Economical evaluation of passive systems for residential buildings in Kerman, Iran

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Abstract

Using passive systems is being popular in building sector. All these systems have their own performances and operation costs. To select the best system for energy saving in building, the life cycle costs and amount of energy saving of passive systems should be considered. This paper assesses the performance of the for passive systems, including roof pond, roof garden, wind catcher and ground cooling on energy saving of the building in hot and arid region in Iran. And then the cost of initial, operation and maintenance of each system is studied. To meet this goal, the individual impact of each system on a one-story residential house with the dimensions of 13.16m×11.11m×2.8m, located in Kerman city, Iran is calculated. This study is conducted for a period of 138-day from May to October, during which the use of cooling systems is considered to be required. The cost of construction, operation and maintenance and the energy saved by each system over a period of 20-year is evaluated. Results shows, wind catcher is most economical system to reduce energy consumption; meanwhile, roof garden is an expensive passive system in Iran. So using the roof garden for energy saving does not have economical rationalization.

Keywords: Passive system; Economic evaluation; Energy saving, Kerman.

1.Introduction

According to the researches, buildings account for about 30-45% of global energy consumption. This energy is consumed in various devises or services such as air conditioning, electrical utilities and lighting [1,2]. Studies show more than 60 percent of this energy is consumed for air conditioning and ventilation [3,4]. In underdeveloped countries, this fraction is much higher than international standards. A research conducted in Greece has reported that although the energy consumed for heating has decreased over the recent years, air-cooling energy consumption has increased by 248% [5]. Besides, the fossil fuel are limit resources with many environmental impacts [6]. So using renewable energies for both cooling and heating are being popular day to day [7,8].

A proper design of building envelope has a huge impact on reducing energy consumption [9]. Sadineni has studied the exterior surfaces and components of buildings and has provided a variety of methods and materials to improve the energy-saving efficiency of components such as the walls, openings, and roofs. According to a study, the optimization of building envelope has a significant impact on reducing its energy consumption [10]. Other studies have also confirmed the positive impact of passive methods such as wind catcher, roof garden, roof pond and underground house on the energy consumption [11-13].

The roof garden is one of the effective methods of improving cooling efficiency in the buildings. In this approach, roof of the building gets covered with a layer of soil and then with a layer of lawn or plants such as Sedum. In general, green roof acts as a barrier against direct sunlight on hot days and reduces heat flux and U-value [12]. Research has proven that green roofs can reduce the ceiling's heat transfer coefficient from 7.76–18.18 to 1.73-1.99 and lead to about 22-45% reduction in building's annual cooling energy consumption [14]. A study in Thailand has assessed the

U-value for green roofs with 10 and 20 cm thick soil-layer and two different types of plant. According to this study, U-value of the dry soil is higher than that of wet soil, and the thermal resistance increases with the increase of soil-layer thickness. This study has also reported that the heat transfer of a green roof with a 10-20 cm thick soil-layer is 46-93 percent lower than a conventional roof [15].

Roof pond is another method of passive cooling, which could be used to reduce the interior temperature and minimize its fluctuations [16-18]. The presence of a water pond on the roof greatly limits the level of access, but it largely increases building's energy efficiency in summers. So pursuing this approach in hot and dry climates could prove effective [19-21]. This approach could be implemented through several methods, but the simplest type includes a pond of water with a depth of 10-30cm, which can reduce the temperature of the roof from 65.6°c to 39.4°c. The more sophisticated designs of this approach employ mechanical equipment such as water spray and movable insulation [13, 22].

Wind Catcher is a simple structural scheme that provides natural ventilation. It directs the flow of outside air into the building and uses buoyancy effect to direct the warm air of the interior to the outside, effectively creating a natural ventilation cycle [11]. So far, many studied have confirmed the effectiveness of wind catcher in providing natural ventilation and thermal comfort, and a number of these studies have been specifically focused on the performance of this system in arid and semi-arid climates [23-27].

