Optimum envelope design toward zero energy buildings in Iran

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Abstract. Buildings, commercial and residential combined, account for around 40% of total energy consumption in Iran. Energy consumption in buildings is predicted to increase in the the coming decades decades and immediate actions are required to meet the needs of future generations. Zero energy building (ZEB) is an important concept that can help nations to have a sustainable future. An important step for building a ZEB is to minimize the energy lost from the building, and the envelope of buildings plays a vital role in achieving minimal energy losses. In this paper, a life cycle cost (LCC) analysis is adopted to find the optimum insulation thickness for the common wall structure in Iran. Then, the Iranian standard (Chapter 19) for building envelopes have been reviewed and compared with the minimum requirements of the ASHRAE standard 90.2. The comparison shows that the Iranian standards for buildings envelopes are comparable with the ASHRAE standard 90.2 for the external wall, while ASHRAE requires higher minimum thermal resistance for ceiling compare to chapter 19. The optimization results suggest smaller minimum thermal resistance compare to chapter 19; this is mainly resulting from the characteristic of the Iranian economy (high inflation rate) and subsidized energy sector. Therefore, energy policy in the country needs to be reformed to promote energy conservation in buildings and hence zero energy buildings.

1 Introduction

Due to the accelerating depletion of fossil fuel and raising awareness of climate change, energy efficiency has become one of the main concerns globally. Ensuring access to affordable, reliable, sustainable and modern energy for all (goal 7) is indispensable for accomplishing the United Nations (UN) sustainable development goals (SDGs) [1]. Buildings account for one-third of the global final energy consumption, half of the global electricity generation and one-third of global carbon emissions [2]. According to the Intergovernmental Panel on Climate Change (IPCC) report on climate change [3], the global heating and cooling energy demands in 2050 are expected to increase 179% and 183%, respectively, compared to the 2010 levels for residential and commercial buildings. Radical changes in the current trends of energy consumption and energy-related CO_2 emission in buildings requires all countries to take immediate action toward broadly implementing the cost-effective best practices and technologies[3], [4].

The building sector is an important economic sector in Iran. Estimated private sector investment in new buildings in urban areas has increased 2.5 times at 2016 compared to 2010, according to the central bank of Iran [5]; during the same period, though, the number of permits for construction have slightly decreased because investors were inclined to build multi-story buildings. This decreasing trend in the number of multi-story building permits is mainly due to increasing the land price and investors tend to maximize their profit margins. According to the 2016 National Population and Housing Census, the population of Iran has reached 80 million people; 75% of the total population settled in the urban areas in 2016, with the average annual growth rate of urbanization of 2.14% during the period of 2011-2016 [6].

Buildings make up an important sector in the energy market in Iran. Buildings account for around 37% of total energy consumption in Iran [7]. Energy-related emission has become an important challenge in day to day life of many people settling in large cities such as Tehran, Arak, Isfahan, and Mashhad. For example, the capital of Iran, Tehran, is one of the most air-polluted cities in the world. Tehran had 111 unhealthy days in 2015, mostly due to the high level of particulate matter. On one day of the 111 unhealthy days, the air quality index reached a hazardous condition that is considered an emergency condition[8]. Buildings were the dominant sector in CO_2 emissions making up 28% of the total emission followed by 27%, 24%, 19% and 2.4% of power generation plants, transportation, manufacturing, and agriculture respectively [9]. Share of energy use by the residential, public and commercial buildings in electricity, natural gas and petroleum product is 47%, 49% and 12%, respectively [10]. The data, as mentioned above along with other data regarding the current status of Iran in terms of energy consumption in the building sector, are presented in Table 1. Furthermore, Iran has a high energy intensity (7 MJ/USD 2011 PPP) compared to the world average of 5.1 in 2016[1].

