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Research article

A sustainable mathematical model for design of net zero energy buildings

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ABSTRACT

Energy is vital recourse for economic development of today's business. The services demanded of residential and commercial buildings require substantial energy use. Energy consumption in this sector has been growing in total, gradually. As a result the high emission of greenhouse gases is released and, hence, the saving energy with better building management have made a major priority of the energy and environment sectors throughout the world. In this direction, to reduce energy consumption and mitigate environmental impacts in buildings, net-zero energy buildings (NZEB) is a very effective solution. As a result, a multi-objective model is developed to identify the best combination of materials and construction options considering their related costs, energy efficiency, and environmental impacts of buildings, simultaneously. This sustainable model is presented to construct a building considering the construction costs and energy consumption of the design options. To design the NZEB, while minimizing costs and carbon emissions, use has been made of a combination of different types of active/heating and cooling systems and renewable equipment through such high-efficiency, effective, and updated technologies as the solar panel. Finally, the case study of a residential building with two scenarios is used to demonstrate the proposed framework. The results show that, for scenarios1 and 2 respectively using insulation thickness such as (wall, roof, and windows) and renewable equipment have the highest sustainable impact in NEBZ's performance.

Practical application

To design net-zero energy buildings, this paper presents an optimization model to decide on the building retrofitting method and selecting materials (ceilings, walls, and windows), installations, and the solar cell system considering the failure rate and life cycle of each facility during the building life cycle. The model calculates the total energy consumption costs and the total CO_2 emissions of the central heating system during the building lifecycle is considered. The real data of case study is analyzed to validate the model's efficiency in order to design net-zero energy buildings.

1. Introduction

The energy sector is facing many challenges expected to worsen in the near future. The International Energy Agency (IEA) has reported that the recent behavior of the energy sector and carbon emissions have caused great concerns in such areas as the environment, energy security, and economic growth [1]. With their long life cycles, buildings have a great share in the global energy consumption and warming due to their greenhouse gas emissions requiring relevant measures in this area [2, 3, 4, 5, 6, 7]. About 30% of the CO_2 emissions are due to the energy consumption in buildings [3, 8] while about 6% of the total emitted pollutants are because of the households' fuel consumptions; hence, a reduction in buildings' environmental impacts can lead to significant environmental benefits [9]; however, appropriate methods to achieve this reduction are almost unknown. Building retrofitting and using efficient renewable energy systems can reduce the energy consumption demand in buildings, greenhouse gas emissions, and the related required investments [10, 11]. Controlling the buildings' in-and-out airflows and insulation of the windows, walls, and ceilings to reduce the energy consumption demand, can increase the heat efficiency and comfort because buildings that use insulated materials store more energy than usual. On the other hand, using appropriate heating, cooling, hot water, energy, and lighting systems and equipment in buildings can also reduce the future energy demand [12, 13]. Building retrofitting can improve

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energy efficiency through lowering maintenance costs, gas emissions, creating job opportunities, and enhancing health [8, 9, 10, 11, 12, 14, 15]. Therefore, through expanding technology, transforming and storing thermal pumps, combining heat-power systems, and using renewable energy resources with solar, wind, geothermal, and biomass technologies, it is possible to achieve a sustainable future [11]. Since these facilities are quite costly, it is necessary to appropriately balance the costs, environmental performance, and the heat load. The life cycle cost (LCC), a benchmark that sums up all the building costs in a given time period, can be used to calculate the economic benefits of the energy resources over the useful lifespan of a building [17]. On the other hand, integrity of buildings can be considered as a multi-criteria decision-making problem wherein the optimal objectives can include the environmental effects, costs, and so on [21]. Marzouk [18] has proposed a GA-based sustainable model to implement a Life-Cycle Cost (LCC) to select the optimum building materials in Egypt. Using combined external-combustion and insulation thermal systems as two parameters, Schwartz [15] has addressed the optimization of a building for costs and greenhouse gas emissions considering renewable energy in its construction. Ulubeyli [16] has performed a study on the macro-environmental through PESTLE (political, economic, social, technical, legal, and environmental) framework to find an optimized green building industry in Turkey. Aiming at reducing the CO_2 emissions and investment costs for a two-story building and using the HVAC system, Hamdy [19] has proposed a revised GA-based multi-objective optimization model that combines the climate and energy conditions with IDA environmental simulation software, and has reduced the CO_2 emissions by 32% and investment costs by 26% compared to the base design. Ascions [20], too, has optimized the initial costs and energy of a building by a GA-based algorithm to retrofit complex buildings considering heating-cooling systems. Fesanghari [21] has presented an SA-based multi-objective optimization model to design an energy-efficient residential complex with low pollution emissions that reduces the life alert cost (LAC) and greenhouse gas (CO_2) emissions. Penna [22] has performed a study on the primary energy, cost, and thermal comfort increase without a change in the initial energy in the climate conditions for an optimized building retrofitting in Italy that shows that the near net zero thermal comfort is achieved in an increased warm weather. Asdai et al. [23] have proposed a multi-objective building-retrofitting model that simultaneously reduces energy consumption and overall costs through different strategies including the installation of several window types and using various insulating materials, walls, ceilings, and solar panels. Anttipov [24] has used the MILP model to optimize buildings with environmental and economic parameters including windows and solar panels that reduce environmental impacts. Schutz [25] has used the MILP and epsilon constraint optimization modeling of the residential building retrofitting to reduce costs and greenhouse gas emissions. Kumar Pal [26] has developed a multi-objective model to optimize life cycle energy (LCE) and life cycle cost (LCC) of building materials in the Finland.

A review of the literature shows that various papers have studied energy consumption, energy savings, and CO_2 emissions that directly affect the thermal comfort of the life alert cost (LAC) through the optimization of the building retrofitting. Based on the LCC, the main building cost components include construction, maintenance, performance, replacement, cleaning, energy, renovation, tax, and disposal [27, 28, 29]. While different studies address the building retrofitting optimization with different objectives, the selection process of specific objectives is not clear so far. However, all of the earlier models have used at least one economic aspect (investment costs, energy costs, etc.) to find the optimum retrofitting strategy. The effort has been made in this study to precisely address the investment and future energy costs and the amount of CO_2 emitted during the NZEB design lifespan.

This paper's contributions can be summarized as follows: 1) presenting an optimization model to decide on the NZEB design method and selecting materials (ceilings, walls, and windows), installations, and the solar panel system considering the failure rate and life cycle of each facility during the NZEB lifespan, 2) calculating the total energy consumption costs of the central heating system considering the inflation rate and the energy price increase during the NZEB lifespan, 3) considering the total CO_2 emitted from the central heating and cooling systems during the NZEB lifespan, 4) using the $\varepsilon-$ constraint method to consider the multi-objective model's MILP and optimization simultaneously, 5) linearizing the problem's real constraints, and 6) using the real data of a case study to validate the model.

This paper has been so organized as follows: the problem scope and the methodology are stated in Section 2. The results of the model implementation in the case study and analyses of different scenarios are presented in Section 3, and, finally, the conclusions and suggestions for the future research are discussed in Section 4.

2. Problem statement

This paper has used a multi-objective optimization model for the act of national building regulations (NBR) LCC and its lifespan CO_2 emissions considering proper decision variables, objective functions, constraints, scenarios, and solution methods in Iran. Decision variables (proper materials for the roof, walls, windows, and central heating and cooling systems) are defined by a binary (0, 1) system and Pareto solutions are suggested to the multi-objective using of the epsilon constraint method considering the existing constraints, different scenarios, and problem relations. Figure 1 shows the phases in the proposed near-zero energy building (NZEB) optimization model. The first phase defines the important criteria for determining NZEB design. The second phase formulates energy consumption and LCC of the NZEB to calculate the economy and CO_2 emission due to selection of materials, cooling and heating equipment. The third phase develops an optimization approach to design NZEB in order to minimize LCC and maximize the environmental performance of the NZEB.

2.1. Decision variables

Decision variables involve all of the measures required to complete the building and all of the complementary measures. The former includes the ceiling, windows, external walls, and the latter consists of the installation and initiation of the solar panel and the central heating and cooling systems.