The use of earth's thermal energy is an ancient construction practice common in many parts of the world. Soil has a higher heat capacity than air, so it can be used as an energy storage system to effectively reduce temperature fluctuations. Also when the walls of the building are in contact with the soil they tend to have less energy exchange with the outside environment [28]. There have been numerous renewable energy studies by author [29-38]. It is clear each of mentioned passive systems has different performance, initial, operation and maintenance cost. In this paper, a numerical study about these for systems in hot and dry regions of Iran have been conducted. First, the performance of each system have been calculated. Then operation costs and the energy saving cost is compared.

2. Climate Overview

Kerman province has an area of about 175069 square kilometers and is located in south-eastern Iran. Based on KÖPPEN-GEIGER classification, climate of this region falls into arid category [39]. Springs of Kerman city starts from 20 March and ends in 20 June and its summers start from 21 June and ends in 21 September [40]. The average annual temperature of this city is 18 degrees, with the highest average temperatures in the months of May and June (42°C) and the lowest in December (-12°C) [41]. The Kerman city climate data are presented in Table1.

Table 1. The main meteorological parameters for the city of Kerman.

Month	Total rainfall (mm)	Temperature (c°)			Relative humidity Evening (%)	Sunlight duration (hours)
		Minimum	Average	Maximum		
Jan	30	-3	5	12.1	38	231
Feb	20	-0.5	8	14.8	29	221
Mar	30	3.8	12	18.7	28	218
Apr	20	8.2	18	24.3	21	270
May	10	12.2	23	29.9	16	286
Jun	00	16.1	28	34.9	13	386
Jul	00	17.7	29	35.7	13	353
Aug	00	14.8	27	34.3	12	360
Sep	00	10.6	23	31.5	13	352
Oct	00	5.5	19	26.0	16	300
Nov	00	0.3	11	19.6	21	222
Dec	20	-2.6	8	14.5	28	180

3. Methodology

To evaluate the amount of energy loss through the building envelope, the amount of heat loss through all its surfaces need to be calculated. The following equation is used to calculate the amount of heat lost through building envelope and openings, including windows, walls, ceiling and floor [42-45].

$$Q = UA\,(T_o - T_i) \tag{1}$$

In the above equation, Q is the amount of energy lost or taken from a surface with area A; T_o denotes the outside air temperature, and T_i denotes the interior air temperature; U is the heat transfer coefficient, which can be obtained from the following equation [42-45]:

$$U = \frac{1}{^1/_{h_o} + \sum_{i=1}^n R_i + ^1/_{h_i}} \tag{2}$$

Where U is the heat transfer coefficient of the entire wall, and R_i denotes the thermal resistance of each layer of the wall, which is obtained by the following equation [42-45]:

$$R_i = X_i/k_i \tag{3}$$

In the above equation, k is the heat transfer coefficient of material, x denotes its thickness, and R denotes its thermal resistance; h is the convective heat transfer coefficient. Value of h depends on the speed of air flow and the outer texture of material. Eqs. (4)-(7) in Table 2 can be used to calculate the convective heat transfer coefficient of building materials near the wall surface [46].

Table 2. Evaluation for convective heat transfer coefficient of different surfaces.

Heat Convection	Material	Number
$h = 1.4 + 0.28V$	Very Smooth Surface	(4)
$h = 1.6 + 0.3V$	Wood or Smooth Plaster	(5)
$h = 2.0 + 0.4V$	Concrete and Smooth Brick	(6)
$h = 2.1 + 0.5V$	Rough Surface	(7)

In Eqs. (4)-(7), the variable V is the velocity of wind near the surface of the wall in miles per hour. When a building is built within the ground, some parts of its envelope are in direct contact with the soil; so in Eq. (1), T_o should be replaced with the soil temperature. The following equation can be used to calculate the soil temperature at specific depths and times [47, 48].

$$t_{s,z} = t_m + A_o \exp\left(-z\sqrt{\frac{\pi}{365\alpha}}\right) \sin\left[\frac{2\pi(n-n_o)}{365} - z\sqrt{\frac{\pi}{365\alpha}} - \frac{\pi}{2}\right] \tag{8}$$

