Energy analysis for construction of a zero-energy residential building using thermal simulation in Iran

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Abstract

Purpose – The purpose of this paper is to examine the feasibility and design of zero-energy buildings (ZEBs) in cold and semi-arid climates. In this study, to maximize the use of renewable energy, energy consumption is diminished using passive solar architecture systems and techniques.

Design/methodology/approach – The case study is a residential building with a floor area of 100 m^2 and four inhabitants in the cold and semi-arid climate, northeast of Iran. For thermal simulation, the climate data such as air temperature, sunshine hours, wind, precipitation and hourly sunlight, are provided from the meteorological station and weather databases of the region. DesignBuilder software is applied for simulation and dynamic analysis of the building, as well as PVsyst software to design and evaluate renewable energy performance.

Findings – The simulation results show a 30% decrease in annual energy consumption of the building by complying with the principles of passive design (optimal selection of direction, Trombe wall, shade, proper insulation selection) from 25,443 kWh to 17,767 kWh. Then, the solar energy photovoltaic (PV) system is designed using PVsyst software, taking into account the annual energy requirement and the system's annual energy yield is estimated to be 26,291 kWh.

Originality/value – The adaptive comparison of the values obtained from the energy analysis indicated that constructing a ZEB is feasible in cold and semi-arid conditions and is considered an effective step to achieve sustainable and environmentally friendly construction.

Keywords Energy sector, Renewable energies, Solar, Energy conversion, Construction, Simulation, Optimization, Zero-energy building, Energy management, Sustainable development, Renewable energy, Photovoltaic, Residential building

Paper type Research paper

Introduction

Studies accomplished by the International Organization for Economic Co-operation and Development (OECD) show that energy consumption in the construction sector has continuously increased since 1960 and will continue to increase in the coming years, mainly because of the high construction intensity in Asia, the Middle East and Latin America. In total, 50% of the

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world's raw materials are used in buildings, while most of them are non-renewable. In fact, buildings are responsible for releasing more than 46% of the total greenhouse gas produced worldwide (Osman, 2014). According to the United Nations Intergovernmental Panel on Climate Change (IPCC) report, from the industrial revolution until the end of the 20th century, the Earth's temperature has increased by 0.5°C and on average, the ozone layer thickness has decreased by 20% in different parts of the world (IPCC, 2016). In Iran, as a developing country, residential buildings include 25% of total greenhouse gas emissions (Eshraghi *et al.*, 2014). With rapid construction development in Iran and electrical energy shortage, energy-efficient buildings and sustainable development of buildings have become the focus of the society (Amani, 2017; Amani, 2018). In the report published by the Public Relations of the Center for the Islamic Consultative Assembly studies, the Energy Studies Bureau, the construction sector with an average consumption of 41.42%, had a high share of energy consumption in the country. Meanwhile, given the figures published, Iran has ranked 11th of the countries with the highest energy consumption (Center for the Islamic Consultative Assembly studies, 2017; GES, 2020). Based on this information, efforts to lower fossil fuel consumption, construction of buildings with optimal energy consumption, the use of devices with high energy rank and the use of renewable energy resources are essential. The measures taken in this regard in the macro-scale programs in the developed countries account for the construction of zero-energy buildings (ZEBs). Advantages of net-zero energy buildings included a reduction in thermal fluctuations in these buildings, which results from adequate isolation and well provides the comfort conditions; energy supply, even in the event of shutting down in the global energy distribution network; protection against the ever-increasing rise in energy prices; reduction in greenhouse gases and saving in energy consumption (Mahdavi Adeli *et al.*, 2020). The basic scheme of a Net-zero building design is to provide thermal comfort with less energy consumption. Sudhakar *et al.* (2019) examined the various building designs in hot and humid climates. It was found that it is most important to concentrate on all possible passive energy-saving actions before adopting active measures. These measures included using the natural ventilation systems in places with high wind speeds; using different design strategies to achieve comfort performance in different seasons; as well as wind tower dehumidification design and ventilated attic building design for the hot and humid regions. To achieve an integrated nZEB standard, during designing and constructing based on the relevant geographic location, factors such as building envelope, window type, optimum air infiltration and tilt angle of PV panels and their proper orientation must be considered (Al-Saeed *et al.*, 2020).

