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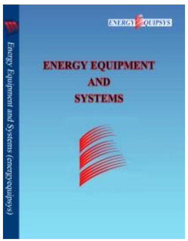

Net zero energy buildings in semi-arid climates: An analysis on 3 case studies in Tehran, Iran

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ABSTRACT

This paper analyzes utilization of renewable energy systems and efficient building envelopes in the semi-arid climate. The proposed model evaluates renewable energy systems solutions as well as economic- and energy-efficient construction materials for the net zero-energy buildings (NZEB) in semi-arid climates. The objective of this paper is to optimize total energy cost and environmental impacts in NZEB. Three real case studies in Tehran, Iran, are used for this analysis. Different potential renewable energy systems, including PV panels, solar thermosiphon systems, geothermal heat pumps, and their combinations, are investigated in two residential buildings and a commercial building. Moreover, analyzing building envelopes using thermodynamic characteristics of building surfaces is done. The results show that the implementation of the proposed model in the buildings in semi-arid climates significantly reduces the negative environmental impacts for both residential and commercial buildings, and also increasing their energy efficiency up to 63% and 38%, respectively.

Keywords: Net Zero Energy Buildings; Renewable Energy; Building Envelope; Energy Efficiency; Environmental Impacts.

1. Introduction

The growing worldwide attention to the energy consumption in the building sector and its effect on the environmental emissions pushes the politicians and researchers to focus on the implementation of green energy systems and efficient building envelopes to achieve higher energy efficiency. Hence, non-renewable energy resources are going to be gradually replaced by the renewable ones. Also, worldwide desire for decentralized power generation increases and the opportunities for smaller and dispatchable power systems become more and more [1]. Design and optimization of net zero-energy buildings are known as effective tools to reduce the energy consumption in the building sector.

Many definitions for net zero-energy buildings (NZEB) exist in the literature [2,3]. Based on what the United States Department of Energy (US-DOE) defined NZEB, it is a residential or commercial building that uses renewable energy systems in order to reduce energy consumptions by making the buildings more efficient [4].

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The biggest energy consumer in Iran is the building sector, accounting for about 40% of total energy usage, with the majority of this taking place in the residential and institutional buildings. Therefore, implementation of renewable energy resources as well as minimizing energy losses, should be considered to achieve more sustainable and efficient buildings. Iran is a country with a considerable rate of solar radiation, and using solar applications in the buildings is an effective way to reduce energy consumption. Tehran, as a metropolitan and the capital city of Iran, has numerous huge buildings in which a significant amount of energy is being wasted. Therefore, using efficient and greener energy systems can lead to effective solutions for sustainable and smart cities and communities [5]. Also, decreasing the building energy consumption, especially in the Heating, Ventilation, and Air Conditioning (HVAC) section, is one of the most important steps in lessening the total energy demand of the building sector [6]. Many energy-saving strategies such as energy bill management, peak shaving, and load shifting can be taken into account by utilization of optimal control of building HVAC systems [7].

Energy efficient buildings are capable of reducing carbon emission by 50% [8], which is a great achievement. The energy consumers in residential buildings can be divided into space heating (54%) [9], electricity for appliances and lighting (14.1%), and hot water production (13.6%) [10]. Various renewable solutions can be useful to reduce building energy consumption. These systems include PV panels for generating electric power, geothermal heat pumps for cooling and heating, and solar thermal systems for space or water heating [11]. Moreover, using low thermal transmittance materials for building envelope can enhance the thermal efficiency of a building significantly [12]. However, as the financial limitation is a determinative factor in the selection of materials and systems in buildings, it is necessary to make a trade-off between energy saving and corresponding expenses.

The aim of this paper is to evaluate the use of different renewable systems in residential and commercial buildings to improve their energy efficiency. Also, building envelopes are analyzed using their thermodynamic characteristics. The calculations of energy consumption in buildings as well as drawing the plan of each building is done using the EnergyPlus software. Solar systems are investigated and evaluated with TRNSYS software. Total cost optimization and analysis of building envelope and renewable energy systems are performed using a mixed-integer linear programming (MILP) model in MATLAB. The focus will be on installing PV panels, geothermal heat pumps, and solar thermal systems as renewable solutions as well as efficient construction materials for external and internal walls, roofs, and windows as building envelopes to identify their impact on energy efficiency, utility expenses and CO_2 emissions. In this regard, three different buildings will be investigated, including two residential apartments with different energy consumptions, and a shopping mall as a commercial building.