In the above equation, $t_{s,z}$ is the soil temperature at the target depth and time, z is the depth from the surface in meters, t_m is the annual average soil temperature in °C, n is the number of target day counting from 31 Dec, n_o is the number of the coldest day of the year counting from 31 Dec. In Eq. 8, A_o denotes the amplitude of soil temperature in °C and is considered to be 16 °C for Kerman city; the term α represents the heat penetration coefficient, which for heavy clayey soil with moisture content of 5%, density of 1925 kg/m³ and heat transfer coefficient of 1.2 kcal/m²h°C is considered to be 0.06 m²/day. The following equation is used to calculate the volume of air entering by air penetration effect, i.e. via openings and gaps [46].

$$q_p = vn \tag{9}$$

In the above equation, q_p is the amount of air penetrated through the openings, v is the volume of the room or space, and n is the number of air changes per hour. The energy corresponding to air penetration or wind catcher is calculated by the following equation [46].

$$Q = q_p \times 1.2 \times 0.24 \times (T_o - T_i) \tag{10}$$

In the above equation, T_o is the air temperature outside and T_i is the air temperature inside the room. The following equation is used to calculate the flow of air outgoing through the wind catcher in $(^{m^3}/_s)q$ [46, 49].

$$q_p = VA \tag{11}$$

In the above equation, V is the velocity of wind passing near the outlet of wind catcher, and A is the area of the outlet in m^2.

4. Case Study

To assess the amount of energy loss through the envelope of residential buildings, a one-story house with a living room, a dining room, a kitchen and two bedrooms, with a total width of 11.11m, total length of 13.16m, and an interior height of 2.8m is considered. The gross area of this house is 128.82 m^2. Plan of this house is shown in Fig. 1. First, we evaluate energy consumption of above ground building including energy loose through building envelope and uncontrolled air penetration and then the impact of each passive system will be investigated. Four passive system include:
1) Roof garden
2) Roof pond
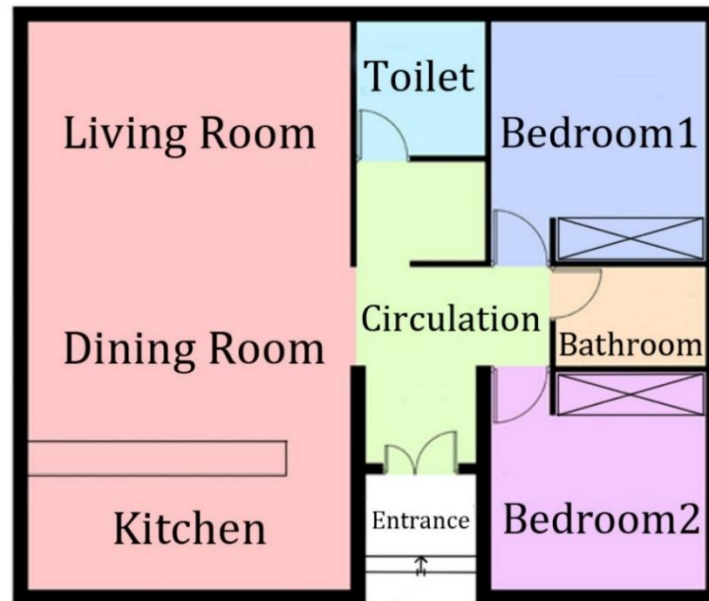3) Wind catcher
4) Underground house

Figure 1. The plan of the house

Table 3 shows the area of the outer surface of the building and the comfort temperature of each room. Due to lack of partitions between living room, dining room and kitchen, these three spaces are considered as a single space.

Table 3. The areas of different surfaces of the house.