The alternative decision variables are 1) type of the window used in the building *i*: 1,2,……,I 2) type of the material used in the roof *j:1,2,……,J,* 3) type of the material used in the surrounding wall *k:1,2,……,K,* 4) type of the cooling system *r:1,2,……, R,* 5) type of heating system *n:1,2,……, N, 6)* type of the solar panel *q:1,2,……, Q.*

It is assumed, for simplicity, that only one design scenario is considered from indices I type of windows (characterized by T_I insulation thicknesses), J type of material for the roof (characterized by T_J insulation thicknesses), K type of material for the surrounding wall (characterized by T_K insulation thicknesses), R type of the cooling system, and Q type of the solar panel to complete the NZEB. It is also assumed that only one installation scenario is considered from indices N types of the heating system, Q type of the solar panel, can (or may not at all) be used to complete the NZEB. So, $I^{T_I} \times J^{T_J} \times K^{T_K} \times N \times R \times Q$ Boolean variables are involved in the evaluation of LCC and ACC.

Binary variable $z^{win}_{iT_I}$ is equal to 1 if window i is used with insulation thickness T_I; otherwise, it is 0. Binary variable $z^{roof}_{jT_J}$ is equal to 1 if roof material j is used with insulation thickness T_J; otherwise, it is 0. Binary variable $z^{wal}_{kT_K}$ is equal to 1 if wall material k is used with insulation thickness T_K; otherwise, it is 0. Binary variable, z^{heat}_{n} is equal to 1 if heating system n is used; otherwise, it is 0. Binary variable z^{sc}_{q} is equal to 1

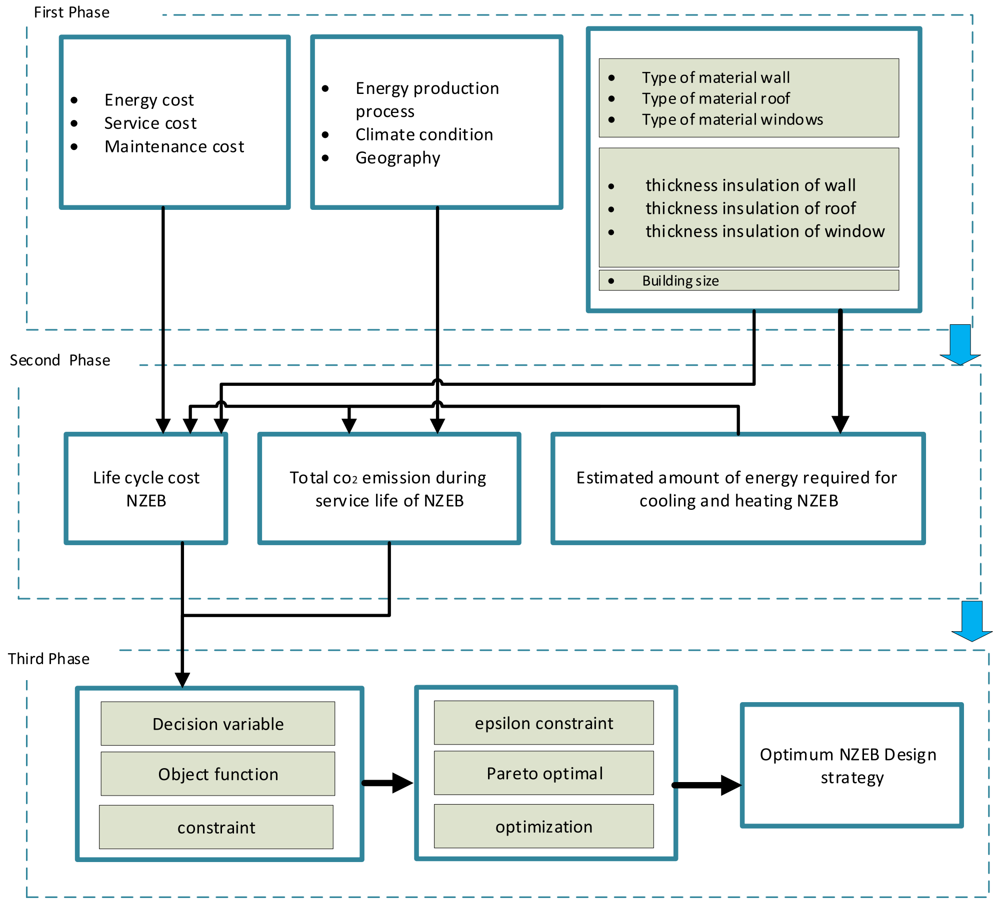

Figure 1. The structure of the proposed approach.

if solar panel q is used; otherwise, it is 0. Binary variable z_r^{cool} is equal to 1 if cooling system R is used; otherwise, it is 0.

2.2. Calculating the objective function of costs

Problem parameters

$cost_{iT_I}^{win}$ Price of the window type i characterized by T_I insulation thickness (Dollar/m^2)

$cost_{kT_K}^{wall}$ Price of the wall material type k characterized by T_K insulation thickness (Dollar/m^2)

$cost_{jT_J}^{roof}$ Price of the roof material type j characterized by T_J insulation thickness (Dollar/m^2)

$cost_n^{heat}$ Price of heating system type n (Dollar)

$cost_q^{sc}$ Price of solar panel type q (Dollar/m^2)

$cost_r^{cool}$ Price of cooling system type r (Dollar)

$cost_{N_{mn}}^{EL}$ Electricity price in the month N_{mn} (Dollar/kWh)

$cost_{N_{mn}}^{GN}$ Natural gas price in the month N_{mn} (Dollar/m^3)

$cost_{N^{\cdot}_{mn}}^{EL}$ Electricity price in the month $N^{\cdot}_{mn}$ (Dollar/kWh)

$cost_{N^{\cdot}_{mn}}^{GN}$ Natural gas price in the month $N^{\cdot}_{mn}$(Dollar/m^3)

$U_{iT_I}^{win}$ Thermal transmittance of window type i with the insulation thickness type $T_I(W/m^{2\circ}C)$

$CG_r^{N^{\cdot}_{mn}}$ Natural gas consumption per unit MJ for cooling system type r in the month $N^{\cdot}_{mn}$ (m^3)

$CG_n^{N_{mn}}$ Natural gas consumption per unit MJ for heating system type n in the month N_{mn} (m^3)

$CE_n^{N_{mn}}$ Electricity consumption per unit MJ for heating system type n in the month N_{mn} (kWh)

$CE_r^{N^{\cdot}_{mn}}$ Electricity consumption per unit MJ for cooling system type r in the month $N^{\cdot}_{mn}$ (kWh)

$\theta_{N_{mn}}^E$ Average temperature outside the building in month N_{mn} (°C)

θ_{LC} Building design temperature in cold season (°C)

θ_{IH} Building design temperature in heat season (°C)

N_{mn} Number of months the heating system is needed

$N^{\cdot}_{mn}$ Number of months the cooling system is needed

N^{sc}Number of the select solar panel to be installed in the building

d_{T_I}thickness of the windows type T_I(m)

d'_{T_K}thickness of the wall insulation T_K(m)

d''_{T_J}thickness of the roof insulation T_J(m)

cservice life of the building

(continued on next column)

(continued)

$I_{N_{mn}}^{win}$ The average intensity of solar radiation in the month $N_{mn}(W/m^2)$

$I_{N^{\cdot}_{mn}}^{win}$ The average intensity of solar radiation in the month $N^{\cdot}_{mn}(W/m^2)$

$\theta_{N_{mn}}^E$ The average temperature outside the building in the month N_{mn}(°C)

cop_n Performance coefficient of heating system type n (%)

cop_r Performance coefficient of cooling system type r (%)

d_k^{wall} thickness of the wall k (m)

g_{iT_I} Solar radiation absorption coefficient

$K_{jT_J}^{roof}$Thermal conductivity of roof type j with insulation thickness type $T_J(W/mK)$

