal insulations lead to a significant reduction in energy consumption. Nevertheless, the external insulation shows a bit more reduction. Intermittent operation outperforms the continuous operation by 8 % on average. The insulator's production phase is considered in the analysis of the insulation environmental benefits. Results show that, in this case, the prioritization of insulators would be different from that case in which this process is not considered. According to results, in terms of social costs, applying thermal insulation to residential buildings is necessary.

1. INTRODUCTION

The demand for energy is increasing due to the population growth and the improvement of thermal comfort along with the enhancement of life standards in Iran. According to statistics, about 40 % of the country's generated energy is used by domestic, commercial, and public building sectors [1, 2], and 70 % of this amount is allocated to the heating and cooling process [3]. In other words, approximately 28 % of the total energy is consumed by air-conditioning equipment. Because 60-80 % of heating and cooling loads relate to the heat transition through the building's envelops [4], it is necessary to improve the thermal characteristics of outer walls by thermal insulation for saveing energy.

Thermal insulation protects the indoor environment from outside temperature fluctuations to provide a high comfort level and reduce energy consumption when it is accompanied by a proper setpoint. Besides, an accurate insulation location could regulate the temperature changes using thermal inertia. Moreover, as a result of energy saving by wall insulation, there would be a remarkable reduction in greenhouse gas emissions, which adversely affect the environment.

In addition to this purpose, many studies have been performed to assess the effectiveness of thermal insulation and their suitable location in the wall by evaluating energy-saving, optimum thickness, emission reduction, and pay-back period of insulation investment as benchmarks. Tabel 1 involves the abstract concepts of these studies and their most important results. Some of these studies tend to evaluate the impact of HVAC system operation on the thermal performance of the building's envelope [5-9]. These studies consider two operations, continuous and intermittent, for the HVAC system and seek a proper insulation location on the wall under each operation. For this purpose, the wall's thermal mass should be considered; therefore, the simulation done by all of these studies has been dynamic. Overall, results show that, under intermittent operation, internal insulation outperforms external insulation [6-9]. However, under continuous operation, the external insulation indicates better performance. However, in some cases, the external insulation performs better than the internal insulation under intermittent operation [5]. The important result of these studies is that different intermittent operation schedules result in different energy-saving and wall configurations; therefore, the exact HVAC operation should be applied to the simulations. Other studies have investigated insulation location without taking HVAC operation type into account [10-14]. These studies have compared performances of different insulation methods (external, internal, or mid insulation) under solely continuous or intermittent operation.

Other types of studies investigate building insulation regarding economical aspects [11, 12, 15-21]. Some of these studies evaluate optimal thickness of different insulators by considering different criteria such as climatic condition [20], wall orientation [19], wall and insulation material [21], glazing area percentage [17, 20], fuel type [20, 21], and life cycle [15]. Other studies that regard economical issues determine the insulation investment payback period by considering different insulator types and insulation methods [12, 16, 22]. It should be emphasized that, in this type of

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studies, economical indexes such as inflation rate, building lifespan, etc. are considered too.

Environmental issues represent another kind of researches that falls into the scope of building insulation studies. These studies evaluate greenhouse gas emission reduction due to the building insulation [16, 18-20, 22]. In this type of studies, mostly, building fuel type and insulation material are considered as criteria. Another school of studies tends to investigate different insulator's material and climatic conditions solely or compare insulation with other thermal enhancement techniques such as shading, natural ventilation, etc. [23-30]. All of them remark thermal insulation as the most important approach for energy-saving. The key information of the above-mentioned references is categorized in Table 1 for more clarification.

In all of the aforementioned studies, building insulation is introduced as a guaranteed method for energy saving, and none of these studies investigates the disadvantages of insulation. In these studies, a condition that the building insulation imposes extra load on the HVAC system (rather than saves the energy) is not taken into account, except in [16] and [25], which are merely noted in a few sentences. In this paper, to highlight those cases where building insulation could increase energy consumption, the thermal performance of a building is simulated by EnergyPlus software. Then, the reasons that cause this increment are investigated and, after resolving this problem, the thermal analysis of building insulation is conducted. In the second part of the paper, the environmental benefits of building insulation are evaluated by determining the greenhouse gas emissions conservation. The aforementioned references exclude the insulator's production phase in environmental analysis. In this paper, by regarding released emission in the insulator's production and transportation phase, greenhouse gas emission payback period is determined.

2. METHODOLOGY

In this work, 4 common insulators in Iran including Polystyrene, Polyurethane, Glass wool, and Rock wool are applied to the internal and external insulation of a residential building's walls. Figure 1 shows the study plan and its steps. As Figure 1 indicates, the first step relates to the thermal analysis in both of the cooling and heating parts for the ASHRAE setpoint. However, because we face disadvantages of thermal insulation (imposing extra cooling load to the HVAC system) in the cooling part, the second step is dedicated to assess the insulation reverse function in this part and resolve it by investigating the proper cooling setpoint. In the next step, thermal analysis is conducted for a new setpoint, and the building's cooling and heating is evaluated by determining energy saving, wall's heat flux, etc. Finally, insulation environmental issues are investigated by calculating greenhouse gas emissions regarding the production and transportation phase. In addition, social cost saving due to greenhouse gas conservation is evaluated to express insulation environmental benefits economically.

Table 1. References abstract & main results.

Ref. number	**Static/Dynamic**	**Experimental**	**Insulator type**	**Insulation location in the wall**	**HVAC system type**	**Energy-saving**	**Optimum thickness**	**GHG***	**Payback period**	**LCA**	**Results**
5	D	No	XPS	External/Internal /Mid	Continuous/ Intermittent	*					Under intermittent operation, it is a better insulation layer placed in exterior side. For selecting the wall's layers' configuration, the real HVAC system operation must be considered.
6	D	Yes	Foamed concrete	External/Internal /Mid	Continuous/ Intermittent	*					Under intermittent operation, the inner surface of wall has the most impact on the thermal response of the wall. Internal insulation has the lowest heat flow among all other wall configurations.
7	D	No	XPS	External/Internal	Continuous/ Semi-continues	*					In climates in which the cooling system operates during part of a day, internal insulation performs better than external insulation. However, in climates with free cooling periods, external insulation outperforms the internal system.
8	D	No	EPS/Light weight self-insulation brick/Heavy weight self-insulation brick	External/Internal /Mid/self-insulation wall	Continuous/ Intermittent	*					Internal insulation outperforms external insulation under intermittent operation. Intermittent operation is more appropriate for occupant than continuous operation.
9	D	Yes	Foamed concrete	External/Internal /Mid	Continuous/ Intermittent	*					Under continuous operation, external insulation performs better than internal insulation. However, under intermittent operation, internal insulation outperforms the external insulation.
10	D	No	Insulation foam	6 Different location in the	Continuous	*					The optimum thermal performance is achievable in the condition that insulator