Title	Room Temperature (C°)	Walls (m²)				Door (m²)	Window (m²)	Ceiling (m²)
		North	South	East	West			
Living, Dining, Kitchen	21	9.3	9.3	6.0	29.5	-	15.0	63.5
Bedroom 1	21	6.7	-	12.5	-	-	4.5	17.8
Bedroom 2	21	-	6.7	11.3	6.0	-	4.5	16.2
Toilet	21	5.7	-	-	-	-	1	6.1
Bathroom	21	-	-	5.2	-	-	-	5.3
Circulation	21	-	1.9	-	-	3.8	-	15.3

In accordance with common construction practice in Kerman city, this house is assumed to be built by masonry materials. The outer walls of the house are made of two different types: Type A, which is normal wall and its U-value is 1.18 and type B, which use for wet area and its U-value is 1.19(kcal/m²h°C). Given the wide variety in the types of roof ponds applicable to this case study, the overall U-value is calculated via Eq. (2) and Eq. (4) for uncovered ponds without spray with depths of 10 cm and 20cm and a 5cm thick insulation. The U-value of both types of roof ponds is shown In Table 5 [13, 16]. Table 4 shows the U-factors of building envelope.

Table 4. Different layers and total U-value for walls [15, 46, 50, 51].

Building Elements	Layers	U value(kcal/m²h°C)
Wall (Type A)	Cement finishing, mortar cement, adobe, mortar gypsum, gypsum finishing	1.18
Wall (Type B)	Cement finishing, mortar cement, adobe, mortar cement, insulation, ceramic	1.19
Roof	15cm thick brick block with 5cm insulation	2.20
Pond Roof	15cm thick concrete with 5cm insulation and 20cm water pool	1.13
Roof Garden	Concrete slab with 20cm wet soil and Savanna grass	0.48
Window	External wood window – two layer glass (12mm)	2.90
Door	38 mm thick external wood door	3.3

5. Calculation of heat loose for building without passive system
5.1. Calculation of heat loos through building envelope

Eq. (1), areas of exterior surfaces provided in Table 3, and heat transfer coefficient provided in Tables 4 can be used to calculate the amount of energy exchanged by conduction and convection through the outer surfaces of the house. Results of this stage of work are presented in Table 5. According to the results shown in Table 5, the greatest portion of energy is wasted through the roof (2732.4 Kcal / h) and the walls (1300.2 Kcal / h). The total energy lost by convection and conduction through all surfaces is 4983 Kcal / h.

Table 5. Heat loss of the houses, including walls, roofs, doors and windows

Title	ΔT (C°)	Walls (Kcal/h)				Door (Kcal=h)	Window (Kcal/h)	Ceiling (Kcal/h)	Q (Kcal/h)
		North	South	East	West				
Living, Dining, Kitchen	10	109.7	109.7	70.8	348.1	-	495	1397	2530.3
Bedroom 1	10	79.1	-	147.5	-	-	148.5	391.6	766.7
Bedroom 2	10	-	79.1	133.3	70.8	-	148.5	356.4	788.1
Toilet	10	67.8	-	-	-	-	33	134.2	235
Bathroom	10	-	-	61.9	-	-	-	116.6	178.5
Circulation	10	-	22.4	-	-	125.4	-	336.6	484.4
Total	-	256.6	211.2	413.5	418.9	125.4	825	2732.4	4983

5.2. Calculation of heat loose by air penetration

Due to dry and hot climate of Kerman city and the dust in its air, usually windows and doors in most buildings are closed during the day; So the ratio of air penetration into the house interior is assumed to be 2 times per hour. The volume of air penetrated into the house can be obtained via Eq. (9):

$$q_p = 791 \ (m^3/h)$$

Eq. (10) can be used to calculate the total amount of energy lost through air penetration:

$$Q_{air\ penetration} = 2278 \ (\text{Kcal/h})$$

5.3. Total energy loose

The total energy loss of the building equals the sum of energy loss through the building envelope (Table 5) and energy loss caused by air penetration:

$$Q_{total} = 7261 \ (\text{Kcal/h})$$

6. Energy saving and economic evaluation of passive systems

6.1. Energy Consumption

Results of the evaluations conducted on the case study are depicted in Fig. 2, which shows the total amount of energy loss in the underground house and the ground level house with and without passive system in Kcal/ h. As can be seen, the highest energy loss is observed in unmodified ground level house and the lowest is observed in ground level house with the wind catcher.
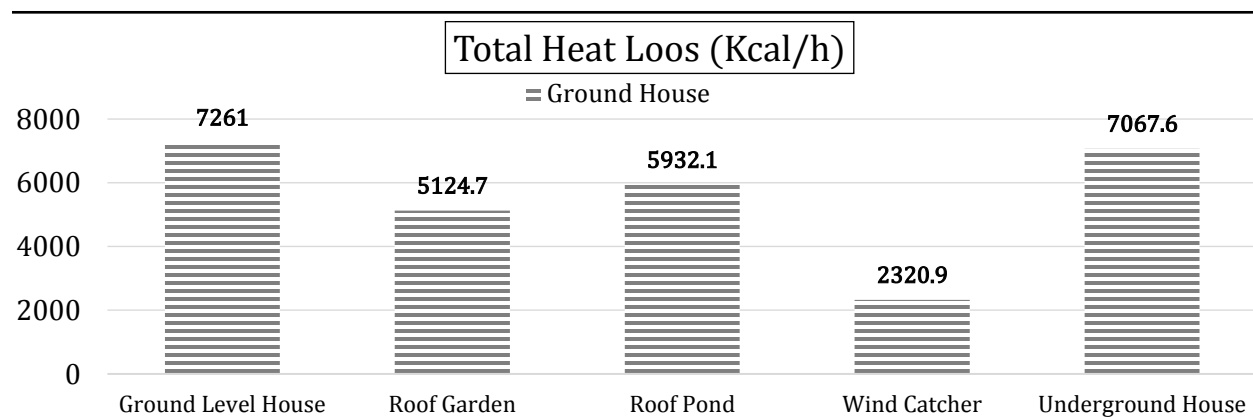

Figure 2. Total amount of heat loss in the underground house and the ground level house with and without passive system

Houses built in Kerman city usually need to be cooled from 15th May to 1st October, which equal a period of 138 days, by an average 14 hours of air-conditioning per day. Table 6 presents daily and annual energy consumption and costs (in Rial and Dollar) for each assessed scenario. Energy cost in Iran is assumed to be 3IRR per kcal/h. As can be seen, the highest annual energy consumption and cost is observed in unmodified ground level house and the lowest is observed in ground level house with the wind catcher.

Table 6. Total energy consumption and cost of ground level house with roof garden, roof pond, wind catcher and underground house

Title	Hours	Days	Energy Loos (Kcal/h)		Annual Cost	
			Daily	Annual	IRR	USD
Ground level house	14	138	101654	1403×10^4	42,090,000	1202.6
Ground Level house with roof garden	14	138	71746	990×10^4	29,700,000	848.6
Ground Level house with roof pond	14	138	83049	1146×10^4	34,380,000	982.3
Ground Level house with wind catcher	14	138	32493	448×10^4	13,440,000	384
Underground house	14	138	98946	1365×10^4	40,950,000	1170

6.2. Energy saving

Table 7 shows the effect of each of the four passive systems on the cooling energy saving (as compared to unmodified ground level house) for 1-year and 20-year periods. As can be seen, the highest energy saving (as compared to unmodified ground level house) is observed in the wind catcher, roof garden, roof pond and underground house scenarios, in that order.

Table 7. Total amount of cooling energy-saving for 1 year and 20 year period

Energy Saving	Underground(Kcal/h)	Roof Garden(Kcal/h)	Roof Pond(Kcal/h)	Wind Catcher(Kcal/h)
Annually	38×10^4	413×10^4	257×10^4	955×10^4
Total (20 years)	760×10^4	8260×10^4	5140×10^4	19100×10^4

6.3 Economic evaluation

6.3.1. Initial Costs of systems

The cost of roof Garden and roof pond should be calculated with respect to the area of the roof (Table 3). The cost of building a roof garden with standard layers, which includes vegetation, growing medium, filter layer, drainage layer and root resistant layer, is 2,500,000IRR (72$) per m^2. It should be noted that this value does not include the primary cost of roofing.