These programs practically apply the standards in the investigation of sustainable architecture such as Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM) with high quality in terms of reducing energy consumption and environmental compatibility and using efficient and modern technologies, provide the ground for the development of technology and technical knowledge in this field (Wang *et al.*, 2009). The Energy Performance of Buildings Directive (EPBD), approved by the European Parliament and Council in relation to the energy efficiency of buildings, pledges the European Union, including 28 European countries, to lower the energy consumption of residential and commercial buildings to near-zero in all new public buildings by 2019 and all new buildings by 2021 (Arbabiyan, 2001; Osmani and O'Reilly, 2009). In the USA, based on a law passed in 2007 to support the construction of ZEB, the net energy consumption must reach zero in half of the commercial buildings by 2040 and all commercial buildings by 2050 (Crawley *et al.*, 2009). The best way to improve the performance of existing buildings toward zero energy performance is an integrated approach of different energy strategies, running in parallel, that tackle behavior, the efficiency of equipment, on-site renewable energy generation and energy storage.

Fonseca *et al.* (2018) achieved nearly zero-energy building goals in the renovation of the university campus building by adopting an integrated approach such as the right combination of different strategies, including energy-efficient technologies and renewable energy. However, further investigations based on software analysis seem to be necessary for energy efficiency and the construction of efficient buildings with near-zero energy consumption. Amani and Reza Soroush (2020) investigated the simultaneous effect of parameters affecting energy consumption in the building. These parameters included Building orientation, window-to-wall ratio (WWR), Window shades, Window glass, Wall and Roof construction, Infiltration, Lighting efficiency, Daylighting and occupancy controls, Plug load efficiency, HVAC system, Operating schedule and photovoltaic system. Their findings showed that the simultaneous investigation of parameters affecting energy consumption in the case study building could save energy costs up to 58.23%. Hence, it can be concluded that each of the building components has a significant role in evaluating the energy performance of the building, which should be considered in the energy analysis.