$K_{kT_K}^{wall}$Thermal conductivity of wall type k with insulation thickness $T_K(W/mK)$

η_q^{sc} Efficiency of solar panel type q

Problem variables

$Q_{N_{mn}}^{heat}$Energy required for building heating in the month N_{mn} (MJ)

$Q_{N_{mn}}^{VEN}$Energy loss through the central heating in the month N_{mn} (MJ)

n^* service life of the heating system

$\tilde{n}$service life of the solar collectors system

n' service life of the cooling system

A^{roof}total area of roof the building (m^2)

A^{wall} total area of wall the building (m^2)

A^{win} total area window the building (m^2)

A_e available roof area for the panel supply system installation (m^2)

$Q_{N^{\cdot}_{mn}}^{cool}$ Energy required for building cooling in the month $N^{\cdot}_{mn}$ (MJ)

AEQ_q^{heat} Total cost of the energy that be made solar panel type q during the heating season of building lifespan (Dollar)

AEQ_q^{cool} Total cost of the energy that be made solar panel type q during the cooling season of building lifespan (Dollar)

$Q_{N^{\cdot}_{mn}}^{VEN}$Energy gained through the central cooling system in the month $N^{\cdot}_{mn}$ $(MJ)$$Q_{N_{mn}}^{iNHG}$ Energy generated by the interior building devices in the month N_{mn} (MJ)

Q^{AINNG} Energy lost by the interior building devices (MJ)

AEC_n^{heat} Total cost of the energy consumed by the heating system type n during the building lifespan c (Dollar)

AEC_r^{cool} Total cost of the energy consumed by the cooling system type r during the building lifespan c (Dollar)

BLCBuilding Load Coefficient $(W/^\circ C)$

2.2.1. Cost function of building materials

These costs are related to the materials used in the building external surrounding wall, roof, and windows considering the type of insulation thickness used in each as follows:

$$IC = A^{win}\sum_{i=1}^{I}\sum_{T_I=T_I^{min}}^{T_I^{max}} cost_{iT_I}^{win} z_{iT_I}^{win} + A^{roof}\sum_{j=1}^{J}\sum_{T_J=T_J^{min}}^{T_J^{max}} cost_{jT_J}^{roof} z_{jT_J}^{roof} + A^{wall}\sum_{k=1}^{K}\sum_{T_K=T_K^{min}}^{T_K^{max}} cost_{kT_K}^{wall} z_{kT_K}^{wall} \quad (1)$$

2.2.2. Cost function of utilizing and replacing installations

A NZEB useful lifespan depends largely on customer expectations and such features as its architecture, geography, and performance. Since time periods are usually 25–50 years [27], a useful lifespan (c) has been considered in the proposed model, and since the interest rate is a key factor depending on the currency depreciation or inflation, it may be constant in a period of time or may vary over the building's useful lifespan; if the interest rate is 2–3% above the inflation rate, it is considered as a value [30]. The useful life of the equipment used in a building is usually 10–25 years [28]; therefore, the inflation rate (a) has been taken to be different for each scenario to approximate the model closer to reality. Eq. (2) shows the total cost function for the selection of the cooling/heating system, solar panel, and considering the repair/replacement cost of each system over the NZEB useful lifespan c and interest rate a (%).

$$PV_{ICMR} = \sum_{n=1}^{N}\sum_{t=1}^{\left[\frac{c}{n^*}\right]} cost_n^{heat}\frac{C_{MRN}}{(1+a)^t}Z_n^{heat} + \sum_{r=1}^{R}\sum_{t=1}^{\left[\frac{c}{n'}\right]} cost_r^{cool}\frac{C_{MRR}}{(1+a)^t}Z_r^{cool} + \sum_{q=1}^{Q}\sum_{t=1}^{\left[\frac{c}{\tilde{n}}\right]} A_q^{sc}N^{sc}cost_q^{sc}\frac{C_{MRR}}{(1+a)^t}Z_r^{cool} \quad (2)$$

Where c_{MRN} is estimated the maintenance and replacement cost of the heating system type n after its n^* years, c_{MRR} is estimated the maintenance and replacement cost of the cooling system type r after its n' years, c_{MRQ} is estimated the maintenance and replacement cost of solar collector type q after its $\bar{n}$ years. Where the number of maintenance and replacement that need to be done respectively for the heating and cooling systems and solar panel during NZEB lifespan.

2.2.3. Total cost of the energy consumed to heat and cool during lifetime of NZEB

Since the mechanisms of the cooling and heating systems are different regarding the electricity and natural gas consumption, this function shows the total consumption cost for both over the NZEB lifespan.

$$PV_{EC} = \sum_{n=1}^{N} AEC_n^{heat}\left(\frac{Z_n^{heat}}{cop_n}\right) + \sum_{r=1}^{R} AEC_r^{cool}\left(\frac{z_r^{cool}}{cop_r}\right) - \sum_{q=1}^{Q} AEQ_q\left(z_q^{sc}\right) \quad (3)$$

$$AEC_n^{heat} = \sum_{N_{mn}=1}^{N_{MN}} Q_{N_{mn}}^{heat} CE_n^{N_{mn}} \cos t_{N_{mn}}^{EL}\left[\frac{\left(1+\left(\frac{a-k}{1+k}\right)\right)^c - 1}{\left(\frac{a-k}{1+k}\right)\left(1+\left(\frac{a-k}{1+k}\right)\right)^c}\right] + \sum_{N_{mn}=1}^{N_{MN}} Q_{N_{mn}}^{heat} CG_n^{N_{mn}} \cos t_{N_{mn}}^{GN}\left[\frac{\left(1+\left(\frac{a-k'}{1+k'}\right)\right)^c - 1}{\left(\frac{a-k'}{1+k'}\right)\left(1+\left(\frac{a-k'}{1+k'}\right)\right)^c}\right] \quad (4)$$

$$AEC_r^{cool} = \sum_{N'_{mn}=1}^{N'_{MN}} Q_{N'_{mn}}^{cool} CE_r^{N'_{mn}} \cos t_{N'_{mn}}^{EL}\left[\frac{\left(1+\left(\frac{a-k}{1+k}\right)\right)^c - 1}{\left(\frac{a-k}{1+k}\right)\left(1+\left(\frac{a-k}{1+k}\right)\right)^c}\right] + \sum_{N'_{mn}=1}^{N'_{MN}} Q_{N'_{mn}}^{cool} CG_r^{N'_{mn}} \cos t_{N'_{mn}}^{GN}\left[\frac{\left(1+\left(\frac{a-k'}{1+k'}\right)\right)^c - 1}{\left(\frac{a-k'}{1+k'}\right)\left(1+\left(\frac{a-k'}{1+k'}\right)\right)^c}\right] \quad (5)$$

$$AEQ_q^{heat} = \sum_{N_{mn}=1}^{N_{MN}} A_q^{sc}N^{sc}\eta_q^{sc} \cos t_{N_{mn}}^{EL} I_{N_{mn}}^{WIN}\left[\frac{\left(1+\left(\frac{a-k}{1+k}\right)\right)^c - 1}{\left(\frac{a-k}{1+k}\right)\left(1+\left(\frac{a-k}{1+k}\right)\right)^c}\right] \quad (6)$$

$$AEQ_q^{cool} = \sum_{N'_{mn}=1}^{N'_{MN}} A_q^{sc}N^{sc}\eta_q^{sc} \cos t_{N'_{mn}}^{EL} I_{N'_{mn}}^{WIN}\left[\frac{\left(1+\left(\frac{a-k}{1+k}\right)\right)^c - 1}{\left(\frac{a-k}{1+k}\right)\left(1+\left(\frac{a-k}{1+k}\right)\right)^c}\right] \quad (7)$$

$$AEQ_q^{heat} + AEQ_q^{cool} = AEQ_q \quad (8)$$

$$Q_{N_{mn}}^{heat} = BLC\left(\theta_{IH} - \theta_{N_{mn}}^{E}\right) + Q_{N_{mn}}^{VEN} - Q_{N_{mn}}^{iNHG} - \sum_{N_{mn}=1}^{N_{MN}}\sum_{i=1}^{I}\sum_{T_I=T_I^{\min}}^{T_I^{\max}} A^{win} I_{N_{mn}}^{\mathrm{win}} g_{iT_I} z_{iT_I}^{win} \quad (9)$$