2. Methodology

For this analysis, we study different renewable solutions and building envelopes on our case studies. The investigated renewable energy systems include PV panels, ground source heat pumps, and thermosiphon solar water heater. The implementation of each renewable system individually and in hybrid forms (the combination of those systems) are studied. Moreover, the efficient materials for walls and windows are found based on their ability to maintain thermal energy for a longer period at the lowest cost.

To calculate the amount of carbon dioxide emissions, it is essential to identify the main electricity resources for the buildings of Tehran. Iran is the second largest provider and supplier of natural gas in the world, and almost all electricity generation is provided by natural gas-fed power plants. Considering the results and based on both technological and economic aspects, the most efficient renewable energy systems and construction materials for each building are chosen.

2.1. Modeling of renewable energy systems

2.1.1. Solar thermosiphon system

One of the most efficient systems satisfying hot water demand in the buildings is the solar thermosiphon system in which the heat is transferred to the water through a collector. A typical solar thermosiphon system includes three main parts: a solar collector, heat pipes, and a holding tank.

To calculate the sufficient area of the collector, and the volume of the tank, the hot water demand of the building is needed. The sum of total heat demand accounting for hot water and heat losses must be divided by the heat generated by one square meter of the collector. Each flat-plate collector unit has an area of $3.5m^2$, an inclination of 400, and a tank with the volume of $0.4\ m^3$. The proposed solar thermosiphon system generates 3,124 kJ of energy, with a price of 4,322 USD per unit. Note that each typical Iranian family with four or five members uses about 260 liters of hot water each month [13]. Hot water load can be calculated using

$$P_{hw} = 12\ V\ C_p \rho\ \Delta\theta \tag{1}$$

where V is the average monthly hot water usage (m3), ρ is the water density (kg/m3), C_p represents the specific heat of water, which is 4.187 (kJ/kg.K), and $\Delta\theta$ is the difference between the input water temperature (15°C) and the output water temperature (60°C). The number of these systems for each case study is found by dividing the hot water load by the heat generated by a solar water heater system.

In order to compute the carbon dioxide emissions produced by these alternative energy systems, the produced heat by each energy system should be converted into the oil barrels. Considering energy conversion coefficients, each kJ of energy is equal to 163*10-9 oil barrel, and an oil barrel generates 10.65 kg of carbon dioxide.

2.1.2. PV panels

The best choice for providing electricity in the buildings by renewable energy systems is utilization of photovoltaic panels. Availability, reasonable price, and high efficiency are among the most recognized features of PV panels. The daily average electricity consumption must be used in order to account for the change in seasons. The following steps should be taken to find the appropriate number of PV panels:

1. Calculation of the daily average electricity consumption based on utility bills.
2. Calculation of the system size by using

$$P_{PV} = \frac{E_{ave}}{E_p\ \eta} \tag{2}$$

where E_{ave} is the daily average electricity consumption, E_p represents the location's average peak sun-hours per day, and η corresponds to the inverter efficiency [8].

3. Estimating the number of PV panels by dividing system size by the watt rating of each module.

Each selected PV module in the present work provides 200 W of electricity with a total efficiency of 14% and inverter efficiency equal to 95%.

2.1.3. Geothermal heat pump

To calculate the sufficient capacity for the geothermal energy system, all heat losses by conduction and convection heat transfer should be considered. After that, the generated heat should be calculated by knowing the local geothermal parameters. Finally, the net heat capacity of the ground heat pump is calculated by subtracting the produced heat from the heat losses. The heating (or cooling) load from this heat pump can be modeled by

$$P_{gp} = UA\Delta T_{lm} \tag{3}$$

where P_{gp} is the total load from the heat pump, U is the overall heat transfer coefficient (W/m^{2}K), A is pipe surface area and ΔT_{lm} is the log mean temperature difference.