				wall							is located on the outer side of the wall and massive materials are exposed to the interior space.
11	D	No	EPS	External/Internal	Continuous/ Semi-continues	*			*		External insulation saves more energy (8 %) than internal insulation. Investment cost for internal insulation is about 50 % less than external insulation.
12	D	No	XPS	External/Internal	Intermittent	*					Internal insulation outperforms the external insulation by 18 %.
13	D	No	EPS	Filled into the hollow brick (External/ Internal)	Intermittent	*					The optimal location of filling insulation materials in brick's hollows depends on filling ratio.
14	S	No	XPS	External/Internal	Intermittent	*					External insulation has better performance than internal insulation.
15	D	No	Mineralwool/Rockwool/Corck/ Fiberglass/ Polystyrene/ Polyurethane	External	Semi-continuous	*	*			*	The best insulator for energy saving is Mineralwool, the optimum thickness of which varies by different life cycle assumptions.
16	S	No	EPS	Mid	-	*	*	*			By optimum thickness utilization, energy consumption reduces up to 46.6 % and Co_2 and So_2 emission decreases 41.53 %.
17	D	No	Insulators with $R=0.88\ m^{2\,\circ}k/W$	-	Semi-continuous	*		*	*		The envelop insulation, airtightness, and the windows replacement result in 45 % energy saving and 70 tons Co_2 reduction annually. The upgrading investment return year is 7.7 years.
18	S	No	XPS/Rockwool	-	-	*	*	*	*		Insulation optimum thickness and payback period vary according to glazing area percentage, climate, and fuel type. Greenhouse gas emission could be reduced up to 54 % by the utilization of optimum thickness.
19	D	Yes	EPS	External	Continuous	*	*				70 % energy saving could be obtained by good insulation associated with thermal inertia. Optimum thickness for cooling energy varies between 1cm and 7 cm.
20	D	No	XPS/EPS	External	Continuous	*	*	*			The least heating energy consumption is related to brick wall with XPS insulation. Optimum thickness changes according to wall's orientation. 85 % saving in greenhouse gas emission is achievable by 9 cm insulation.
21	S	No	Fumed silica/Glass fiber/EPS	-	-	*		*	*		10.2 %, 41.3 %, and 26.7 % reductions in annual heating and carbon dioxide emission are achievable in three different buildings by implementing vacuum insulators in buildings. Fumed Silica has the shortest payback period among the evaluated insulation.
22	S	No	Foam polyvinylchloride /Polyurethane/ EPS/Rockwool glasswool/5 wall structure	-	-	*	*		*		Optimum thickness, investment return year, and energy cost-saving vary between 0.2 cm- 14 cm, 0.66 year- 11.6 year and 3$ -155$, respectively. These parameters depend on wall and insulation material and fuel typ.
23	D	No	EPS	External	Intermittent	*					Necessary measure (among external insulation, shading technology, and natural ventilation) that contributes to energy saving in all climates is external insulation.
24	D	No	Composite insulated block (mid-plane EPS)	Mid	-	*					Wall insulation with 16 cm EPS makes 30 % energy saving and thermal bridge insulation with 5cm EPS makes 23 % energy saving.

25	-	Review		-	-						One of the most important techniques to improve the performance of the NZEB buildings is envelope insulation by considering climatic condition, heat sources, and the comfort temperature.
26	D	No	-	-	-	*					This paper introduces ROBESim software, a retrofit-oriented building energy simulator, which uses Energy Plus engine. Part of the simulation is allocated to evaluating insulation efficiency on energy reduction. Results show that 7.5-15 cm insulation of wall could lead to 4-10 % energy savings.
27	D	No	Insulation with k=0.03 W/m^2 $^\circ$k	Internal	-	*					34-56 % energy saving is achievable by using just a 2.5 cm insulation under Tehran's climate condition.
28	-	Yes	Polyurethane/ Polystyrene/ Mineral wool	Mid	-	*					More than 65 % cooling energy saving is achievable by insulation. It equals 37 % about heating energy.
29	-	Yes	XPS	External	-	*					Insulation makes 23.5 % energy saving in the summer.
30	S	No	Nano vacuum panel/Polystyrene	Mid	-	*					Utilization of nano-vacuum insulators associated with Nano gel glazing outperforms polystyrene insulation-associated double glazing by 18 %.

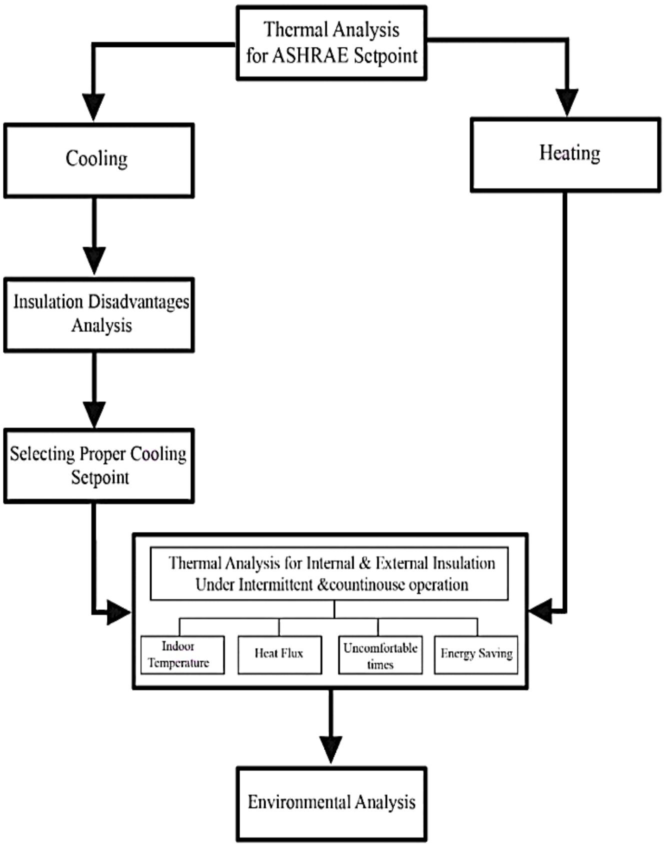


Figure 1. Flowchart of simulation steps.

2.1. Physical model description

Figure 2 shows the simulated building that is a unit in the mid-floor of the 7-story block and located in the metropolitan and industrial city of Tabriz with 38.05°N and 46.17°E coordinates. Each unit consists of one bedroom, one living room, a kitchen, and a bathroom. The bedroom and bathroom are assumed as an individual zone, but the living room and kitchen are considered as a unit zone. Except bathroom, other zones are equipped with the HVAC system.

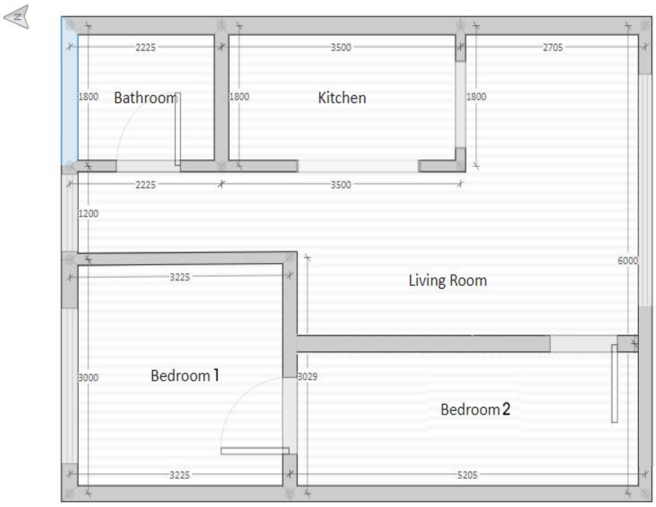
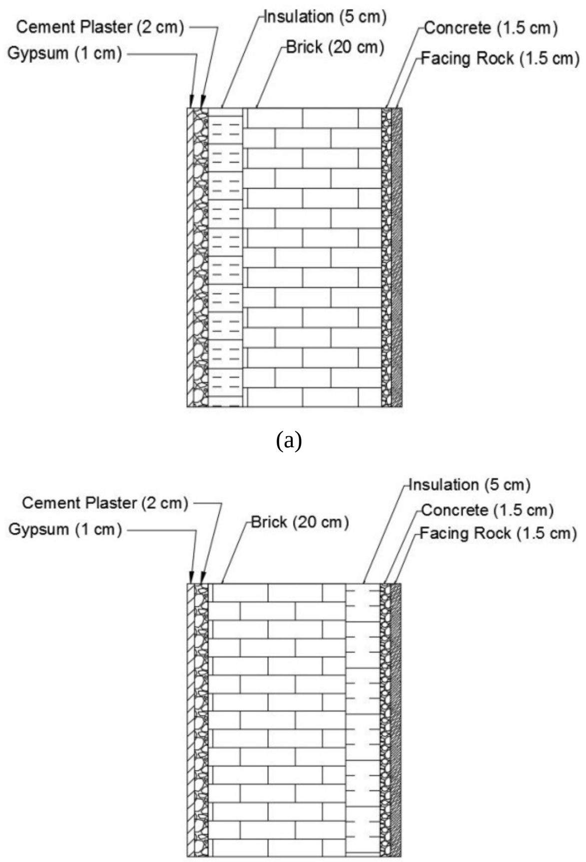