$$Q_{N'_{mn}}^{cool} = \sum_{N'_{mn}=1}^{N'_{MN}}\sum_{i=1}^{I}\sum_{T_I=T_I^{\min}}^{T_I=T_I^{\max}} A^{win} I_{N'_{mn}}^{win} g_{iT_I} z_{iT_I}^{win} + Q^{AINNG} - BLC\left(\theta_{LC} - \theta_{N'_{mn}}^{E}\right) - Q_{N'_{mn}}^{VEN} \quad (10)$$

$$BLC = \sum_{i=1}^{I}\sum_{T_I=T_I^{\min}}^{T_I^{\max}} A^{win} U_{iT_I}^{win} z_{iT_I}^{win} + \sum_{k=1}^{K}\sum_{T_K=T_K^{\min}}^{T_K^{\max}} A^{wall}\frac{K_{kT_K}^{wall}}{d_k^{wall} + d'_{T_K}} z_{kT_K}^{wall} + \sum_{j=1}^{J}\sum_{T_J=T_J^{\min}}^{T_J^{\max}} A^{roof}\frac{K_{jT_J}^{roof}}{d_j^{roof} + d''_{T_J}} z_{jT_J}^{roof} \quad (11)$$

Eq. (3) shows the value of the energy consumed by selecting the heating and cooling systems according to Performance coefficient for each of them (cop_n, cop_r), respectively; here, the energy generated by the solar panel type q has also been considered. Eqs. (4) and (5) show the total value of the energy consumed by the heating system type n and the cooling system type r, respectively considering the rise in the price of electricity (k) and natural gas (k') during the NZEB lifetime (c). Eqs. (6) and (7) show the total value of the renewable energy generated by solar panel type q in months N_{mn} and N'_{mn}, respectively, Eq. (8) shows the total energy consumption cost that had produced solar panel during the NZEB lifetime; and Eqs. (9) and (10) are the total energy required by respectively the heating and cooling systems during the NZEB lifetime (c); Eq. (11) shows the thermal load coefficient of the NZEB.

Eq. (3) has been found from Eqs. (4), (5), (6), (7), (8), (9), (10), and (11). When Eqs. (4), (5), (6), (7), (8), (9), (10), and (11) are substituted in Eq. (3), the total value of the energy consumed by the cooling and heating systems during the NZEB lifespan (PV_{EC}) will turn into a nonlinear equation, hence, it should be linearized which is presented in Section 2–5.

Cooling and heating systems with performance coefficients of 100%, 10%, 30% to generate 25 *MJ* energy respectively need to 6.9, 6.2*kWh*, 5 kWh electricity, and also to generate 1 *Mj* energy respectively need to 947.8 *Btu*, 853.01 *Btu*, 6663.42 *Btu*[1] natural gas [31]. The average temperature in Tehran in the cold and warm season are, 8°*C* and 25

[1] 1 cubic foot natural gas (NG) wet = 1.109 Btu.

°Crespectively (Figure 2), and the intensity of solar radiation is averagely 5.5 kWh/m^2 and 7.2 kWh/m^2 in the cold and hot months ($I^{win}_{N_{mn}}$ and $I^{win}_{N_{mn}}$), respectively [32].

2.3. Objective function of costs

The total LCCobjective function includes the initial investment cost (IC), the current cost of maintenance/replacement equipment (PV_{ICMR}), and the total cost of the energy consumed by the heating and cooling systems (PV_{EC}) during the NZEB useful life. Eq. (12) minimizes IC, PV_{ICMR} and PV_{EC}.

$$\min LCC = IC + PV_{ICMR} + PV_{EC} \tag{12}$$

2.4. NZEB environmental objective function

About 80% of the total energy is consumed by buildings causing considerable effects on the environment; the greenhouse gas emission has a serious effect [28]. Since power is generated differently in the world, the environmental impacts are also different. Generating electricity from fossil fuels emits greenhouse gases into the atmosphere causing acidic rains and global climate variations [34]. Accordingly, the US EPA (Environmental Protection Agency) determines the greenhouse gas emission factors based on the type of the regional power networks; each region's power generation gas emission rate is compared with a national average. Natural gas produces less pollution than other fossil fuels and its increase can potentially reduce harmful pollutions [35]. The greenhouse gas analyzed in this study is CO_2[29].

Improving the building energy efficiency can reduce carbon emission into the atmosphere; therefore, this part of the study focuses on the amount of greenhouse gas emissions from the energy consumption of the cooling/heating systems. The carbon emission during a building lifespan can be found as follows:

$$ACC = (AES \times E_{CO_2} + AGS \times G_{CO_2}) \tag{13}$$

$$AGS = \sum_{n=1}^{N} \sum_{N_{mn}=1}^{N_{MN}} Q^{heat}_{N_{mn}} CG^{N_{mn}}_{n} z^{heat}_{n} + \sum_{r=1}^{R} \sum_{N'_{mn}=1}^{N'_{MN}} Q^{cool}_{N'_{mn}} CG^{N'_{mn}}_{r} z^{cool}_{r} \tag{14}$$

$$AES = \sum_{n=1}^{N} \sum_{N_{mn}=1}^{N_{MN}} Q^{heat}_{N_{mn}} CE^{N_{mn}}_{n} Z^{heat}_{n} + \sum_{r=1}^{R} \sum_{N'_{mn}=1}^{N'_{MN}} Q^{cool}_{N'_{mn}} CE^{N'_{mn}}_{r} Z^{cool}_{r} - \sum_{q=1}^{Q} \sum_{N_{mn}=1}^{N_{MN}} A^{sc}_{q} N^{sc} \eta^{sc}_{q} I^{WIN}_{N_{mn}} Z^{sc}_{q} - \sum_{q=1}^{Q} \sum_{N'_{mn}=1}^{N'_{mn}} A^{sc}_{q} N^{sc} \eta^{sc}_{q} I^{WIN}_{N'_{mn}} Z^{sc}_{q} \tag{15}$$

Eq. (13) shows the total carbon emitted from the energy consumed by the cooling/heating systems' during a NZEB lifespan. In Eqs. (14) and (15), AGS and AES show the total consumed power (kwh) and natural gas ($MBtu$) for the building cooling/heating installations, respectively.

E_{CO_2}And G_{CO_2}in Eq. (13) are the carbon emission per unit of consumed electric power(lbs/kWh) and the carbon emission per unit of consumed natural gas($lbs/MBtu$), respectively. This paper has considered them equal to 0.876$lbs/kWh$and 117 $lbs/MBtu$, respectively [30]. Since Eqs. (14) and (15) have been found from Eqs. (9) and (10) the latter have been obtained from Eq. (11), AES and AGS become nonlinear; Section 2–5 will address this issue.

2.5. Linearization of the nonlinear objective functions

First terms of the Eqs. (3), (14), and (15) are respectively multiplications of the eqs AEC^{heat}_{n}, $Q^{heat}_{N_{mn}}$, $Q^{heat}_{N_{mn}}$by the binary variable z^{heat}_{n}. Eq $AEC^{heat}_{n}$is the multiplication of eq $Q^{heat}_{N_{mn}}$by some parameters. Eq $Q^{heat}_{N_{mn}}$is also the multiplication of eq $BLC$by some parameters. Eq $BLC$is the sum of these binary variables $z^{win}_{iT_I}$,$z^{wall}_{kT_K}$,$z^{roof}_{jT_J}$. So all these Eqs. (3), (14), and (15) are results of multiplying binary variables $z^{win}_{iT_I}$ by z^{heat}_{n} , $z^{wall}_{kT_K}$ by z^{heat}_{n}, $z^{roof}_{jT_J}$ by z^{heat}_{n} . $X^{T_I}_{in}$ is an artificial binary variable created from the product of $z^{win}_{iT_I}$ and z^{heat}_{n}; it is 1 when both binary variables equal 1; otherwise, it is 0. $X^{T_K}_{kn}$ is an artificial binary variable created from the product of $z^{wall}_{kT_K}$ and z^{heat}_{n}; it is 1 when both binary variables equal 1; otherwise, it is 0. $X^{T_J}_{jn}$ is an artificial binary variable created from the product of $z^{roof}_{jT_J}$ and z^{heat}_{n}; it is 1 when both binary variables equal 1; otherwise, it is 0. Thus, constraints (16), (17), (18), (19), (20), (21), (22), 23) and (24) will be applied because of the linearization of $z^{win}_{iT_I} \times z^{heat}_{n}$, $z^{wall}_{kT_K} \times z^{heat}_{n}$, and $z^{roof}_{jT_J} \times z^{heat}_{n}$ respectively.