2.2. Heat transfer analysis of building surfaces

The primary motivation to find the best construction materials is their potential in maintaining the heat and lowering the temperature fluctuations. By calculating the overall heat transfer coefficients, the most thermally efficient materials can be chosen. The overall heat transfer coefficient is found by

$$\frac{1}{UA}=\frac{1}{h_1A_1}+\frac{t_1}{k_1A_f}+\frac{t_2}{k_2A_f}+\frac{t_3}{k_3A_f}+\frac{1}{h_2A_2} \qquad (4)$$

where U is the overall heat transfer coefficient (W/m^{2}K), A_f represents the fluid contact area at each side (m^2), k corresponds to the thermal conductivity of the material (W/mK), h is the individual convection heat transfer coefficient for each fluid (W/m^{2}K), and t is regarded as the wall thickness (m). The amount of heat transferred through the surfaces can be calculated as a function of the overall heat transfer coefficient as

$$Q_s = UA\Delta\theta \qquad (5)$$

where Q is the heat transfer (W), A represents the effective area (m^2), and $\Delta\theta$ is the temperature difference between two sides of the surface.

2.3. Optimization model

The proposed MILP model in this analysis is given as

$$\min\left\{\kappa G+\sum_{i=1}^{n}((c_i-k_i)\,P_i)+\sum_{j=1}^{m}(c_jQ_j)\right\} \qquad (6)$$

In this equation, κ is the cost of imported electricity from the grid, G is the amount of imported electricity, c_i is the unit cost of energy production for each renewable technology, k_i is the unit cost of carbon emission, P_i is the power generation from renewables, c_j is the unit cost of energy for new materials for the building surfaces, Q_j is the transferred heat to building surfaces.

3. Case studies

To investigate utilization of alternative energy systems in buildings and to make comparison between the construction materials, three different buildings in Tehran with the latitude of 35.70N, longitude of 51.40E and altitude of 1,191 m are considered including two different residential buildings with different architectures and living areas and a shopping mall with four floors.

Architecture

In the present work, three different buildings are considered: an 84m^2 (12m*7m) residential house with two bedrooms, a 162m^2 (18m*9m) residential house with four bedrooms, and a shopping mall as a commercial building which includes four 3072m^2 (96m*32m) floors. Different materials for walls, windows, roofs, doors, etc. are investigated for each building. One of the most important decision-making parameters in choosing buildings construction materials is the overall heat transfer coefficient. Buildings with higher heat transfer coefficients (U) are capable of keeping the energy for a longer period to improve overall energy efficiency.

Electricity, heating and cooling demands

The energy consumption of each building is monitored, and the obtained heating and cooling demands of each case for the year 2017 are presented in Table 1. Moreover, Figure 1 to Figure 3 depicts the energy consumption in all case studies for each month. It is worth mentioning that the highest consumption is about 11, 14 and 1120 kWh/day for case studies 1, 2 and 3, respectively.

Table 1. Annual heating and cooling demands for each case study

	Heating Load (kW)	Cooling Load (kW)
Case Study 1	4.33	8.59
Case Study 2	6.85	10.94
Case Study 3	605.13	972.45