Figure 2. Floor plan of case study.

The composition and properties of the materials used in the walls are presented in Table 2 [31]. Moreover, the internal and external insulation configurations are shown in Figure 3.

Table 2. Wall materials' characteristics.

Material	**Density (kg/m^3)**	**Conduction heat transfer Coe. (W/K.m)**	**Heat capacity Coe. (J/kg.K)**
Facing rock	2590	2.9	860
Concrete	1300	1.75	750
Brick	1900	1.34	900
Cement plaster	1860	0.72	800
Gypsum plaster	1200	0.5	1090
Glass wool	80	0.038	670
Rock wool	70	0.042	840
Polystyrene	40	0.038	1210
Polyurethane	33	0.035	1400



(a)

(b)

Figure 3. Wall's layer's configurations: a) internal insulation and b) external insulation.

2.2. Simulation parameters

Annual heating and cooling loads of the building are simulated by EnergyPlus software. An Ideal Load System is established to investigate the building performance. Simulation time-step equals one minute. HVAC system operation schedule is presented in Table 3 for continuous and intermittent cases. Four inhabitants (parents and two children) with average sensible and latent cooling load are assumed. Furthermore, all internal thermal sources such as the lighting of spaces and electrical equipment are included in the calculations. Table 4 shows internal gain of occupancy presence, lighting, and equipment operation [32]. Natural gas and electricity grid are used for heating and cooling demand, respectively. The averaged typical meteorological year (TMY) [33] data was used for simulating the weather conditions with a 1-minute time step that makes the calculations precise.

2.3. Environmental parameters

Building insulation causes energy conservation and consequent greenhouse gas emission reduction. For calculating the saving of these emissions, it is assumed that the heating energy is supplied by natural gas in the site and cooling energy is supplied by electricity through electric power distribution. To evaluate the pollution caused by the building's cooling, the energy consumption of electricity is converted to the base energy by a conversion factor of 0.33 (the average conversion factor for natural gas-fueled power plants in Iran) [34]. These gas emissions are calculated for both insulated and non-insulated buildings and, by this approach, the saving amount is determined.

Although wall insulation diminishes environmental costs, insulation producing processes and transportation to the building location release emission to the environment. Therefore, for evaluating the actual effect of insulation on the environment, the amount of released greenhouse gas emission during the producing process and transportation is determined. In the production phase, different steps including raw materials transportation, fabrication, and packing are considered, as shown in Figure 4. Emissions of production and transportation phases are extracted by Simapro software. It is assumed that the insulation factors are placed in the Tehran (distance= 630 km), and insulators are transported to the Tabriz by road transportation.

Greenhouse gases have many social and environmental costs for people, government, and business. This emission causes climate change and, consequently, inflicts damages including changes in agricultural production, human health, property damages, and change in energy system cost (such as cooling energy cost increment). The imposed cost of these changes is called emission social cost. Although the current social cost does not include all physical, ecological, and economic damages, it could express how much emissions may impose the economical cost.

Table 3. HVAC operation schedule.

HVAC Operation cases	**Operation mode**	**Time**	**Working status**		
			Living room	Bedroom 1	Bedroom 2
Case 1	Continuous	Whole days	On	On	On
Case 2	Intermittent	00:00 – 06:30	Off	On	On
		06:30 – 08:00	On	Off	Off
		08:00 – 14:00	Off	Off	Off
		14:00 – 15:00	Off	On	Off
		15:00 – 17:00	On	Off	Off
		17:00 -19:00	Off	On	On
		19:00 – 22:00	On	Off	Off
		22:00 – 24:00	Off	On	On

Table 4. Internal gains schedule.

Time	**Living room**			**Bedroom 1**			**Bedroom 2**		
	Occupancy (W)	**Equipment (W/m^2)**	**Lighting (W/m^2)**	**Occupancy (W)**	**Equipment (W/m^2)**	**Lighting (W/m^2)**	**Occupancy (W)**	**Equipment (W/m^2)**	**Lighting (W/m^2)**
00.00-6:30	0	249.1	0	72	0	0.25	72	0	0.25
6:30-8:00	108	249.1	2.5	0	0	0.625	0	0	0.625
8:00-14:00	0	249.1	0	0	0	0	0	0	0
14:00-15:00	0	249.1	0	108	50	1.25	108	0	0
15:00-16:00	128.5	249.1	2.5	0	0	0	0	0	0
16:00-17:00	126	530	2.5	0	0	0	0	0	0
17:00-19:00	0	249.1	0	108	50	1.25	108	50	1.25
19:00-20:00	142	530	2.5	0	0	0	0	0	0
20:00-22:00	108	530	2.5	0	0	0	0	0	0
22:00-24:00	0	249.1	0	72	0	0	72	0	0

As mentioned before, the heating and cooling of residential buildings constitute a significant portion of the country's energy consumption and subsequently great amount of social cost. Therefore, social cost conservation owing to building insulation is determined in this study. The social cost of different greenhouse gases is reported in Table 5. These amounts are extracted from Balance IE. Deputy for Electricity and Energy, Ministry of Energy [3].

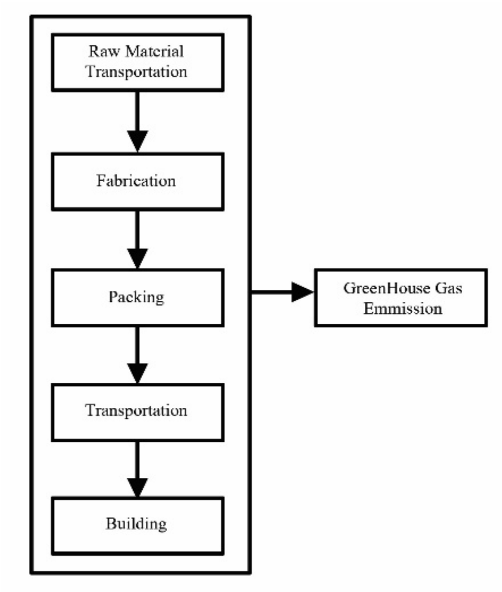


Figure 4. Insulation producing phase’s steps.

Table 5. Different emission social costs.