Second terms the Eqs. (3), (14), and (15) the multiplied eqs AEC^{cool}_{r}, $Q^{cool}_{N_{mn}}$, $Q^{cool}_{N_{mn}}$ in the binary variable z^{cool}_{r}, respectively. Then, Eq AEC^{cool}_{r} is the multiplication of Eq Q^{heat} by some parameters. Eq $Q^{cool}_{N_{mn}}$ is also the multiplication of eq BLC by some parameters. Eq BLC is the sum of these binary variables $z^{win}_{iT_I}$, $z^{wall}_{kT_K}$, $z^{roof}_{jT_J}$. So all these Eqs. (3), (14), and (15) are results of multiplying binary variables $z^{win}_{iT_I}$ by z^{cool}_{r} , $z^{wall}_{kT_K}$ by z^{cool}_{r}, $z^{roof}_{jT_J}$ by z^{cool}_{r} . $X^{T_I}_{ir}$ is an artificial binary variable created from the product of $z^{win}_{iT_I}$ and z^{cool}_{r}; it is 1 when both binary variables equal 1; otherwise, it is 0. $X^{T_K}_{kr}$ is an artificial binary variable created from the product of $z^{wall}_{kT_K}$ and z^{cool}_{r}; it is 1 when both binary variables equal 1; otherwise, it is 0.$X^{T_J}_{jr}$ is an artificial binary variable created from the product of $z^{roof}_{jT_J}$ and z^{cool}_{r}; it is 1 when both binary variables equal 1; otherwise, it is 0. Thus, constraints (25), (26), (27), (28), (29), (30), (31), 32) and (33) will be applied

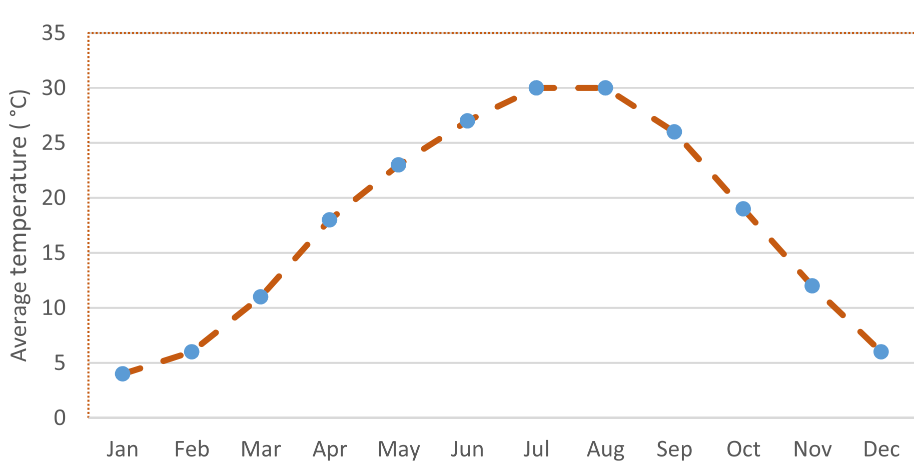

Figure 2. onthly average temperature for the city of Tehran (data source: [27]).

because of the linearization of $z^{win}_{iT_I} \times z^{cool}_r$, $z^{wall}_{kT_K} \times z^{cool}_r$, and $z^{roof}_{jT_J} \times z^{cool}_r$ respectively.

$$X^{T_I}_{in} \le z^{win}_{iT_I} \quad \forall i, n, T_I \tag{16}$$

$$X^{T_I}_{in} \le z^{heat}_n \quad \forall i, n, T_I \tag{17}$$

$$X^{T_I}_{in} \ge z^{win}_{iT_I} + z^{heat}_n - 1 \quad \forall i, n, T_I \tag{18}$$

$$X^{T_K}_{kn} \le z^{wall}_{kT_K} \quad \forall k, n, T_K \tag{19}$$

$$X^{T_K}_{kn} \le z^{heat}_n \quad \forall k, n, T_K \tag{20}$$

$$X^{T_K}_{kn} \ge z^{wall}_{kT_K} + z^{heat}_n - 1 \quad \forall k, n, T_K \tag{21}$$

$$X^{T_J}_{jn} \le z^{roof}_{jT_J} \quad \forall j, n, T_J \tag{22}$$

$$X^{T_J}_{jn} \le z^{heat}_n \quad \forall j, n, T_J \tag{23}$$

$$X^{T_J}_{jn} \ge z^{roof}_{jT_J} + z^{heat}_n - 1 \quad \forall j, n, T_J \tag{24}$$

$$X^{T_I}_{ir} \le z^{win}_{iT_I} \quad \forall i, r, T_I \tag{25}$$

$$X^{T_I}_{ir} \le z^{cool}_r \quad \forall i, r, T_I \tag{26}$$

$$X^{T_I}_{ir} \ge z^{win}_{iT_I} + z^{cool}_r - 1 \quad \forall i, r, T_I \tag{27}$$

$$X^{T_K}_{kr} \le z^{wall}_{kT_K} \quad \forall k, r, T_K \tag{28}$$

$$X^{T_K}_{kr} \le z^{cool}_r \quad \forall k, r, T_K \tag{29}$$

$$X^{T_K}_{kr} \ge z^{wall}_{kT_K} + z^{cool}_r - 1 \quad \forall k, r, T_K \tag{30}$$

$$X^{T_J}_{jr} \le z^{roof}_{jT_J} \quad \forall j, r, T_J \tag{31}$$

$$X^{T_J}_{jr} \le z^{cool}_r \quad \forall j, r, T_J \tag{32}$$

$$X_{jr} \ge z^{roof}_{jT_J} + z^{cool}_r - 1 \quad \forall j, r, T_J \tag{33}$$

2.6. The objective functions

$$\begin{array}{l} \min \ LCC \\ \min \ ACC \end{array} \tag{34}$$

$$\sum_{i=1}^{I} \sum_{T_I=T_I^{min}}^{T_I^{max}} z^{win}_{iT_I} = 1$$

$$\begin{cases} \sum_{r=1}^{R} z^{cool}_r = 1 \\ \sum_{n=1}^{N} z^{heat}_n = 1 \\ \sum_{j=1}^{J} \sum_{T_J=T_J^{min}}^{T_J^{max}} z^{roof}_{jT_J} = 1 \\ \sum_{q=1}^{Q} z^{sc}_q \le 1 \end{cases} \tag{35}$$

$$\sum_{k=1}^{K} \sum_{T_K=T_K^{min}}^{T_K^{max}} z^{wall}_{kT_K} = 1$$

Table 1. Price and thermal conductivity coefficient to select external wall materials.

K	Type	T_K	d'_{T_K} (cm)	$K^{wall}_{kT_K}$ (w/mk)	cost $(\$/m^2)$
1	Clay blocks	1	3	.180	11.7
		2	5	.0460	13.45
		3	7	.0420	15.8
		4	10	.0300	16.1
2	Concrete blocks of polystyrene	1	3	0.16	11.3
		2	5	.0480	13.2
		3	7	.0420	15.06
		4	10	.0480	15.73
3	3D panel	1	3	.1680	26.6
		2	5	0.046	30.5
		3	7	.0440	32.25
		4	10	.0240	36.9
4	Pumice Blocks	1	3	0.170	11.1
		2	5	0.039	12.8
		3	7	0.042	14.7
		4	10	.0420	15.2
5	Brick solid pressure	1	3	.1580	13
		2	5	.0490	15.1
		3	7	.0440	16.3
		4	10	.0430	18.07

Table 2. Price and thermal conductivity coefficient to select roof materials.