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Table 1. Statistical data on population, household and floor area in Iran (these data have been adopted from[1], [5]–[7])

Parameter	value
Population (millions)	79.9
Percentage of people living in urban areas (%)	75
Average household size (person)	3.3
Floor area per person (m^2/person)	30
Estimate private sector investment in new buildings in urban areas (billion USD) (bank Markazi)	5.8
Number of the permits issued for new buildings in urban areas (thousands)	126.7
Residential and commercial share of energy consumption (%)	37
Share of renewable energies in total final consumption (%)	>1
Share of electricity use in residential, public and commercial buildings (%)	47
Share of natural gas use in residential, public and commercial buildings (%)	49
Share of petroleum product used in residential, public and commercial buildings (%)	12
Share of Co_2 emission from residential, public and commercial buildings (%)	28
Energy intensity (MJ/USD 2011 PPP)	7.0

2 Zero energy buildings

The concept of zero energy building (ZEB) has come to fore in various research papers. In concept, ZEB refers to a building in which the energy demand, through efficiency gains, is significantly reduced, and renewable energy sources can supply energy demand. Renewable energy can either be supplied in the border of the building (in-site) or from the sources out of the border of building (off-site)[11]. Despite popularity among researchers, there is not a common and clear definition of ZEB[12]. Torcellini et al. [11] documented four different definitions depending on the boundary and the metric namely zero site energy, zero source energy, zero energy costs, and zero emissions. Pless and Torcellini [13] extended their definition of ZEB based on the renewable source of the building uses. Regardless of the ambiguity of the definition of ZEB, this can be accepted that in a zero energy building, the total amount of energy used by the building on an annual basis is roughly equal to the amount of renewable energy generated. Incorporating renewable energy sources together with energy efficiency, is essential to have a ZEB.

Energy efficiency in buildings is a very first step toward zero energy buildings. Energy consumption in buildings depends on many parameters including building shape and orientation, occupancy, the number of people living in the building, floor area, construction year of the building, type of window, envelope characteristics, occupants' behavior, and appliance characteristics, heating, cooling, lighting and air conditioning equipment. Energy efficiency is at the top of the political agenda of countries aiming to reduce wasteful energy consumption, strengthen energy security, and cut greenhouse emissions [14]. The energy price in Iran is very low in comparison with international prices and for this reason, nobody pays attention to energy saving. However, people's awareness is increasing toward energy security and reducing harmful emissions.

Iran's geographic and climate condition is very favorable for renewable energy. However, the Iranian energy market is mainly shaped by the conventional energy source; this is because Iran holds large crude oil and natural gas reserves. Total 2013 installed capacity of 70.2 GW electricity is composed of 14.84% of renewable energy translating to 10.4 GW electricity production. Water, wind, PV, and biogas are contributors for producing 14.61%, 0.16%, 0.05% and 0.01% of renewable electricity production, respectively [9].

The renewable energy inclusion in buildings is not the focus of the current study, and one can look at these references for further information [9], [15]. The focus of this paper is on the efficiency gain and particularly on the effects of building envelope on energy consumption for Iranian buildings. Iranian households consume most of their energy for heating, cooling, lighting and cooking. Energy loss from the floor, wall, and ceiling (31%), ductwork (15%), chimneys (14%), plumbing (13%), doors (11%), windows (10%), ventilation fans (4%) and electricity outlets (2%) are the main contributors for energy waste is Iranian buildings [9]. The envelope of buildings (walls, floor, ceiling and fenestrations) serves as an interface between the indoor and outdoor of the buildings and they are the main sources of energy dissipation from the buildings. Therefore, an effective building envelope is critical to reducing the energy demand in building.

3 Climate and population density of Iran

Iran is a vast country with different types of climate: wet and mild on the coast of the Caspian Sea, continental and arid in the plateau, cold in high mountains, desertic and hot in the southern coast and the southeast. The average temperature in Iran ranges from 5°C in January to approximately 30°C in August. On the humid south coast, the temperature can soar up to 40°C in the summer and temperature can drop below zero in the northern and north-western mountains. In the central and east parts of the country, the desert climate is ruled and it is characterized by very low rainfall, unbroken sunshine for the whole year and maximum temperature of 40 to 45°C[14].

Heating degree days (HDDs) and cooling degree days (CDDs) are quantitative indices that reflect the energy needs to provide a comfortable indoor environment. CDDs and HDDs are calculated from the following equations [16]:

$$\mathrm{CDD_{day}} = \begin{cases} 0, & \mathrm{T_b} > \mathrm{T_m} \\ \mathrm{T_m} - \mathrm{T_b}, & \mathrm{T_b} < \mathrm{T_m} \end{cases} \quad (1)$$

$$\mathrm{HDD_{day}} = \begin{cases} 0, & \mathrm{T_b} < \mathrm{T_m} \\ \mathrm{T_b} - \mathrm{T_m}, & \mathrm{T_b} > \mathrm{T_m} \end{cases} \quad (2)$$