Emission social cost in Iran (¢/kg)				
CO_2	CO	NO_x	SO_2	PM
0.238	4.3	14.5	43.2	102.5

3. RESULTS AND DISCUSSION

Building insulation simulation results are shown in this section. At first, simulation results for the ASHRAE setpoint range are mentioned. Then, the reverse function of insulation in cooling part for this range is discussed, and a proper setpoint is determined. After that, desired factors are studied at an optimum setpoint temperature. First, indoor temperature and heat flux distribution factors are discussed. Then, deliberation about energy consumption, saving percentage, etc. are considered. Finally, environmental discussion and social expenses are represented.

3.1. Simulation results for ASHRAE range

The weather condition has a profound impact on energy consumption and saving potential. Figure 5 shows the annual temperature and solar radiation distribution for Tabriz. The range of temperature varies from -10 °C to 30 °C, and the daily (24 hours) average solar radiation ranges from 50 to 166 W/m^2. Although the maximum direct solar radiation occurs in June, the maximum dry bulb temperature is recorded in mid of July. Based on these data, Iran Metrological Organization categorizes Tabriz city as a cold climate region in its official climate classification [35]. Therefore, more heating demand is needed for 205 days, from 1 October to 20 May, whereas the cooling system operates in the remaining days.

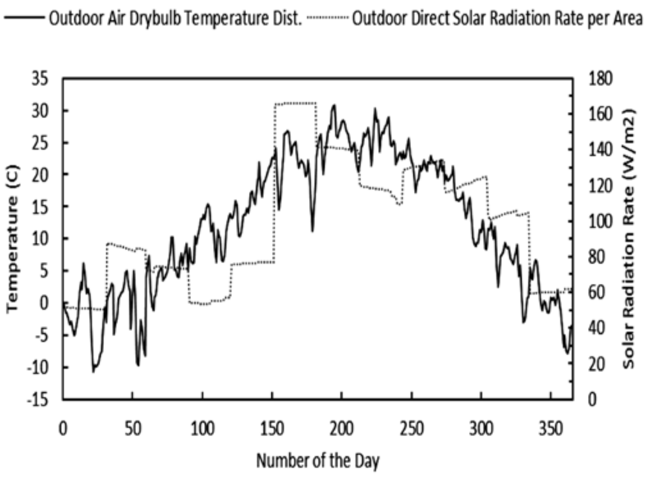


Figure 5. Outdoor air dry-bulb temperature distribution and daily average direct solar radiation rate for Tabriz.

Figure 6 shows the psychometric diagram and the temperature and moisture range for the resident’s comfort for the ASHRAE organization [35]. According to this index, in this section, the temperatures of 20 °C and 24 °C are selected as comfort setpoints for cold and warm days, respectively. The operation schedule for the intermittent HVAC system is indicated in Table 3.

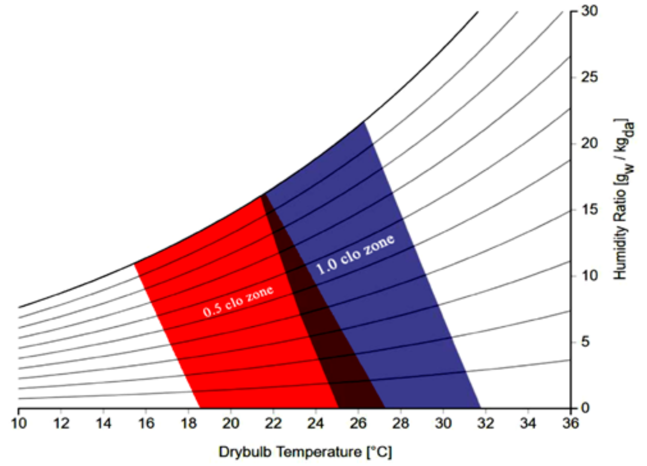


Figure 6. AHRAE comfort condition range.

Indoor temperature distribution for Polyurethane in both inside and outside insulations is shown in Figure 7 due to survey the comfort condition in the intermittent mode. As a result of off times, the temperature fluctuates out of the selected setpoint range. Under continuous operation, indoor temperature fluctuation would be 20 ^{o}C and 24 ^{o}C.

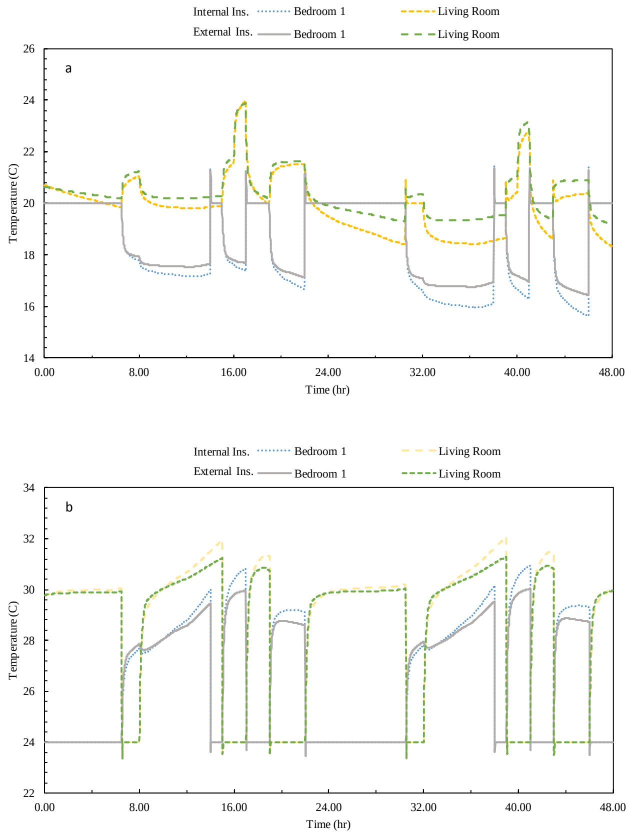


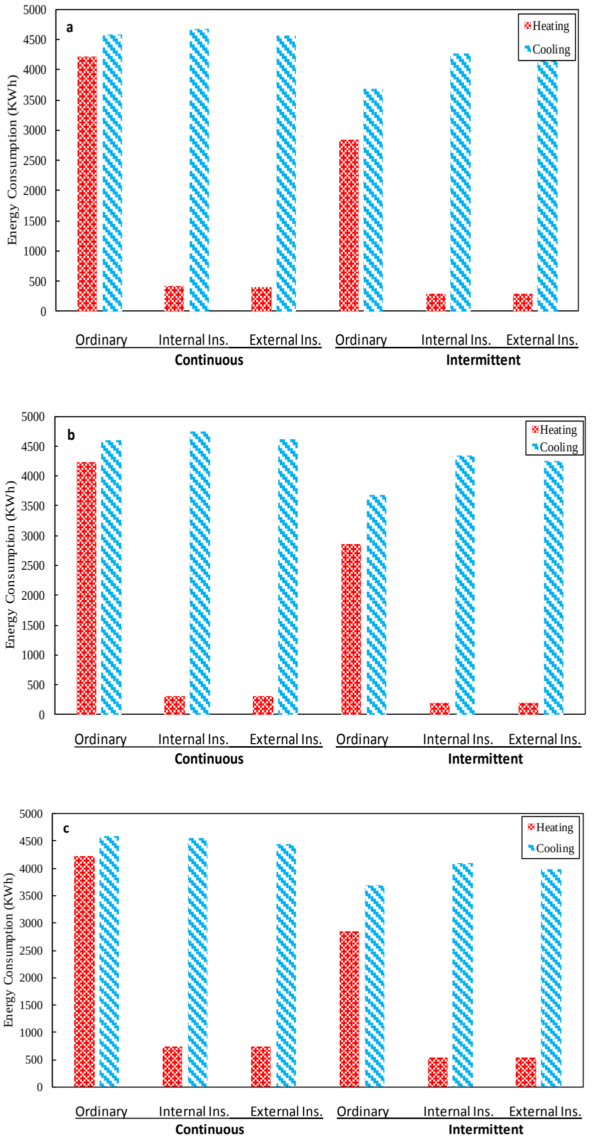
Figure 7. Indoor air temperature distribution for polyurethane insulation under intermittent HVAC operation mode for ASHRAE range, a) 21 and 22 January, b) 21 and 22 August.