J	*Type*	T_J	d''_{T_J} (cm)	$K^{roof}_{jT_J}$ (w/mk)	cost $(\$/m^2)$
1	Piles of blocks	1	3	0.35	55.4
		2	5	0.301	58.1
		3	7	0.262	59.8
		4	10	0.205	63.2
2	Concrete slab	1	3	0.331	61.1
		2	5	0.28	64.5
		3	7	264.0	68.1
		4	10	.200	73.3
3	Piles of pottery	1	3	.360	52.6
		2	5	.3030	56.3
		3	7	0.267	60.8
		4	10	.0235	64.7
4	Piles of concrete	1	3	.380	51.6
		2	5	.3250	56.6
		3	7	.2710	62.8
		4	10	.250	65.2
5	Steel deck	1	3	0.340	56.7
		2	5	.3080	59.3
		3	7	.2600	66.2
		4	10	.2400	70.4

Table 3. Price and thermal conductivity coefficient to select windows.

I	Type	T_I	d_{T_I} (mm)	$U^{win}_{iT_I}$ $(w/m^{2°}C)$	g_{iT_I} (%)	cost $(\$/m^2)$
1	UPVC	1	8.6	6.14	85	38.19
		2	14	3.4	72	42.4
		3	18.5	1.6	59	92.6
2	Aluminum	1	8.6	7.1	86	32.8
		2	14	4.3	75	35.6
		3	18.5	1.9	62	84

Table 4. Price to select the cooling system.

R	Type	$cost_r^{cool}(\$)$
1	Hot water boiler	56154
2	Solar hot water boiler	59413
3	Hot water unit package	51294
4	Solar hot water unit package	50948
5	Heat pumps	37901

Table 5. Price to select a heating system.

N	Type	$cost_n^{heat}$ ($)
1	Vapor-compression chiller	59458
2	Heat pumps	41579
3	Absorption chiller	32745
4	Solar absorption chiller	35910

Table 6. Price and efficiency to select solar panels.

Q	Type	A_q^{SC} (m^2)	η_q^{sc}	$cost_q^{sc}(\$/m^2)$
1	SPT255-20/WD	1.627	15.7%	900.78
2	YL190P-23B	1.297	14.7%	592.62
3	YL265C-30B	1.624	16.3%	942.30
4	CS6X-300P	1.919	15.6%	870.33
5	HSL60P6-PB-1-240B	1.616	14.8%	704.82
6	Sharp ND 245 Poly	1.642	14.9%	1023.12
7	SW 275 MONO	1.593	16.4%	1042.50

$$\sum_{q=1}^{Q} A_q^{SC} N^{SC} z_q^{SC} \le A_e \tag{36}$$

Constraint (35) of the model requires uniform choices in the NZEB design, i.e. just one type of material, one type of the heating and cooling systems and one type of solar panel can be used for the whole building, constraint (36) shows the limit on the usable area of the roof for solar panel system installation, boundary limits on the decision variables, and constraints (15), (16), (17), (18), (19), (20), (21), (22), (23), (24), (25), (26), (27), (28), (29), (30), 31) and (32) show the penalties for the linearization of the problem model and boundary limits on the decision variables.

2.7. Model solution

Among different optimization methods for multi-objective problems, without loss of generality, we prosed the epsilon-constraint method is a posteriori method which is used for finding a suitable picture of a Pareto optimal set helping decision-make [39]. This method is based on calculating a set of single-objective functions, while the other functions are transferred to the auxiliary constraint that bound them within some allowable limits. The common general form of which is as follows [40]:

$$\begin{array}{l} \min \; LCC \\ \text{s.t} \end{array} \tag{37}$$

$$\begin{array}{l} ACC \le \varepsilon \\ [ACC]^{min} \le ACC \le [ACC]^{max} \\ \text{Eqs. } (35-36) \text{ and } (16-33) \end{array} \tag{38}$$

Then, the right-hand side of constrained objective functions (epsilons) are changed and efficient solutions are gained for the problem. Finally, the decision-maker can use all of the solutions obtained to make the decision [41].

This MILP model is aimed to simultaneously optimize the LCC and carbon emission objective functions (discussed in more detail in the Case Study).

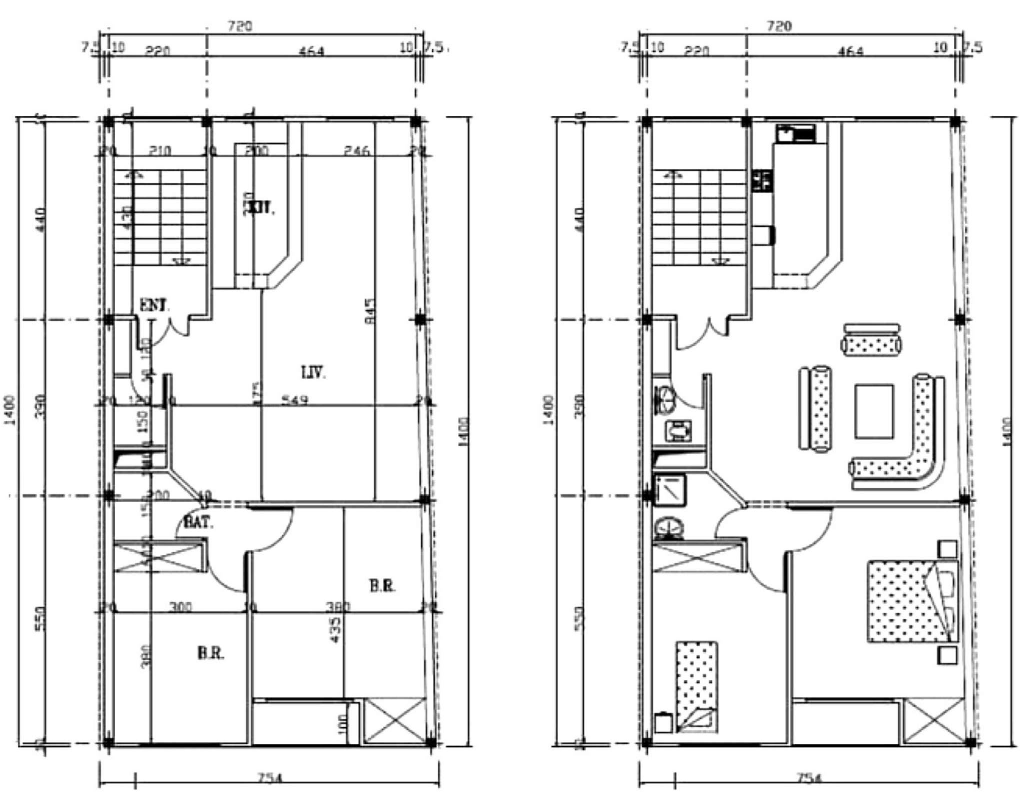

Figure 3. View of case study building and ground floor view.