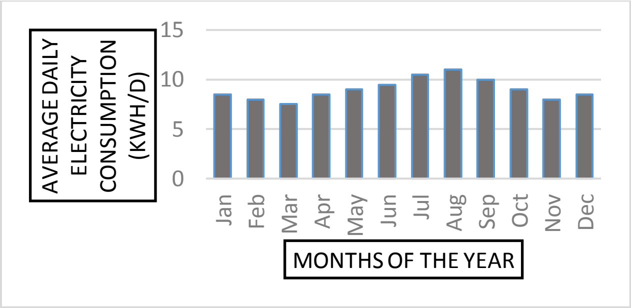

Fig. 1. Electricity consumption for different months in case study 1

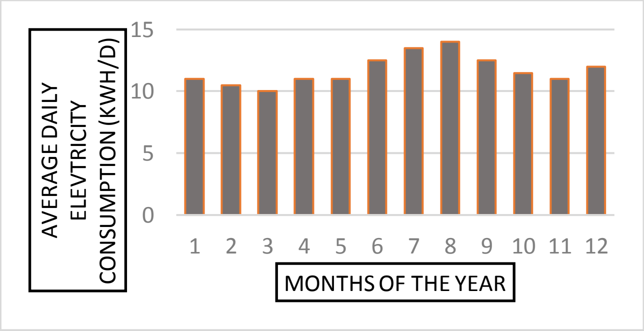

Fig. 2. Electricity consumption for different months in case study 2

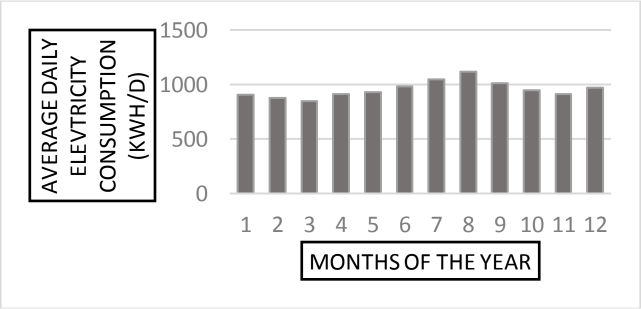

Fig. 3. Electricity consumption for different months in case study 3

Figure 4 shows electricity usage distributions for two residential and one commercial buildings. Heating or cooling and electrical devices are the sections which consume the most amount of electricity in two residential buildings. On the other hand, Fig. 4 B clears that the heating and lightening load utilizes the biggest part of the supplied electricity in the commercial building.

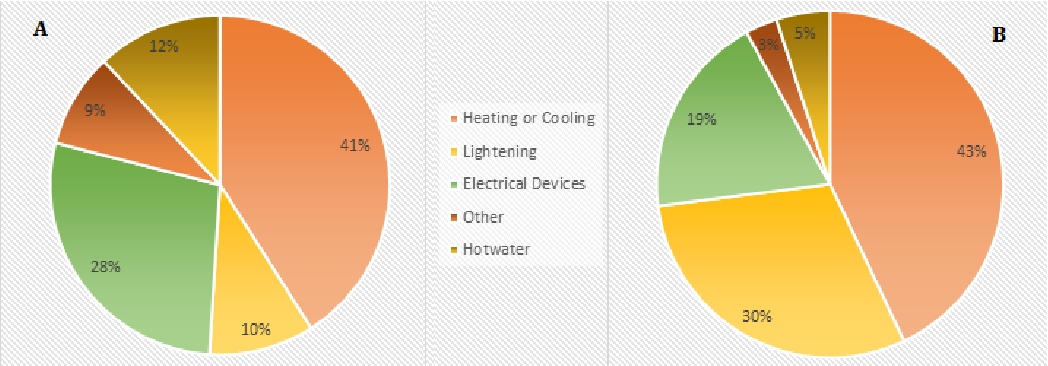

Fig. 4. A) Distribution of the energy usage in the first and second case study, B) Distribution of the energy usage in the third case study

4. Results

Based on the utility bills, the electricity consumption of the first building is 2480 kWh, consuming 1240 m^3 natural gas annually. After finding a required power of heat pump, various geothermal heat pumps of Career Company are considered, and the ones with the closest capacity to our results were chosen. To provide the required heat capacity for the first residential building, the model GZ was selected. This heat pump has a cooling capacity between 2 to 6 tons and a heating capacity between 25000 to 76000 kJ/h. Note that each GHP system in table 2 provides a unit of the Career GZ model.

Also, the electricity consumption of the second case is 4532 kWh/year with the natural gas consumption of $2260m^3$. The commercial building also consumes a considerable amount of energy to provide its needs; hence, utilization of renewable energy systems might result in a considerable energy saving. In 2017, the electricity consumption of the commercial building was 5,924,373 kWh (5.92 GWh), and $624{,}144m^3$ of natural gas was used to satisfy the energy demands of this building. In order to study the effects of simultaneous implementation of renewable energy systems, different systems, including individual renewable systems and their combinations, are studied, and the results are presented in Table 2.

According to the heat transfer analysis of surface materials of each building, and the proposed optimization model, the optimal construction materials for the surface of each case study are as follows in Table 3 and 4.