Where T_b is the base temperature ($T_b = 10°C$ for CDD and $T_b = 18°C$ for HDD calculations) and T_m is the daily outdoor average temperature. Annual cooling and heating degree days are calculated by taking an arithmetic average of CDD_{day} and HDD_{day} over 15 years as follows, respectively:

$$\mathrm{CDD_{annual}} = \frac{\sum_{\mathrm{days}} \mathrm{CDD_{day}}}{15} \quad (3)$$

$$\mathrm{HDD_{annual}} = \frac{\sum_{\mathrm{days}} \mathrm{HDD_{day}}}{15} \quad (4)$$

Figure 1 shows annual CDD for Iran; the data has been taken from [17]. According to this figure, the annual CDD ranges from 1148 to 6831, with the main cooling need in the southern part of the country. Figure 2 represents the annual HDD for Iran according to the data extracting from [18]. The highest annual heating demand is less than 4000 units and heating demand occurs mainly in the north-western part of Iran. Based on Figures 1 and 2, the climate map of Iran, following to the ASHRAE thermal climate zone definition[19] presented in Table 2, is prepared and presented in Figure 3. Furthermore, the percentage surface area locating in each climate zone is presented in Table 2. The majority of Iran is situated in thermal zones 2-4. It is also important to note that in the central and eastern parts of Iran (hot and very hot), the population density is less than 20 people per square kilometer (Figure 4).

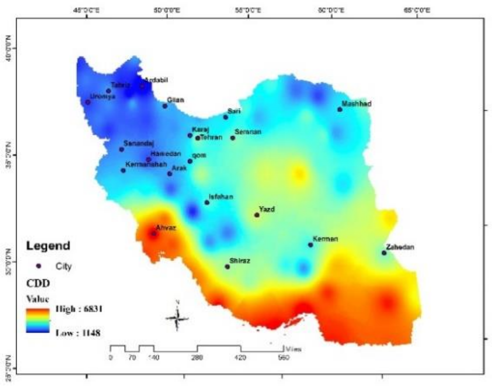

Fig. 1. Annual CDDs for Iran generated from the data provided in[17] for the 15 years (2003-2018)

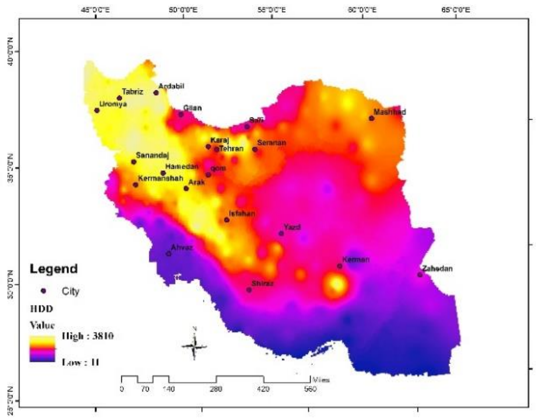

Fig. 2. Annual HDDs for Iran generated from the data provided in[18] for five years (2006-2011)

Table 2. The ASHRAE climate zone definition[19] and percentage area of Iran locating in each thermal zone

Thermal zone	Name	Percentage ara (%)
0	Extremely hot	5.6
1	Very hot	14.2
2	Hot	32.8
3	Warm	24.4
4	Mixed	21.3
5	Cool	1.7
6	Cold	0
7	Very cold	0
8	Subarctice/artctic	0

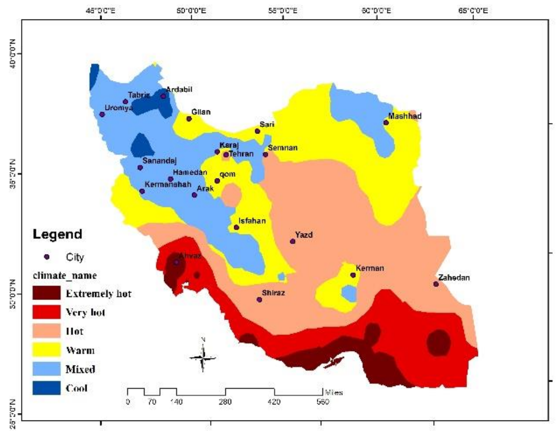

Fig. 3. Climate map of Iran based on ASHRAE definition[19]