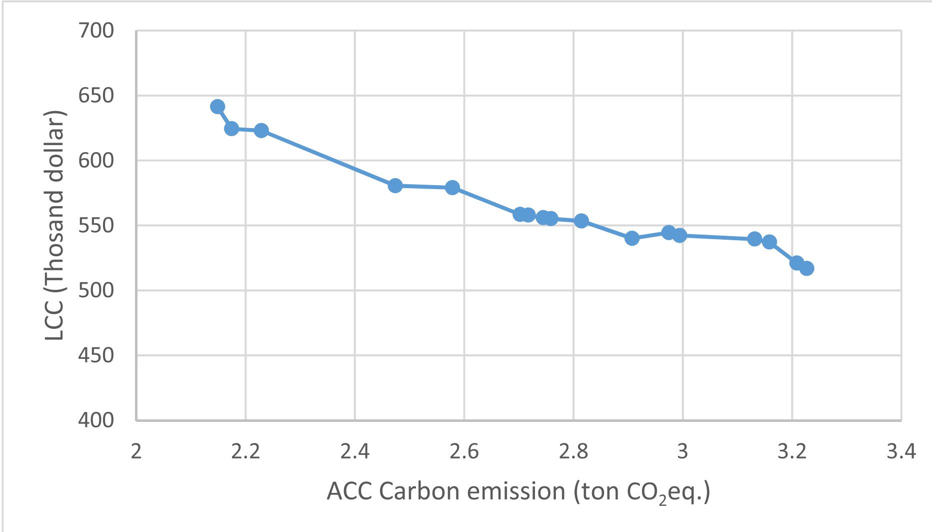

Figure 4. The Pareto optimal solution for first scenario.

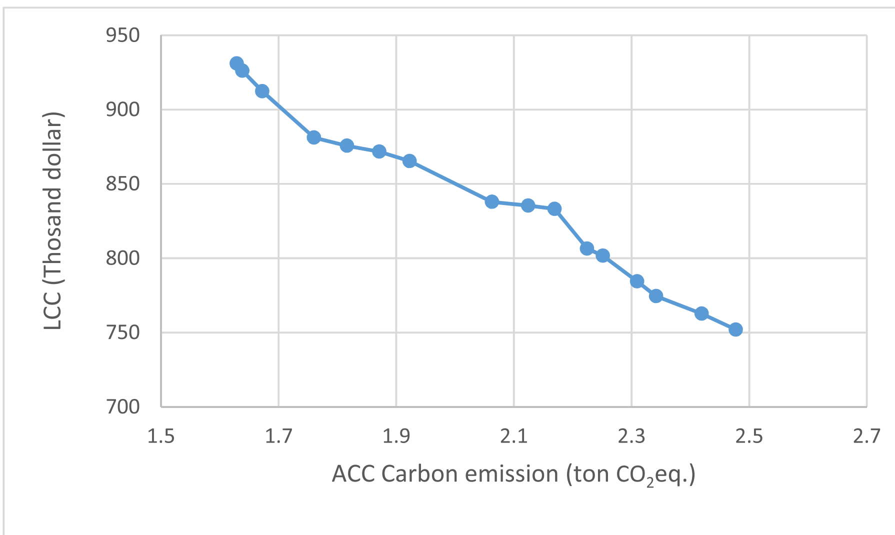

Figure 5. The Pareto optimal solution for the second scenario.

3. Result and discussion

This case study examines an 8-unit (100 m^2 area each), 2-story building in Tehran with 240 m^2 open peripheral area, 320 m^2 roofs, and 800 m^2 peripheral surface areas; the thicknesses of the perimeter wall and roofs are 30 and 35 cm, respectively. The building requires 4 months for the cooling and 5 for heating systems. Here, the optimization is aimed to minimize both the LCC and carbon emission (ACC) due to the energy consumed by the heating and cooling systems in the NZEB. Based on the decision-makers' objectives, the problem addresses two scenarios considering the material price (Tables 1, 2, 3, 4, and 5) and solar panel price (Table 6) that were directed by using data from papers [36, 37]. NZEB shape, dimensions, and openings are presented in the plan view (Figure 3).

First Scenario (1): Here, the building's useful life is 40 years, the interest rate is 5%, energy increase rates for power and natural gas are 0.06% and 0.05%, respectively, price per 1 kWh power is 0.12 (Dollar), and that for 1 m^3 natural gas is 0.176 (Dollar); maximum and minimum insulation thickness is used for windows, external walls, and roof, respectively.

Second Scenario (2): Here, the building's useful life is 40 years, the interest rate is 5%, energy increase rates for power and natural gas are 6 %and 10%, respectively, price per 1 kWh power is 0.12 (Dollar), and that for 1 m^3natural gas is 0.176 (Dollar);

Considering the NZEB materials, the cooling and heating systems, solar panel equipment collectively and applying appropriate constraints related to the existing condition, we can select the most suitable ways to reduce life cycle cost and CO_2 emission in the NZEB designs. Section 19 of the Iran National Building Regulations (section 19 INBR) is collected to enhance the building sustainability. The principles of design, implementation, and computation of thermal insulation of buildings, solar panels, the cooling and heating systems, and lighting are demonstrated by the issue 19 of the NBR act of Iran [42].

Based on the possible alternatives compatible with section 19 of the NBR of Iran, decision variables are chosen for both passive and active

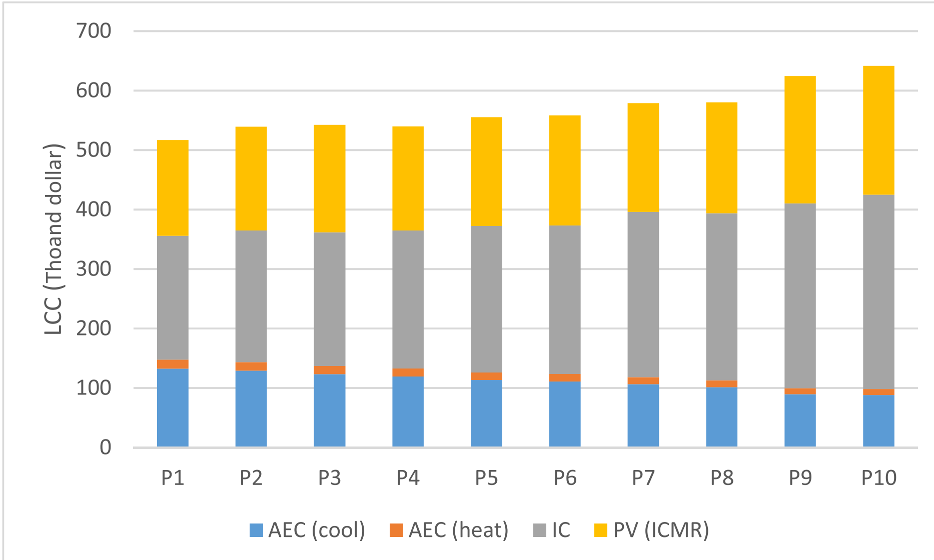

Figure 6. Amount of LCC, incidence analysis for the ten points of the Pareto frontier in the first scenario.

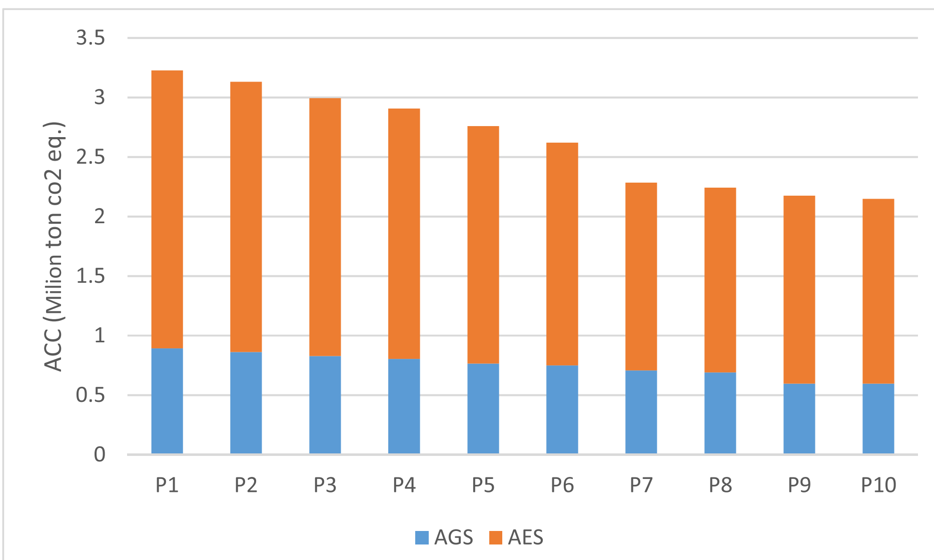

Figure 7. Amount of environmental impact, incidence analysis for the ten points of the Pareto frontier in the first scenario.

cooling-heating systems and solar panels and building envelope materials.