Annual heating and cooling energy consumption rates are illustrated in Figure 8 for different insulation configurations and non-insulated building under intermittent and continuous modes. Envelope insulation reduces heating energy consumption that equals 81-92 % for different configurations on average. External insulation has better performance than the internal one in the heating sector. However, as Figure 8 shows, building insulation increases the cooling load. Different insulations impose -2 % to -16.38 % extra load on average on the HVAC system. The reason for this reverse function of insulation is investigated in the next section.

3.2. Insulation reverse function and optimum setpoint

If the building is assumed as a control volume, there are two internal and external sources for heating and cooling load. External sources include envelope heat transition, air infiltration, and solar radiation from transparent surfaces. Internal sources contain occupancy, lighting and equipment heat gain, warm water pipe, etc. Wall insulation reduces heat flux in the wall. If internal gain increases significantly, insulation creates thermal accumulation inside the building. This phenomenon has both positive and negative effects on energy conservation. During cold seasons, heat accumulation reduces HVAC system heating load and benefits from building energy conservation. Concerning warm seasons, however, it imposes extra loads on the system and increases energy consumption. For diminishing this negative effect, there are several solutions:

a) Reducing wall thermal resistance
b) Reducing internal gain
c) Changing operation setpoint



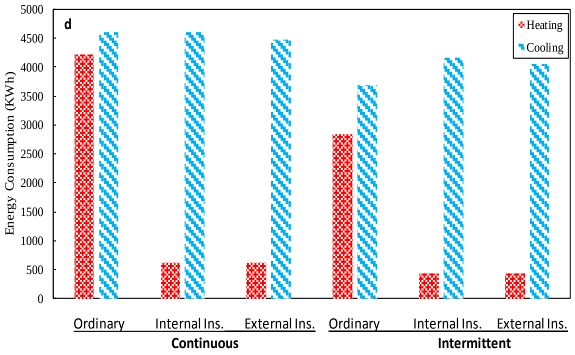


Figure 8. Yearly heating and cooling energy consumption: a) Polystyrene, b) Polyurethane, c) Glasswool and d) Rockwool.

Solution (a) can not be applied because it affects heating load negatively. Solution (b) is not as practical as expected because we can not change or remove equipment capacity. Therefore, changing the operation setpoint is the only alternative. Energy consumption profiles are shown in Figure 9 for non-insulated and insulated buildings against temperature setpoint variation. As can be seen, the reduction rate in the non-insulated building's cooling energy consumption is higher than the insulated one with the increasing setpoint temperature. The crossing point of insulated and non-insulated profiles (about 22 ºC) illustrates the temperature at which the Anti-Insulation phenomenon appears after that. In other words, wall insulation makes increments in the building's cooling load. Therefore, for diminishing the negative effect and prohibiting Anti-Insulation phenomenon upon results and ASHRAE standard comfort condition, temperatures of 20 ºC and 21 ºC are assumed for heating and cooling setpoints in this study.

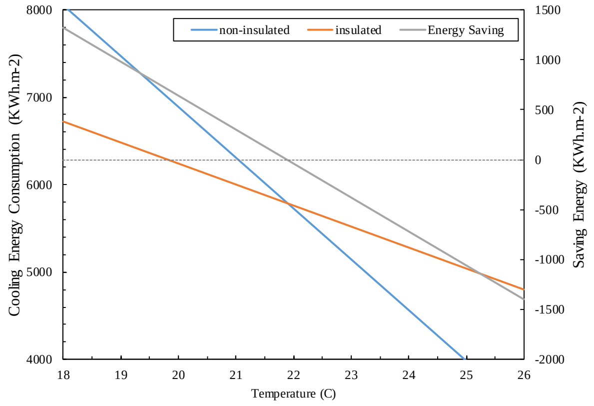


Figure 9. Energy consumption profile at different set point temperature.

3.3. Indoor temperature and heat flux distribution

For comparing different insulation modes in detail, indoor temperature and heat flux distribution for different zones are presented in this part.

3.3.1. Indoor temperature

In the continuous mode, the indoor temperature of zones varies in the comfort range (20 ºC to 21ºC). However, to check the quality of comfort condition in the intermittent operation, the internal temperature distribution of different zones is illustrated in Figure 10 for insulated buildings with polyurethane for instance. Under intermittent operation, the indoor temperature fluctuates out of the selected temperature range. During off intervals, gradients of temperature diagrams are smoother in the external insulation than the internal insulation. It is implied that temperature fluctuation in external insulation is low. Therefore, it provides a more comfortable condition for occupancy. Moreover, there is a more extreme deviation from the comfort range in the internal insulation. It is stated in the continuous operation, too.

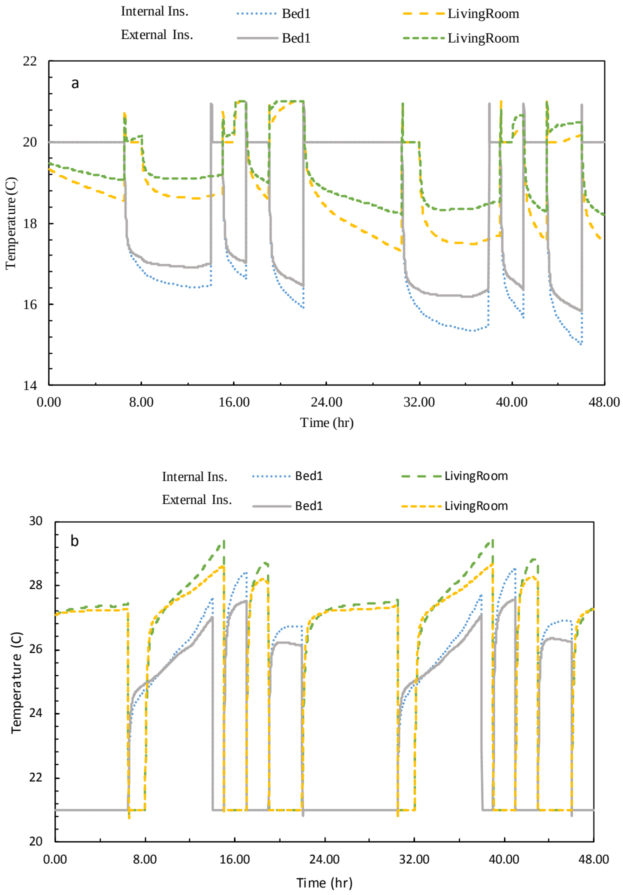


Figure 10. Indoor air temperature distribution for polyurethane insulation under intermittent HVAC operation mode: a) 21 and 22 January, b) 21 and 22 August.