The cost of building an uncovered roof pond without spray, which includes concrete slab, insulation and pond, is 2,500,000IRR ($72) per m^2. Assuming that the cost of a conventional brick roof with basic regular insulation is 2,000,000IRR ($57) per m^2, building a roof pond instead of a conventional roof imposes an additional cost of only 500,000IRR ($15) per m^2.

Due to dryness and low humidity of the air, moisture should be continuously added to the air flowing in through the wind catcher to reduce the air temperature [52]. This can be done by the use of moisturizing system common in evaporative coolers which includes some evaporative pads and a recirculation water pump. The cost of building a wind catcher in Iran is 2,000,000 IRR ($57) per meter. So the cost of building a 6m high wind catcher in is 12,000,000IRR ($345). Moreover, the cost of mentioned moisturizing system, which is about 2,000,000IRR ($57), should be added to the above value.

To calculate the cost of building the underground house, we should estimate the extra cost arising from excavation and insulation of the walls. The extra required volume of excavation is calculated via Eq. (12).

$$M_{soil} = A \times h = 146.2 \ \times 1 = 146.2 \ m^3 \tag{12}$$

In the above equation, M is the total volume of excavation (in m^3), A is the area of the building (in m^2), and h is the height of the wall that is built under the ground surface (in m). The cost of the excavation is 250,000IRR ($7.2) per cubic meter, so the total cost of excavation is 36,550,000IRR ($1045). The cost extra layer of insulation that should

be applied between the walls and the soil is 90,000IRR ($2.6) per square meter, so the total cost of extra insulation is 41,354,200IRR ($1184). Table 8 shows the list of additional costs imposed by each passive system.

6.3.2. Operating costs of systems

Power consumption of recirculation water pump is 56 (w/h); so its power consumption for 14 hour of cooling per day is 784 (w/h) for 1 day, and 108 (kw/h) for 138 days. The price of electricity in the residential sector of Iran in 2015 is 410IRR ($ 0.012) per kWh; so the total cost of power consumed by recirculation water pump in 138 days is 44,280 IRR ($ 1.26). Meanwhile, the amount of water required for evaporative cooling of a house with an area of 150-170 (m^2) is 20 liters per hour; so the total water consumption for 14 hour of cooling per day is 280 (liter) for 1 day, and 38,640 (liter) for 138 days. The price of water in the residential sector of Iran in 2015 is 3,490 IRR($0.1) per cubic meter; so the total cost of water consumed by evaporative cooling process of wind catcher in 138 days is 134,850IRR ($3.9). So overall, the annual operating cost of wind catcher, which is the sum of the costs of electricity and water, is 179,130IRR (5.1$).

Due to semi-arid climate of the region and the type of the soil considered for calculations (wet soil), roof garden need to be watered so that soil could keep its moisture. The average amount of water required for watering lawns is 3 liter per day per square meter. Given the area of the roof (Table 3), watering the roof garden and maintaining soil moisture requires 372.6 *liters* of water per day, which means that for a period of 138 days this process needs 51.5m^3 of water. Price of water is 3,490IRR ($0.1) per cubic meter, so the annual operating cost of green roof (for 138 days of cooling per year) is 179,740IRR ($5.1).

The operating cost of uncovered roof pond without spray equals the costs the water required to fill the pond. This pond had a depth of 0.2 m and an area of 124.2 m^2 , so the total amount of water required fill it is 24.84 (m^3). To prevent pollution and hygiene issues, water of the roof pond needs to be changed every 30 days; so in a period of 138 days, this water needs to be changed 5 times, and therefore the total amount of water required by this system is 124.2 (m^3). As a result, the total cost of water in this scenario is 433,460IRR ($ 12.4). Table 8 shows the operating costs of each system for 138 days.