Table 2. Summary of different individual and hybrid renewable energy systems for each case study

Renewable Systems	Case Study 1	Case Study 2	Case Study 3
PV Panels	18 PV	32 PV	146 PV
Ground Heat Pump	1 GHP	1 GHP	15 GHP
Solar Thermosiphon	1 STS	2 STS	25 STS
Hybrid System 1	1 STS+ 14 PV	2 STS+ 22 PV	25 STS+ 125 PV
Hybrid System 2	1 GHP+ 10 PV	1 GHP + 12PV	10 GHP+ 85 PV
Hybrid System 3	1 GHP + 1 STS	1 GHP + 2STS	10 GHP+ 20 STS
Hybrid System 4	1 GHP +1 STS + 10 PV	1 GHP+2 STS +12 PV	8 GHP+20 STS +80 PV

Table 3. The construction materials for the residential buildings

Elements of Buildings	Materials Description	U (W/m^2K)
External Walls	120 mm polyurethane, 120 mm glass wool, 15 mm plaster	0.161
Internal Walls	40 mm glass wool, 15 mm plaster	0.958
Roof Construction	120 mm polyurethane, 120 mm glass wool	0.091
Doors	2 inches wood	2.435
Glazing Construction	Double insulating glass	1.512

Table 4. The construction materials for the shopping mall

Elements of Buildings	Materials Description	U (W/m^2K)
External Walls	130 mm polyurethane, 130 mm glass wool, 20 mm plaster	0.143
Internal Walls	30 mm glass wool, 10 mm plaster	0.989
Roof Construction	140 mm polyurethane, 160 mm glass wool	0.079
Doors	2 inches wood	2.435
Glazing Construction	Double insulating glass	1.512

The results of applying the introduced alternative energy systems to each case study are presented in Table 5. One should note that two numbers are being presented in each cell, which correspond to the implementation of new systems without and with considering efficient construction materials, respectively. According to Table 5, utilization of the proposed alternative energy systems dramatically reduces carbon dioxide emissions. This effect is even more noticeable when applying efficient construction materials to the case studies. Fig. 5 illustrates a helpful picture regarding the effect of using the proposed alternative energy systems in the buildings. By utilization of PV panels in residential buildings, all electricity demand can be satisfied. The first two combination systems can supply more than 70% of the total load for the residential buildings. Furthermore, by implementation of the fourth combination system, the energy efficiency increases up to 63% and 38% for the residential and commercial cases, respectively.

Table 5. Results of implementation of renewable energy systems and efficient materials in case studies (the first number illustrates the effect of renewables with new building envelopes and the second one shows the implementation of renewables on the old building envelope)

	Case Study 1	**Case Study 2**	**Case Study 3**
Environmental Emissions (kgCO_2)			
PV Panels	1444 – 1298	2067 – 1846	17712 – 13433
Ground Heat Pump	2670 – 2509	2670 – 2394	36752 – 29875
Solar Thermosiphon	1026 – 938	1851 – 1637	15526 – 13687
Hybrid System 1	2048 – 1892	2516 – 2310	42183 – 38969
Hybrid System 2	3491 – 3264	3622 – 3394	48868 – 43601
Hybrid System 3	3608 – 3394	3852 – 3609	55934 – 48237
Hybrid System 4	3867 – 3607	4329 – 4164	68348 – 61042
Total Cost (USD)			
PV Panels	23796 – 30928	42304 – 52630	193012 – 327412
Ground Heat Pump	26500 – 33632	26500 – 36826	397500 – 531900
Solar Thermosiphon	4322 – 11454	8644 – 18970	86440 – 220840
Hybrid System 1	24830 – 31962	45686 – 56012	226312 – 360712
Hybrid System 2	39720 – 46852	58296 – 68622	523964 – 658364
Hybrid System 3	30822 – 37954	47144 – 57470	462660 – 597060
Hybrid System 4	43296 – 50428	61008 – 71334	637352 – 771752