Finally, the results have been validated by using the real data of two scenarios studied in Tehran.

As the results show, the amount of energy consumption cost (AEC) in the first and second scenarios accounts for between 15.3% to 28.5% and 21.5%–39.2% of LCC respectably (Figures 6 and 8), while cooling energy consumption makes up the most proportion of LCC.

According to Figures 6 and 8, the initial cost of NZEB (IC) is about 40.2%–50.9% and 27.6%–35.2% of LCC in the first and second scenarios respectably. With the select low-insulation thickness (for example wall and roof insulation thickness are decreased up to 5cm and window insulation thickness is decreased up 14 mm) and material above up,$K^{wall}_{kT_K} = 0.039\left(W/_{mk}\right), K^{roof}_{jT_J} = 0.264\left(W/_{mk}\right), U^{win}_{iT_I} = 4.3(W/m^{2\circ}C)$ we're not able to decrease the co_2 emission (ACC) and LCC for optimal design NZEB (Figure 4), but, with a low significant investment cost (IC), the model suggests high insulation thickness for external walls and roof and window that are able to decrease the energy consumption cost (AEC) 22% and consequence, the CO_2 emission (ACC) reduces, by 23%, which LCC of NZEB increase gradually by 7.3% (Figures 5 and 6) in the first scenario, not suggests the installation of solar panel equipment for any Pareto solution. The solar panel is not recommended and does not justify its high level of efficiency for Iranians in this scenario because the cost of energy consumption is low in this country (see Figure 7).

In scenario #2, by increasing the high cost of energy consumption in this scenario the amount of LCC has not changed completely, compared to another scenario, because the model suggestion the insulation solar panel. Therefore, AEQ in the scenario accounts for approximately 11.6%–20.5% of LCC, while the amount of CO_2 emission reduced by 26% compared to scenario 1 (Figure 5). However, the model suggests the insulation thickness of material (wall, roof, windows) by increasing 5.4% LCC and decreasing CO_2 emission for NZEB design (Figures 8 and 9).

Analyses of the models developed in different scenarios help decision-makers to select the optimal solution considering the combination of equipment to decide on the type of the building design because they

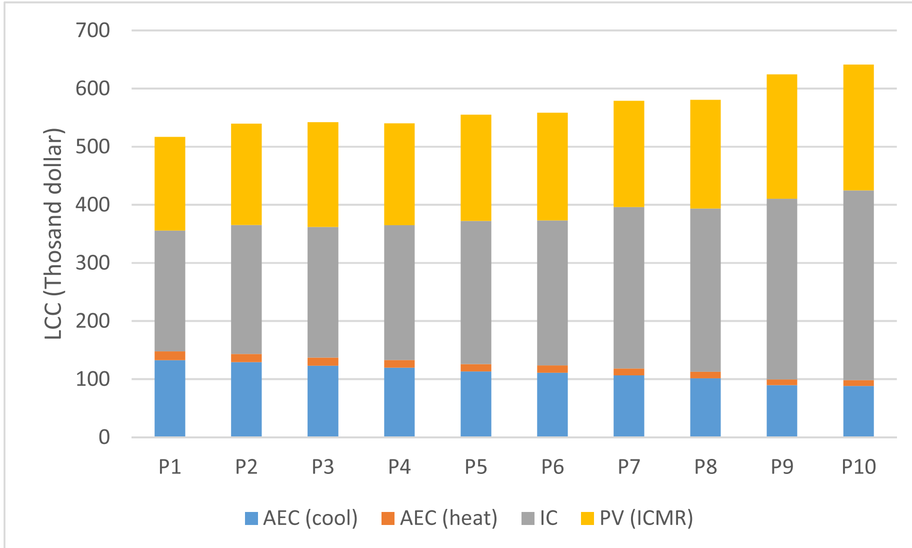

Figure 8. Amount of LCC, incidence analysis for the ten points of the Pareto frontier in the second scenario.

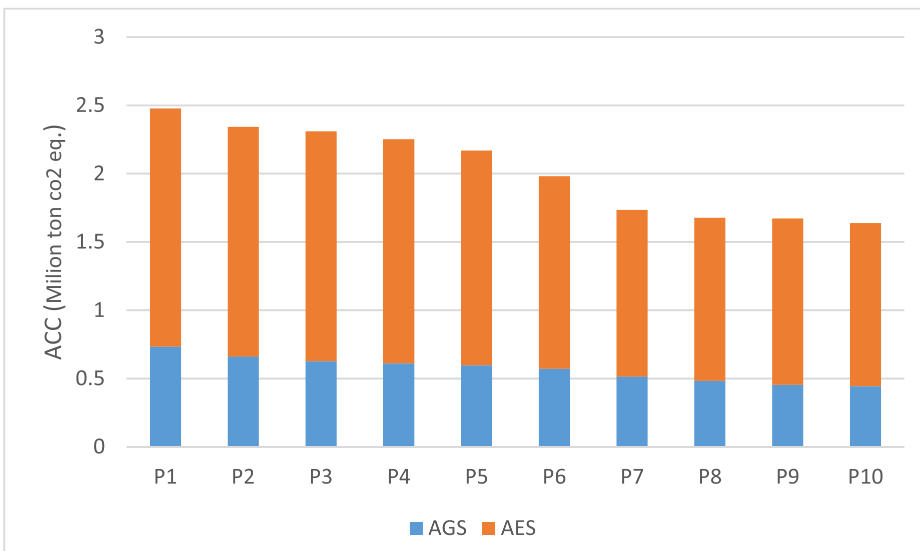

Figure 9. Amount of environmental impact, incidence analysis for the ten points of the Pareto frontier in the second scenario.

provide information on the required LCC and ACC and help them to evaluate different design options. Thus, it is suggested that the NEZB design insulation thickness should be used because the amounts of AEC and ACC drop significantly. Also, by using solar panel in long run, LCC experiences a gradual rise, whereas ACC declines by some 23%, Figure 8. The two scenarios differ principally by the increasing rate of electric power and natural gas. The implementation time of each scenario run is about 1.32 h. The model suggests that high insulation of the buildings is able to decrease both the LCC and the ACC, while, due to the low cost of energy and PESTLE (political, economic, social, technical, legal, and environmental) in Iran, the model does not suggest the use of solar panels.

4. Conclusions and suggestions for future research

Although using novel construction methods to enhance the building sustainability and reduce its energy consumption simultaneously is a very complicated process, this approach can be used to get close to the net-zero energy buildings. One of the first priorities worldwide is to improve energy efficiency in buildings, so, in this study, efforts have been made to analyze two important aspects of sustainability, economic and environmental, for NZEB design. The approach used is based on the MILP model that presents the best options for the simultaneous economic-environmental building performance improvements. This study proposes a multi-objective mathematical model for assessing different construction methods and installation options for building retrofitting and making decisions on different scenarios considering the environmental aspects. The optimum design parameters for building sustainability shows that the model selects initial costs (IC) for both scenarios, 9.3% and 7.6% for the first scenario and the second scenario respectively. Meanwhile, the co_2 emission (ACC) reduces by 23% for the first scenario and 26% for the second one. Furthermore, the LCC increases by 7.3% for the first and 5.4% for the second scenario. Numerical results show that investing in the insulation thickness options proposed in Scenario 1 can considerably reduce the environmental effects of a building.

In the long run, solar panels (renewable energy equipment) proposed in Scenario 2 are preferable because they can cause more reduction in energy consumption and greenhouse gas emissions over the NZEB lifespan. For future studies, it is suggested that: 1) the energy consumed by different building appliances, cost of the building lighting system, and building tax should be examined more accurately, 2) the social costs and amount of pollution due to building construction should be addressed, and 3) uncertainties in parameters should be considered through robust and fuzzy methods to make the model closer to reality [43].

Declarations

Author contribution statement

Hamed Delavar & Hadi Sahebi: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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