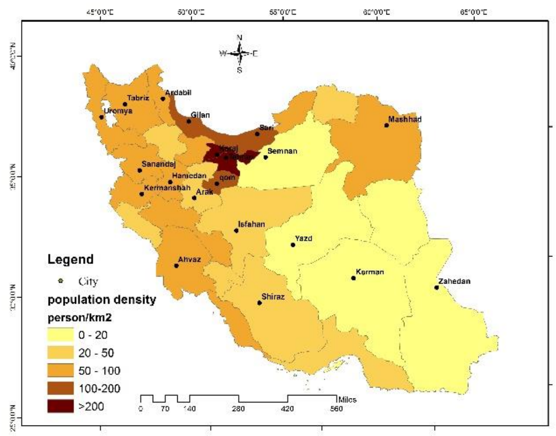

Fig. 4. The population density in Iran from the latest 2016 National Population and Housing Census of Iran[6]

4 Regulations, standard, and codes on energy efficiency for buildings in Iran

The importance of energy efficiency in both production and consumption sides has been known by the Iranian scholars and the government for many years. However, due to the lack of a consistent and systematic approach to design and implement energy efficiency measures, energy efficiency policies have been ineffective in promoting energy efficiency in Iran[9]. Furthermore, the implication of energy price reform to modify the subsidized energy sector as a prerequisite for energy efficiency policy in the economy has been overdue [9]. Considerable potential for improving energy efficiency by the household through implementing energy efficiency standards in buildings and appliances and raising people's awareness and providing education is available for the government.

There are several non-compulsory standards related to energy efficiency in buildings, mechanical room equipment and inspection, and lighting which are prepared by the Institute of standards and industrial research of Iran[20]. Particularly, a standards entitled "residential building-criteria for energy consumption and energy labeling instruction- ISIRI 14253" and " Non-residential building criteria for energy consumption and energy labeling instruction- ISIRI 14254" which set the amount of energy consumption (per square meter) of residential and non-residential buildings for energy labeling purpose. Energy labeling can be an important policy to improve energy efficiency and raising people's awareness of conserving energy in their buildings. In ISIRI 14253 and 14254, energy consumption per square meter for the ideal buildings are presented for different climate zones of the country. The amount of energy consumption for the residential reference building based on ISIRI 14253 is presented in Table 3. An energy label (A-G) will be given to the building by comparing the annual building energy consumption with the reference buildings. Annual energy consumption can be obtained either by the direct measurement of yearly energy consumption (existing buildings) or by calculating the energy consumption (new and existing buildings). ISIRI 14253 & 14254 do not have any recommendations for the envelope design of buildings.

Table 3. The amount of energy consumption for a residential reference building based on ISIRI 14253[20]

Climate	Energy consumption index (Kwh/year.m2)		Sample city
	Small house < 1000 m^2	large house > 1000 m^2	
Very cold	111	102	Sarab
Cold	111	102	Tabriz
Mild and rainy	156	106	Rasht
Half mild and rainy	156	106	Moghan
Half dry	83	87	Tehran
Hot and dry	86	75	Zahedan
Very hot and dry	150	138	Ahvaz
Very hot and humid	130	118	Bandarabbas

Chapter 19 of the National Regulations for Buildings of Iran, entitled "energy conservation", is the only reference code for energy efficiency in building in Iran. This code was first passed by the government in 1991 and was amended in 2000[21]. The ministry of roads and urban development is given the responsibility for monitoring and updating this code. Chapter 19 must be implemented in new public and private small and large buildings. The code covers the following elements of the buildings:

- Minimum thermal resistance for external walls
- Minimum thermal resistance and SHGC for fenestrations
- Requirements for the mechanical room, heating, cooling, ventilation and supply hot water equipment including minimum efficiency of equipment, piping and ducts insulation, control requirements, maximum ventilation rate and sealing quality
- Lighting system and electrical appliances requirements

Building envelope accounts for an important part of chapter 19 of building code. From chapter 19, two calculations methods were introduced to design the building envelope: The perspective and performance method. In the performance method, buildings are divided into four groups based on the severity of energy efficiency requirements (1-4; with groups 1 and 4 are buildings with highest and least needs for energy efficiency respectively). Buildings are classified in groups based on building occupancy, amount of energy demand (low, high and medium), floor area and the population of the city where the building is located (large and small). "Reference heat transfer coefficient" is defined as the maximum allowable heat transfer rate from roofs, walls, floors, doors and openings combined. The reference heat transfer coefficients are specified for different building groups in chapter 19.