3.3.2. Heat flux

Average heat flux in external walls for different zones in both non-insulated and insulated buildings with Polyurethane is shown in Figures 11,12, and 13. Considering these figures, it could be understood that heat flux partially grows with internal gains increment. As expected, wall insulation decreases heat flux in the insulated building compared with non-insulated buildings. Similarly, there is a heat flux reduction when the HVAC operation mode turns from the continuous to intermittent operation mode. In general, external insulation heat flux is lower than the internal one in both operation modes. However, during the working time of intermittent operation, the internal insulated building owns fewer heat flux values than external configuration.

As a result of intermittent operation, there are intervals at which the zone does not meet the comfortable setpoint (because of the delay for achieving the desired temperature after the HVAC system starts to work). Table 6 shows these uncomfortable times for each month; as can be seen, these time durations are very short, about 25 hours in a year. Therefore, the implementation of intermittent operation could be justified.

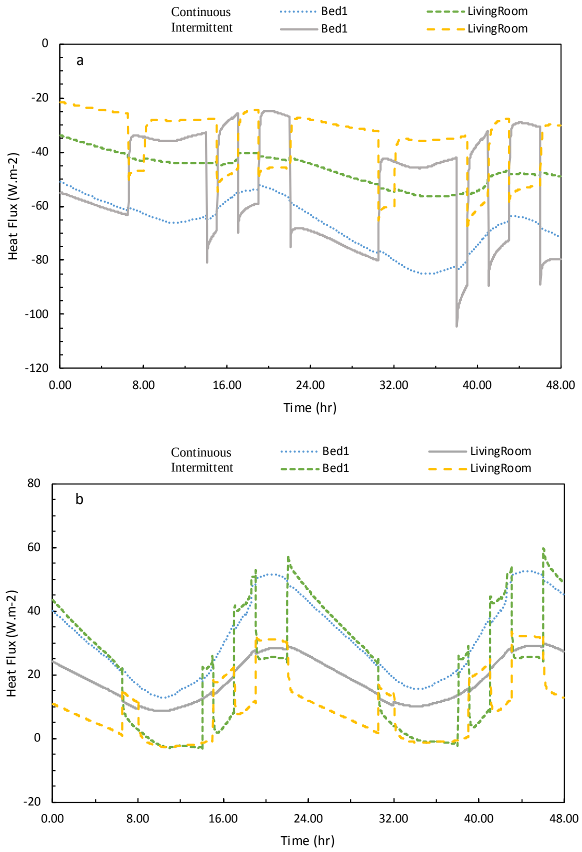


Figure 11. Building external walls heat flux for non-insulated building under continuous and intermittent mode: a) 21 and 22 January, b) 21 and 22 August.

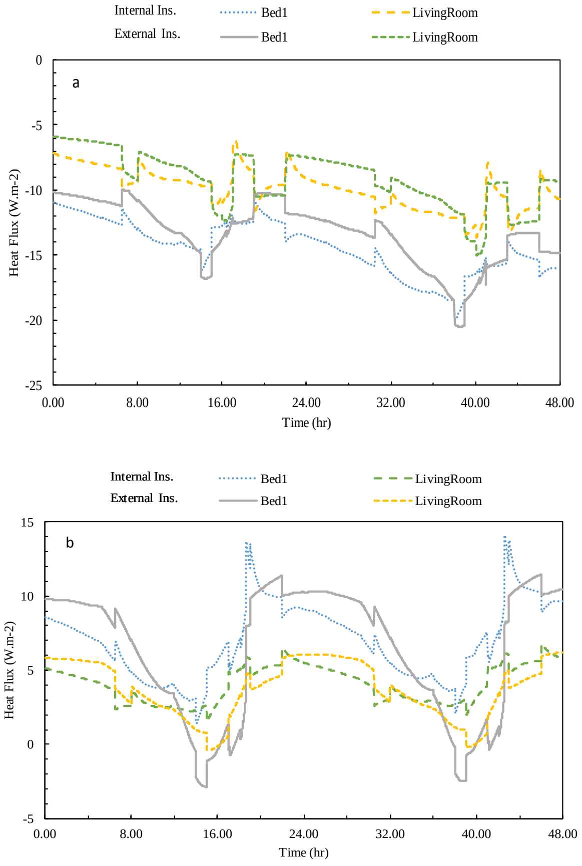


Figure 12. Building external walls heat flux for polyurethane insulation under hvac continuous operation mode: a) 21 and 22 January, b) 21 and 22 August.

3.4. Energy conservation

Annual heating and cooling energy conservation of building for each insulator under two operations of the HVAC system are calculated regarding non-insulated building with continuous operation, shown in Figure 14. As depicted in the diagram, heating energy saving is achieved by applying insulation to both continuous and intermittent HVAC operation modes and external insulation results in a relatively greater heating energy reduction due to the utilization of thermal mass.

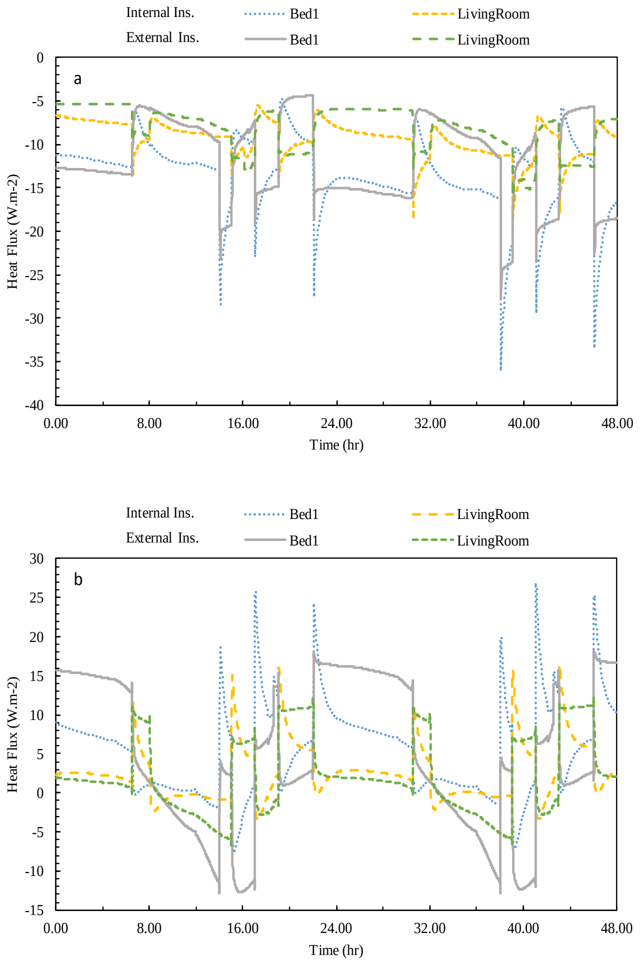


Figure 13. Building external walls heat flux for polyurethane insulation under hvac intermittent operation mode: a) 21 and 22 January b) 21 and 22 August.

According to Figure 14, cooling energy conservation is less than heating energy because of high internal gains that play a positive role in zone heating and a negative one in the cooling part. In other words, this high internal gain is trapped in the building by insulation, which compensates for a large portion of building heating demand, but imposes additional cooling load.

Tables 7 and 8 present energy-saving percentages in various cases of insulation and HVAC system operation. According to Table 7, 80-90 % heating and 8-11 % cooling energy-saving arise from the implementation of insulation in the continuous operation mode. As mentioned before, one of the reasons for high heating energy conservation is the trapped internal gains.