6.3.3. Maintenance costs of systems

The maintenance cost of roof garden, including the cost of watering and maintenance of soil and plants, is assumed to be 3,000,000IRR ($ 85.7) per year. Meanwhile, the annual maintenance cost of pond roof is assumed to be 500,000IRR ($14.2), and the maintenance cost of wind catcher and its moisturizing system is assumed to be 650,000 IRR ($18.6) per year. Table 8 shows the cost of construction, operation and maintenance of the four assessed passive system for a year and for a period of 20 years. According to Table 8, for an operation period of 20 years, roof garden is the most expensive and wind catcher is the least expensive system.

Table 8. Cost of each passive system (USD)

Title	Underground house	Roof Garden	Roof Pond	Wind Catcher
	USD	USD	USD	USD
Initial	1184	8942	1863	402
Operation (Annually)	-	5.1	12.4	5.1
Maintenance (Annually)	-	85.7	14.2	18.6
Total (20 years)	1184	10758	2395	876

Considering the fact that the impact of each passive system on total construction cost is a key factor in its selection, we must examine the share of each system in total cost of construction. The average construction cost of a ground level house without any passive system and with common materials in Iran is 10,000,000 IRR ($ 286) per square

meter. Given the area of the house, the construction cost of the studied unmodified building is 1,288,200,000IRR ($ 36806). The construction costs of different assessed scenarios are compared in Fig. 3.

As Fig. 3 shows, building a roof garden instead of a conventional roof adds 24.3% to the cost of construction. This value is about 5.1% for pond roof, and about 1.1% for wind catcher. Building the house 1 meter into the ground adds 3.2% to the cost of construction. So overall, roof garden and wind catcher have the most and the least impact on the cost of construction respectively.
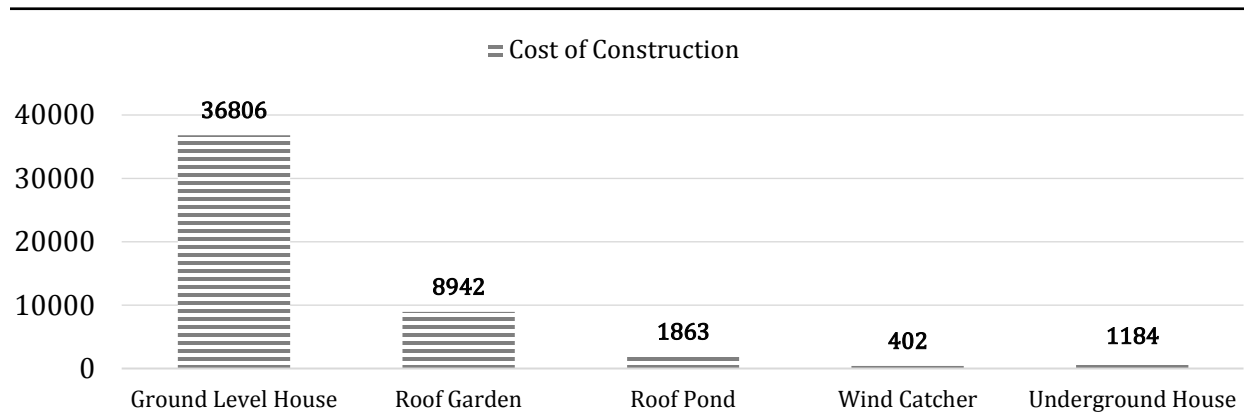

Figure 3. Comparison of ground level house cost with construction cost of roof garden, roof pond wind catcher and underground house

6.3.4. Comparison of systems cost and their energy saving

Fig. 4 shows the cost of energy saved by underground house, roof garden, roof pond and wind catcher over a period of 20 years in comparison with the cost of construction, operation and maintenance of each systems over the same period. It should be noted that all costs are calculated with respect to current prices and sudden changes in prices are not considered.