The minimum thermal resistance (or maximum thermal conductance) of elements of the building envelope (external walls, windows, and floor) are presented in the perspective method independently. This approach is simple but restricted to buildings with a floor area less than 2000 m^2 and a building up to nine floors. The perspective approach is also applicable to all buildings in group 3 in terms of energy efficiency requirements.

Although fenestration is of great importance in terms of energy losses from the buildings, the external wall thermal properties are the main focus of this paper. The focus of this paper is the envelope of buildings. To do so, an LCC approach is utilized to determine the optimum insulation thickness on a common wall structure for Tehran, the capital of Iran. The authors have previously published the complete discussion and further development of optimal insulation thickness[7], [22]. In the next section, the LCC approach used in the previous studies will be briefly explained. The results of this optimization will be compared with the prescribed method of chapter 19 and ASHRAE standard 90.2. Furthermore, Rosti et al.[23] have also utilized the same LCC approach to obtain the optimal insulation thickness for nine cities in Iran and these results will also be used for comparison.

5 Optimum wall thermal resistance: summary of the LCC approach

In this section an overview of a method that used to optimize the insulation thickness for two common wall structures in Iran will be explained[7]. The optimized wall thermal resistance (insulation thickness, EPS) will also be compared to the minimum requirements in chapter 19. Rosti et al. [23] have recently used a similar methodology to optimize the insulation thickness of common and modern wall structures in several cities in Iran. The optimal insulation thickness is used to calculate the optimal thermal resistance. In the following, the methodology will be briefly explained.

A schematic of an ordinary multi-layer wall structure, thermos-physical properties, width of each layer and the boundary conditions on the wall are shown in Figure 5. The optimum insulation thickness (EPS) is obtained by performing an economic analysis over the life cycle of the building. The economic parameters are the initial cost of the insulation and the energy consumption reduction after the application of insulation on the wall. The detailed formulation to optimize the wall structure is taken from [22] and summarized in Table 4. The output of the economic analysis is the optimal insulation thickness which corresponds to the minimum life cycle cost (LCC), as displayed in Figure 6. Thus, in this approach as shown in Figure 6, the total costs of insulation and energy cost over the life cycle period will be minimized. The heating and cooling transmission loads from the wall of different orientations are obtained through the numerical solutions of the governing equations presented in Table 4. The economic parameters that are used in the insulation optimization studies are energy cost, insulation cost per square meter, inflation and discount rates; these values are used in the LCC analysis to obtain the present value of the energy consumption reduction after application of insulation on the wall.

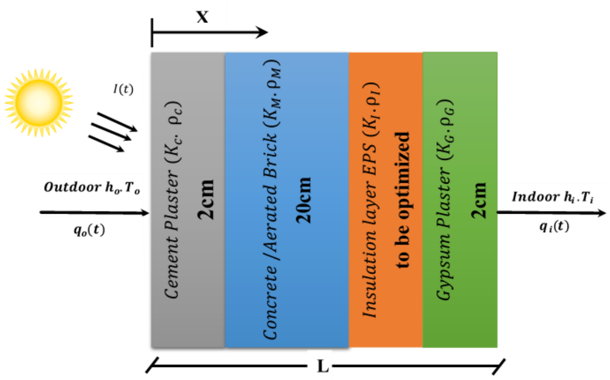

Figure 5. Schematic of multi-layer a wall and boundary conditions on it. Insulation materials can be placed on the inside surface of the main wall materials (current structure) or the outside of the wall between the cement plaster and the main wall material [22].