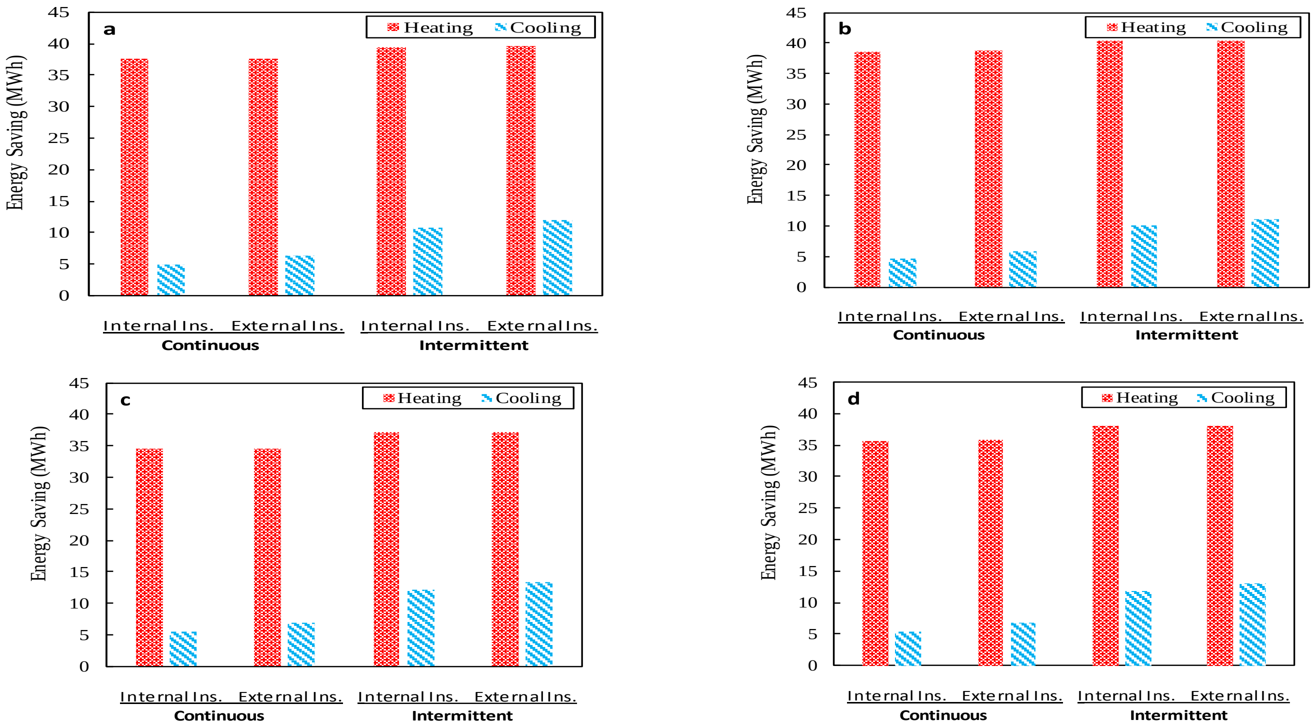


Figure 14. Yearly heating and cooling energy consumption: a) polystyrene, b) polyurethane, c) glasswool and d) rockwool.

Table 6. Zone heating and cooling setpoint not met time [hr].

	Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Ann.
Internal Ins.	Polystyrene	1.73	0.65	0.48	2.00	3.07	3.00	3.10	3.10	3.00	2.82	0.85	1.18	24.98
	Polyurethane	1.53	0.45	0.60	2.07	3.07	3.00	3.10	3.10	3.00	2.88	1.00	0.78	24.58
	Glasswool	2.43	1.23	0.32	1.58	3.05	3.00	3.10	3.10	3.00	2.68	0.63	1.65	25.78
	Rockwool	2.10	1.00	0.37	1.67	3.07	3.00	3.10	3.10	3.00	2.70	0.68	1.50	25.28
External Ins.	Polystyrene	1.60	0.57	0.37	1.75	3.05	3.00	3.10	3.10	3.00	2.80	0.68	0.90	23.92
	Polyurethane	1.22	0.30	0.47	1.93	3.07	3.00	3.10	3.10	3.00	2.85	0.95	0.52	23.50
	Glasswool	2.30	1.07	0.15	1.30	3.00	3.00	3.10	3.10	3.00	2.62	0.50	1.52	24.65
	Rockwool	1.97	0.92	0.13	1.48	3.02	3.00	3.10	3.10	3.00	2.70	0.47	1.35	24.23

Table 8 shows the energy saving values under the intermittent operation mode, which is 8 % higher than continuous mode values on average. In this case, there is more heating energy saving the same as the continuous operation. In both operations, external insulation makes more conservation than internal insulation due to the usage of the wall's thermal inertia. Regarding the heating and total energy, Polyurethane, Polystyrene, Rockwool, and Glasswool have the most to the least energy-saving, respectively. However, this sort stands in contrast to the cooling part. Because Polyurethane has higher thermal resistance, it is highly able to trap the internal gains and impose extra cooling load. Moreover, Glasswool's thermal conductivity is lower than Rockwool, and Rockwool total energy conservation is a bit higher than Glasswool's due to its greater heat capacity. The comparison of energy-saving of Glasswool and Polystyrene with the same conductivity, yet different heat capacitie, authenticates this principle too; greater heat capacity of Polystyrene facilitates greater energy saving.

3.5. Environmental and social expenses

Table 9 shows the yearly amount of reduction in greenhouse emission gained by wall insulation in terms of mass per unit of insulation area. Results indicate that employing wall insulation could reduce CO_2 emission at least 14 kg/m^2 insulator under continuous operation mode in comparison with non-insulated building in a year. Moreover, the intermittent operation decreases 18 kg/m^2 insulator CO_2 gas emission. Other greenhouse gas emission reduction amounts are shown in Table 9.

Table 10 represents amounts of CO_2 and CO greenhouse gas emissions that are released during producing process and transportation.

According to the values of Tables 9 and 10, a greenhouse gas emission reduction due to wall insulation compensates emission, released into the environment during insulator production and transportation processes just in few months, as shown in Table. 11. Therefore, the environmental benefit caused by wall insulation is justified entirely by this view. Moreover, the comparison of the payback period of greenhouse gas emissions shows that deciding about the insulator's environmental benefit based only on the emission reduction cannot be correct or efficient. Comparing two insulators Glasswool and Polyurethane could illustrate this point. As mentioned in Table 9, Polyurethane makes a greater gas emission reduction than Glasswool, but its payback period is longer. This is the process of releasing much more pollution to the air by the Polyurethane Production process than Glasswool. It is worth mentioning that emission payback periods of insulation are negligible compared to a building lifespan. However, if water pollution, soil pollution, energy usage for production, and wastes during production and after building lifespan be considered too, the environmental impact would be an important criterion in choosing the insulation. This subject would be investigated in future studies.

The amounts of social costs saving are presented in Table. 12. On average, there would be 5.15 ¢ social cost savings per unit of insulation area annually. This amount is 4 $ for the sample building. This may initially be small for a building, but at the macro level, like the 3.6 million houses of Iran's last great construction project, it will be over 14,500,000 $, which is a substantial amount. Therefore, in terms of social costs, thermal insulation in residential buildings is necessary.

Table 7. Energy saving percentage-continuous operation.

	Polystyrene		**Polyurethane**		**Glasswool**		**Rockwool**	
	Inter. Ins.	**Exter. Ins.**	**Inter. Ins.**	**Exter. Ins.**	**Inter. Ins.**	**Exter. Ins.**	**Inter. Ins.**	**Exter. Ins.**
Heating	87.80	88.16	90.32	90.74	80.63	80.82	83.50	83.76
Cooling	8.01	10.08	7.42	9.41	8.97	11.30	8.68	10.91
Total	40.56	41.94	41.24	42.59	38.20	39.66	39.20	40.63

Table 8. Energy saving percentage-intermittent operation.