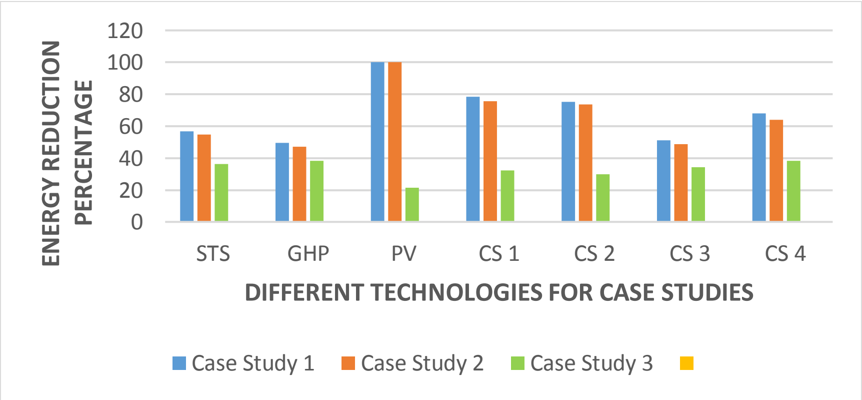

Fig. 5. Effects of using alternative systems and materials on the building energy consumption

The amount of reduction in environmental emissions resulted from utilization of the alternative systems is presented in Fig. 6. The solar thermosiphon system is the first choice to reduce environmental emissions. Utilization of the solar thermosyphon system decreases the carbon dioxide emissions to less than 20% of its initial value. Comparing combination systems, it is found that the first hybrid system is the most useful one regarding CO_2 emission reduction.

Fig.7 and Fig. 8 represent the cost of utilization of alternative energy systems in case studies 1 and 2 with and without applying new construction materials, respectively. It can be seen that the solar thermosiphon system is the cheapest option. Moreover, implementation of the first hybrid system, which includes a solar water heater system and PV panels, is an economical choice.

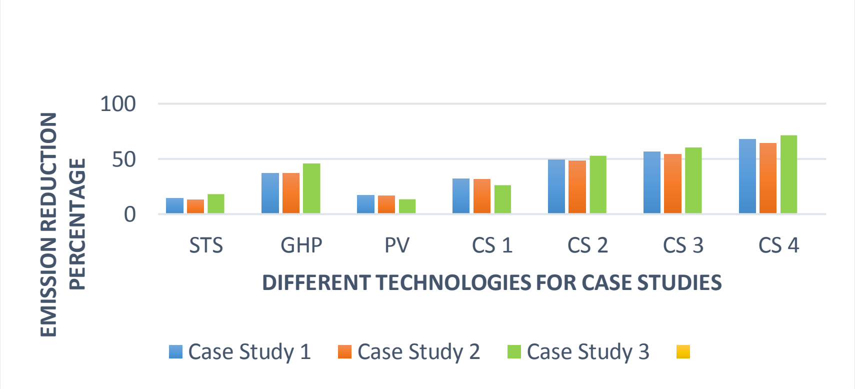

Fig. 6. Effects of using alternative systems and materials on environmental emissions

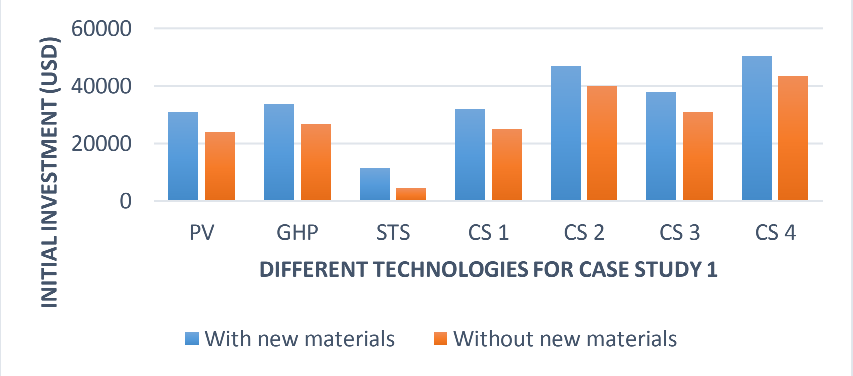

Fig. 7. Total cost of applying different energy systems with and without implementation of new materials for case study 1