6 Thermal resistance comparison

The results of the optimization of insulation thickness are obtained for Tehran[7], [22] and several cities[23] in Iran will be discussed in this section. Table 5 summarized the minimum thermal resistance resulting from the two optimization studieis[7], [23], ASHRAE standard 90.2 for low-rise residential buildings [19] as well as the values extracted from the prescription method from the chapter 19 of building energy consumption of Iran (NA stands for “Not available”)[21]. The minimum thermal resistance (m^2.K/W) for both external walls and ceiling are presented in this table. What is stand at the first glance in this table is the considerable difference between the minimum thermal resistance for ceilings prescribed by ASHRAE 90.2 and the results suggested by chapter 19 and insulation thickness optimization. The other observation from the minimum thermal resistance from chapter 19 is that they are different even for the same climate condition and this is the result of the classification of buildings in chapter 19 that accounts for the severity of energy conservation requirements for each city. The suggested minimum thermal resistance values for external walls are comparable from ASHRAE 90.2 and chapter 19. However, the optimization values from Rosti et al.[23] are much smaller than values from ASHRAE 90.2 and chapter 19. The minimum thermal resistance for Tehran obtained from the study by Ramin et al.[7] is larger than the one from Rosti et al[23]. This can be because of the fact that they have used different wall structures and the economic situation in Iran has changed over this period. The smaller thermal resistance from the optimization study compare to chapter 19 and ASHRAE 90.2 s mainly because of the economic features of Iran (high inflation rate and discount rate) and low energy price that make the application of insulation for energy conservation not economical.

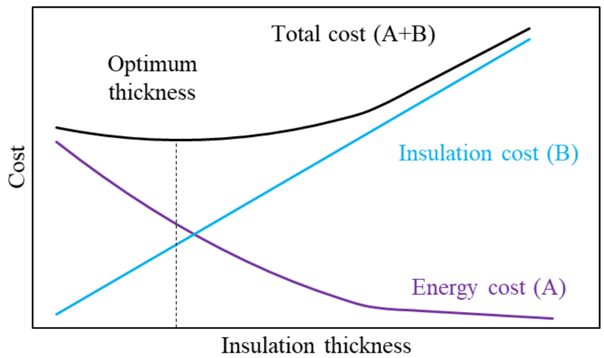

Figure 6. A schematic of economic analysis to determine optimum insulation thickness

Table 4. Governing equations for one-dimensional heat transfer problem within a multilayer wall [22]

Governing equations and boundary conditions	Description	
$\frac{\partial^2 T_j}{\partial x_j^2} = \frac{1}{\alpha_j}\frac{\partial T_j}{\partial t}$	heat conduction in wall	(5)
$-k_M \frac{\partial T}{\partial x}\Big\|_{x=L} = h_i(T_{x=L} - T_i)$	wall's inside convection boundary condition	(6)
$k_1 \frac{\partial T}{\partial x}\Big\|_{x=0} = h_o(T_{x=0} - T_e(t))$	wall's outside convection boundary condition	(7)
$Te(t) = T_o + \frac{\alpha I_T}{h_o} - \frac{\epsilon \Delta T}{h_o}$	sol-air temperature	(8)
$q_i = h_i(T_{x=L} - T_i)$	inside heat transfer through a wall	(9)
$I_T = R_b I_b + I_d\left(\frac{1+\cos(\beta)}{2}\right) + I\rho_g\left(\frac{1-\cos(\beta)}{2}\right)$	total solar radiation (I_T), total solar radiation on a horizontal surface (I), beam solar radiation on a horizontal surface (I_b), diffuse solar radiation on a horizontal surface (I_d).	(10)
$\text{Solar time} = \text{Standard time} - 4(L_{st} - L_{loc}) + E$	the relation between solar time and standard time	(11)
$E = 229.2(0.000075 + 0.001868\ \text{CosB} - 0.032077\ \text{sinB} - 0.014615\ \cos 2B - 0.04089\ \sin\ 2B$	E in equation (11)	(12)
$B = (n-1)\frac{360}{365} \qquad 1 \le n \le 365$	B in equation (12)	(13)
$\delta = 23.45 \sin\left(360\frac{284+n}{365}\right) \qquad n = \text{the day of the year } 1 \le n \le 365$	declination angle- the angular position of the sun at solar noon with respect to the plane of the equator	(14)
$\cos(\theta) = \sin(\delta)\sin(\phi)\cos(\beta) - \sin(\delta)\cos(\phi)\sin(\beta)\cos(\gamma) + \cos(\delta)\cos(\phi)\cos(\beta)\cos(\omega) + \cos(\delta)\sin(\phi)\sin(\beta)\cos(\gamma)\cos(\omega) + \cos(\delta)\sin(\beta)\sin(\gamma)\sin(\omega)$	the angle of incidence (θ)- the angle between the sun's rays and a tilted surface-, latitude angle (ϕ), the slope of the surface (β), surface azimuth angle (γ), hour angle (ω)	(15)
$\omega = \frac{360}{24}\frac{(\text{Solar Time} - 720)}{60}$	hour angle(ω)	(16)
$\cos(\theta_z) = \sin(\delta)\sin(\phi) + \cos(\delta)\cos(\phi)\cos(\omega)$	zenith angle (θ_z)	(17)
$\cos(\omega_s) = -\tan(\phi)\tan(\delta)$	hour angle at sunset (ω_s)	(18)
$N = \frac{2}{15}\cos^{-1}(-\tan(\phi)\tan(\delta))$	number of daylight hours (N)	(19)
$\text{sunset time} = \frac{60}{15}\cos^{-1}(-\tan(\phi)\tan(\delta))$		(20)
$\text{sunrise time} = \text{sunset time} - N$		(21)
Economic analysis and optimized insulation thickness	**Description**	
$PWF(n,i,d) = \sum_{u=1}^{n}\left(\frac{1+i}{1+d}\right)^u = \begin{cases}\frac{1+i}{d-i}\left[1-\left(\frac{1+i}{1+d}\right)^n\right], & i \ne d \\ \frac{n}{1+i}, & i = d\end{cases}$	i, d, n are the interest rate, inflation rate, and lifetime of the building wall respectively. PWF is the present worth factor that is used to evaluate the net energy saving from using insulation over the period of wall lifetime.	(22)
$C_{enr} = PWF\left(\frac{Q_c}{COP}\frac{C_{el}}{3.6 \times 10^6} + \frac{Q_h}{H_u \eta_s}C_g\right)$	C_{enr} is the total present cost of heating and cooling per unit surface area during the lifetime of the wall. Q_c, Q_h, C_{el} and C_g are the annual cooling transmission load, annual heating transmission load, the electricity cost per kWh and the cost of natural gas per cubic meter respectively. H_u, η_s and COP are the lower heating value of the fuel, efficiency of the heating system and coefficient of performance of the air-conditioning system respectively.	(23)
$C_t = C_{enr} + C_i = C_{enr} + C_{ins}L_{ins}$	C_t is a combination of transmission load and insulation material cost. C_{ins} is the cost of insulation per volume and L_{ins} is the thickness of the insulation.	(24)
$S_e = PWF\left(\frac{Q_c}{COP}\frac{C_{el}}{3.6 \times 10^6} + \frac{Q_h}{H_u \eta_s}C_g\right) - C_{ins}L_{ins}$	S_e is the net energy saving per unit surface area of the wall through its period of the lifetime. L_{ins} is to find in a way that S_e be maximized.	(25)