	Polystyrene		**Polyurethane**		**Glasswool**		**Rockwool**	
	Inter. Ins.	**Exter. Ins.**	**Inter. Ins.**	**Exter. Ins.**	**Inter. Ins.**	**Exter. Ins.**	**Inter. Ins.**	**Exter. Ins.**
Heating	92.41	92.54	94.23	94.39	86.00	86.85	89.00	89.14
Cooling	17.44	19.35	16.23	17.96	19.65	21.64	18.96	20.91
Total	48.03	49.21	48.06	49.14	47.13	48.24	47.61	48.75

Table 9. Greenhouse gas emission reduction per square of insulated area in one year (gr/m^2).

			CO_2	CO	CH_4	NO_x	N_2O	SO_2	PM
Continuous	**Polystyrene**	**Inter. Ins.**	18033.54	13.64	0.37	26.33	0.27	14.79	1.58
		Exter. Ins.	16340.81	11.96	0.32	19.42	0.27	7.62	1.26
	Polyurethane	**Inter. Ins.**	16169.77	11.70	0.32	17.75	0.28	5.63	1.19
		Exter. Ins.	16627.90	12.13	0.33	19.27	0.28	7.12	1.26
	Glasswool	**Inter. Ins.**	14895.22	10.89	0.29	17.57	0.25	6.78	1.15
		Exter. Ins.	15385.81	11.35	0.31	19.32	0.25	8.53	1.23
	Rockwool	**Inter. Ins.**	15306.27	11.16	0.30	17.75	0.26	6.57	1.16
		Exter. Ins.	15787.86	11.62	0.31	19.44	0.26	8.24	1.25
Intermittent	**Polystyrene**	**Inter. Ins.**	18480.71	13.84	0.37	25.44	0.29	13.14	1.56
		Exter. Ins.	18877.29	14.21	0.38	26.87	0.29	14.57	1.63
	Polyurethane	**Inter. Ins.**	18540.19	13.82	0.37	24.79	0.29	12.24	1.54
		Exter. Ins.	18905.20	14.16	0.38	26.09	0.29	13.53	1.60
	Glasswool	**Inter. Ins.**	18033.54	13.64	0.37	26.33	0.27	14.79	1.58
		Exter. Ins.	18400.24	14.00	0.37	27.78	0.27	16.28	1.65
	Rockwool	**Inter. Ins.**	18254.69	13.76	0.37	26.12	0.28	14.27	1.58
		Exter. Ins.	18631.17	14.12	0.38	27.56	0.28	15.74	1.65

Table 10. Greenhouse gas emissions in the process of insulator production and transportation.

	Polystyrene	**Polyurethane**	**Glasswool**	**Rockwool**
CO_2 (kg/m^2)	2.584	6.03	0.714	1.407
CO (g/m^2)	1.48	4.05	0.6405	1.239

Table 11. Greenhouse gas emissions payback period (month).

		Polystyrene		**Polyurethane**		**Glasswool**		**Rockwool**	
		Inter. Ins.	**Exter. Ins.**	**Inter. Ins.**	**Exter. Ins.**	**Inter. Ins.**	**Exter. Ins.**	**Inter. Ins.**	**Exter. Ins.**
Continuous	CO_2	1.72	1.90	4.47	4.35	0.58	0.56	1.10	1.07
	CO	1.30	1.48	4.15	4.01	0.71	0.68	1.33	1.28
Intermittent	CO_2	1.68	1.64	3.90	3.83	0.47	0.47	0.92	0.91
	CO	1.28	1.25	0.00	0.00	0.00	0.00	0.00	0.00

Table 12. Saving social cost due emission reduction (¢/m^2.year).

			CO_2	**CO**	**No_x**	**SO_2**	**PM**
Continuous	**Polystyrene**	**Inter. Ins.**	4.29	0.06	0.38	0.64	0.16
		Exter. Ins.	3.89	0.05	0.28	0.33	0.13
	Polyurethane	**Inter. Ins.**	3.85	0.05	0.25	0.24	0.12
		Exter. Ins.	3.96	0.05	0.28	0.31	0.13
	Glasswool	**Inter. Ins.**	3.55	0.05	0.25	0.29	0.12
		Exter. Ins.	3.66	0.05	0.28	0.37	0.13
	Rockwool	**Inter. Ins.**	3.64	0.05	0.25	0.29	0.12
		Exter. Ins.	3.76	0.05	0.28	0.36	0.13
Intermittent	**Polystyrene**	**Inter. Ins.**	4.40	0.06	0.36	0.57	0.16
		Exter. Ins.	4.49	0.06	0.38	0.63	0.17
	Polyurethane	**Inter. Ins.**	4.41	0.06	0.35	0.53	0.16
		Exter. Ins.	4.50	0.06	0.37	0.59	0.16
	Glasswool	**Inter. Ins.**	4.29	0.06	0.38	0.64	0.16
		Exter. Ins.	4.38	0.06	0.40	0.71	0.17
	Rockwool	**Inter. Ins.**	4.35	0.06	0.37	0.62	0.16
		Exter. Ins.	4.44	0.06	0.39	0.68	0.17

4. CONCLUSIONS

The present study assessed the insulation reverse function (Anti-Insulation phenomenon) and investigated proper setpoint temperature for insulated building. The thermal performances of four typical insulators including Polystyrene, Polyurethane, Glasswool, and Rockwool in both external and internal configurations were studied. Moreover, the continuous and intermittent operation modes of the air-conditioning system were investigated in this study. In addition, environmental benefits were evaluated by calculating the payback period of greenhouse gas emissions and social cost conservation. The case study is a unit in mid-floor of 7-story block in the cold region of Tabriz. EnergyPlus software was used for evaluating the envelope thermal performance. The main results of this study are given below.

- Considering temperature setpoint range in the insulated building is essential, and comfortable setpoint could not be selected just based on the standards range, because simulation indicates that choosing wrong setpoints in the insulated building could lead to the Anti-Insulation phenomenon and impose extra load on HVAC system.
- Anti-Insulation phenomenon occurs at 22 ºC for simulated building.
- Implementation of insulators enhances 38-42 % energy saving. Insulators Polyurethane, Polystyrene, Rock wool, and Glasswool have the most to the least energy saving, respectively, regarding heating and total energy. But, this sort stands in contrast to the cooling energy.
- Insulator Rockwool thermal conductivity coefficient is 9.5 % larger than Glasswool. However, its energy saving is 1 % more than Glasswool, because the heat capacity of Rockwool is 20 % more than Glasswool. This phenomenon states about Glasswool and Polystyrene compared with their saving percentage.
- External insulation results in a relatively more energy reduction due to the utilization of thermal mass. Moreover, the amplitude of indoor temperature fluctuation is smaller in external insulation.
- Intermittent operation of the air-conditioning system outperforms the continuous operation by 8 % on average. The uncomfortable times as a result of the intermittent operation in the building are just 24 hours in the year.
- The payback period of greenhouse gas emissions is about a few months. The significant result is that the insulator selection based on the payback period of the emissions is different from an emission reduction base.
- Based on the result, over 14,500,000 $ is the annual social cost saving due to the insulation of 3.6 million houses of Iran’s last great construction project, which is a significant amount.

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