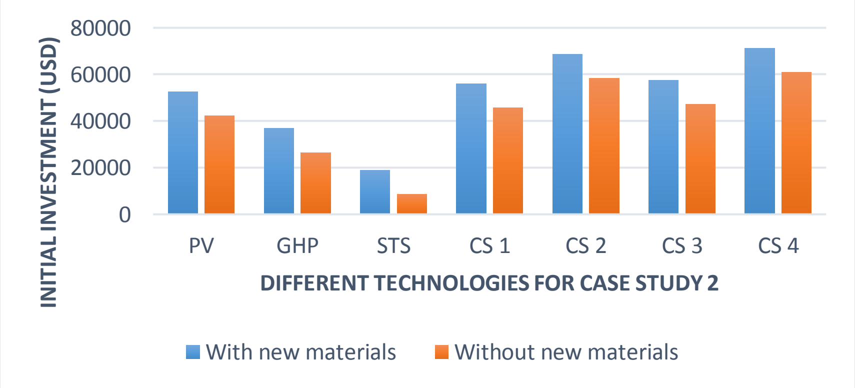

Fig. 8. Total cost of applying alternative systems with and without implementation of new materials for case study2

According to Fig. 9, the most suitable technologies are solar water heater systems, and PV panels as geothermal systems cost so much, especially in a shopping mall for which a significant number of units must be used. Generally, commercial buildings need a substantial initial investment to implement new alternative energy systems. As depicted in Fig. 9, applying solar thermosiphon systems to the shopping mall with and without new construction materials requires notable funding of 86440 USD and 134400 USD, respectively. Applying the last combination system as well as new construction materials for the commercial case commands a price of 771752 USD, which may not be affordable for some private sectors.

5. Conclusion

The following results are obtained from our simulations and analyses of applying different energy systems and construction materials to the semi-arid climate buildings:

- By using PV panels, residential buildings can consume electricity without the need for the electricity grid.
- Solar thermosiphon systems are appropriate options for providing hot water in residential buildings, releasing the least amount of carbon dioxide at a reasonable price of 4322 USD per each unit.
- Implementation of new construction materials for residential buildings is an effective and almost inexpensive way to reduce energy losses and environmental emissions. Applying alternative materials to the selected buildings costs 7132 USD, 10326 USD, and 134400 USD, and reduces carbon dioxide emission up to 100 kg, 200 kg, and 5000 kg per annum for each case study, respectively.
- The ground source heat pump can provide about half of the total building energy demand for cooling and heating while reducing CO_2 emissions up to more than 50%.
- The initial investment of applying new energy systems and construction materials for residential buildings is affordable and economical while the procedure is relatively expensive for commercial buildings; however, considering the corresponding environmental and technical advantages, implementation of the proposed systems can be regarded as "economic" on a long-term basis.

Future research works can consider newer renewable energy systems and materials to improve building energy efficiency even more. An analysis of two-phase fluids in the heat exchangers also could be helpful to increase the efficiency of entire HVAC systems and reduce the environmental impacts [14]. Also, CHP systems can be considered for buildings since they provide power and thermal energy from the same fuel source [15]. In addition to all mentioned materials and systems, advanced demand-side management methods could also be investigated in the semi-arid climate buildings to reduce peak demand and total energy consumption [16]. The return of the initial investment is another important factor which can also be calculated to facilitate the decision-making process.

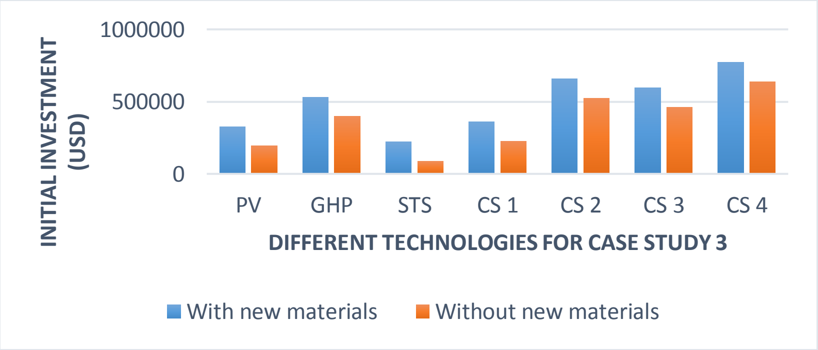

Fig. 9. Total cost of applying alternative systems with and without implementation of new materials for case study3

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