Having the costs of construction, operation and maintenance of each system over a period of 20 years (Table 8) and the cost energy to be saved by each system over that period (Table 6), we can now evaluate the cost efficiency of each system. According to Fig. 4, for a period of 20 years, the cost of energy saved by pond roof and wind catcher is higher than the total cost of their construction, operation and maintenance, so unlike roof garden and underground house, using these two systems to save energy is economically feasible.
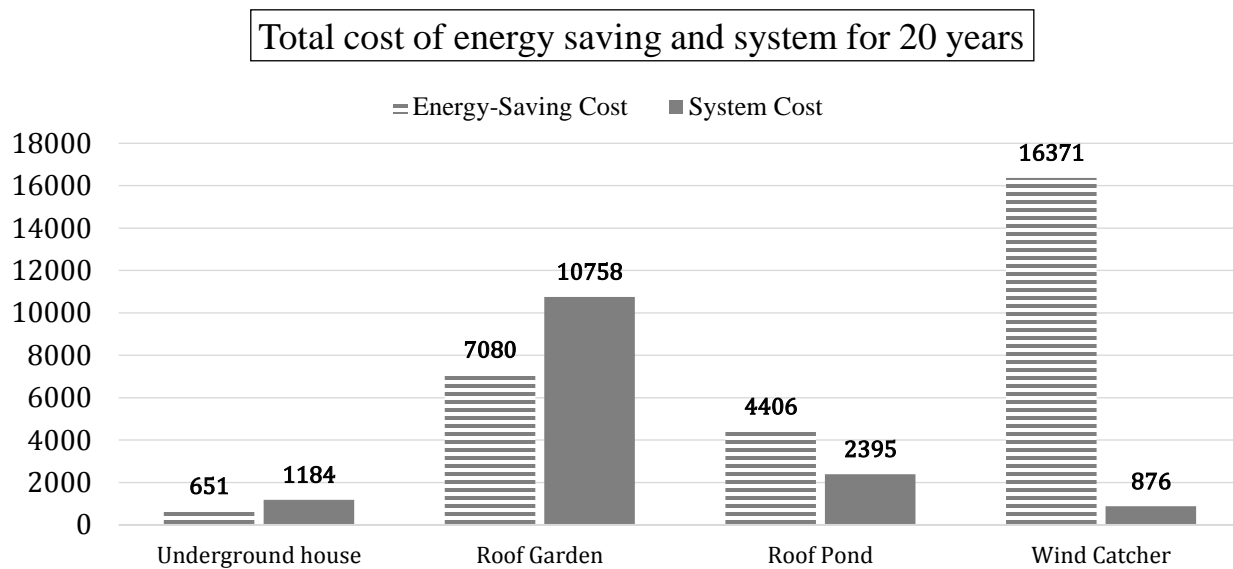
Figure 4. Cost of each passive system and it's energy-saved during 20 years

7. Conclusion

This paper studied about economical evaluation of four passive systems, including roof garden, roof pond, wind catcher and underground house in reducing the energy consumed for the cooling of a house built in Iran's semi-arid region. Results shows, building of roof garden impose 24.3% additional cost. This amount is 5.1% for roof pond, 1.1% for wind catcher and 3.2% for underground buildings. Therefore, building roof garden and wind catcher have the most and the least impact on the cost of construction respectively. Economic analysis shows, for a period of 20 years, the cost of energy saved by pond roof and wind catcher is higher than the total cost of their construction, operation and maintenance, so unlike roof garden and underground house, using these two systems to save energy is completely economical. Results of this study are as follows:

Numerical analysis showed that building the house 1 meter into the ground reduces the total energy lost by 3.9%. Over a period of 20 years, the added cost of construction in this case is 182% more than the cost of saved energy; therefore the use of this method is uneconomical. In addition, green roof reduced the total energy loss through by 29.4%. Over a period of 20 years, the added cost of roof garden is 152% more than the cost of saved energy.

Analysis showed that uncovered pond roof without spray reduced the energy loss of the building. Considering the low cost of construction, operation and maintenance of this type of roof in hot-arid regions the cost of energy saved by this method over a period of 20 years is 184% more than its added costs. This study found that building a wind catcher compensated the energy loss by 68%. Moreover, economic analysis showed that the cost of construction, operation and maintenance of wind catcher is 5.5% of the cost of energy it will save over a period of 20 years. As a result, the use of wind catcher to reduce the cooling load of the building is quite economic.

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