Table 5. Minimum thermal resistance for the envelope of buildings in Iran from chapter 19, ASHRAE standard 90.2 and optimization studies of Ramin et al.[7] and Rosti et al.[23]

		ASHRAE[19]		Rosti et al.[23][a]		Chapter 19		Ramin et al.[7][b]	
City	ASHRAE climate zone	Minimum thermal resistance (m^2K/w)							
		wall	ceiling	wall	ceiling	wall	ceiling	wall	ceiling
Ardabil	Cool (5)	2.1	5.9	1.2	NA	2.0	2.8	NA	NA
Hamadan	Mixed (4)	1.3	5.9	1.3	NA	2.0	2.8	NA	NA
Rasht	Warm (3)	1.3	5	1.3	NA	1.1	1.6	NA	NA
Gorgan	Warm (3)	1.3	5	1.4	NA	1.1	2.0	NA	NA
Tehran	Hot (2)	1.1	5	1.7	NA	1.3	2.0	1.5	1.6
Zahedan	Hot (2)	1.1	5	1.3	NA	1.3	1.6	NA	NA
Ahvaz	extremely hot (0)	0.9	5	1.8	NA	2.0	2.8	NA	NA
Bandar Abbas	extremely hot (0)	0.9	5	1.6	NA	2.0	2.8	NA	NA

7 Conclusions

Energy is critical for ensuring a sustainable future. Buildings account for a considerable share of total energy consumption globally. In this paper, the minimum external wall and ceiling thermal resistance prescribed by Iranian standard (chapter 19) and ASHRAE 90.2 are compared and the comparison reveals that values from both sources for walls are comparable, while ASHRAE 90.2 requires higher thermal resistance for ceilings. Furthermore, the results of life cycle cost optimization of insulation thickness for different cities of Iran showed that due to the economic conditions of Iran and subsidized energy market, higher thermal resistance (thicker insulation) is not economical and the optimization results suggested smaller thermal resistance compare to ASHRAE 90.2 and chapter 19.

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