The use of a photovoltaic (PV) system for zero-energy buildings is crucial to balance energy consumption. The potential of using PV systems for residential buildings in different climatic zones of China was investigated by Liu *et al.* (2019), taking into account parameters such as tilt angle, orientation, plot ratio, PV conversion efficiency and location. The results indicate that southwest China is the best place to develop zero energy buildings. Low-rise residential buildings can realize zero energy in China when the PV conversion efficiency is higher than 20%. The potential of using nearly zero-energy buildings (nZEB) was investigated by Al-Saeed *et al.* (2020) to improve the performance of residential buildings in the hot and dry climate of Iraq. Their findings showed that both significant annual energy reductions and nZEB standards have been achieved, which could range from 41% to 87% for current climatic conditions. Walter Costa *et al.* (2020) conducted a study on pure energy office buildings in the hot climate of Brasilia. Their studies showed that the nZEB goal could be achieved in office buildings up to four floors in the Brazilian climate zone by following the nearly zero-energy building improvement guidelines. These guidelines included measurement of available building shell for collecting solar irradiation, the reduction of the WWR, using glasses with a Solar Heat Gain Coefficient of 43% or lower, the addition of solar shading devices, the reduction of the installed power density of the lighting system by 25% and the use of natural ventilation. The potential impacts of energy-efficient measures for retrofitting existing UK hotels to reach the nearly zero-energy building (nZEB) standard were investigated by Salem *et al.* (2019). The findings show that it is possible to achieve the nZEB standard for older UK hotel buildings. Thus, attention must first be paid to improving the building fabric or building envelope elements, then if necessary, to achieve the nZEB goal in the historical buildings can be used the renewable energy systems. Al-Saadi and Shaaban (2019) conducted a study based on the design of sustainable architectural and engineering systems for a zero-energy building (ZEB) in the hot climate of Oman. Sustainable passive and active energy systems have been successfully integrated into this building typology. Passive strategies have resulted in a small equipment capacity of air conditioning systems. However, a PV system was installed on the rooftop providing electrical energy for immediate house demand. A solar water heater was also installed to provide free hot water. The results showed that when grid interaction was considered, 40% of the building load was supplied by site generation, which meets zero energy targets. Albadry *et al.* (2017) proposed increasing insulation surfaces to reduce energy consumption and design a photovoltaic system for renewable energy to reach the nZEB targets for a 5-story residential building in Egypt. Charisi (2017) stated that the appropriate combination of the building shell and increasing the insulation layer thickness in achieving the nearly zero-energy building of a residential building in Greece could save up to 30% in energy consumption. The heating and cooling loads between a ZEB and a similar building in a very cold area in China were simulated and compared by Li *et al.* (2015). The findings indicated that the overall energy savings were more than 55%, among which the air conditioning system played a significant role in saving energy. Ferrari and Beccali (2017) were able to reduce the primary energy demand and CO2 emissions by up to 40% by adopting accessible technological solutions in a building at the Polytechnic School of the University of Milan, Italy. The use of semi-transparent photovoltaics (STPV), which transmits visible light yet, at the same time, produces electricity has most likely the highest potential to achieve the nZEB goal. Refat and Sajjad (2020) showed that for 50% visible transmittance, STPV on clear glass saves about 50% and 30% of the energy demand in tropical and hot desert regions, respectively, and around 20%–25% in Scandinavian and cold continental regions. Moreover, when combined with low-emissivity glass, the net saving reaches as high as 90% in tropical regions, 60% in hot desert regions and 45%–70% in the rest of the regions. Renewable energy systems (RES) in buildings are designed to operate over their lifetime. Sobhani *et al.* (2020) stated that without considering the potential future changes in influential parameters such as climate and energy price data may lead to inappropriate solutions for long-term operation. Findings showed a decrease in heating and electricity demand by 14.6% and 2.29% and an increase in cooling demand by 19.9% after 20 years. The consideration of uncertainties in the design would further increase the computing cost significantly. It may also lead to low energy efficiency and even failure of achieving zero/low energy goal in operation, as each design option needs to be evaluated under a large number of uncertain scenarios. Li and Wang (2020) reviewed a coordinated robust optimal design method to efficiently identify the global optimal design solutions for the entire zero/low energy buildings under uncertainties. Their studies showed that taking into account uncertainties in design optimizations of building envelope and energy systems would save more than 90% of computational time. Also, the durability of materials and technologies is an important aspect that warrants further analysis to assess the proper efficiencies and the expected lifetime of a ZEB. Past studies have shown that ZEB performance in the building life cycle has decreased due to the instability of building materials (Danza *et al.*, 2018). Mahdavi Adeli *et al.* (2020) conducted a study on an office building in the hot and dry climate of Iran with the aim of thermal comfort as well as optimizing energy consumption. Their findings showed that using photovoltaic panels alone is not able to create a net-zero energy building. They found that using wind turbines for electricity generation in cold seasons would be an appropriate substitute for the reduction in the electricity generated by photovoltaic panels.

Table 1 shows the review of previous studies in the field of ZEBs. These studies have been derived from prestigious scientific bases such as ScienceDirect, Taylor and Francis, Wiley, ASCE, Springer and Emerald. The investigation of ZEB, feasibility studies and research on its components have been conducted in studies by Albadry *et al.* (2017) Al-Saadi and Shaaban (2019), Al-Saeed *et al.* (2020), Cellura *et al.* (2015), Charisi (2017), Danza *et al.* (2018), Ferrari and Beccali (2017), Fonseca *et al.* (2018), Heravi and Qaemi (2014), Li and Wang (2020), Li *et al.* (2015), Liu *et al.* (2019), Lizana *et al.* (2017), Mahdavi Adeli *et al.* (2020), Salem *et al.* (2019), Sudhakar *et al.* (2019), Walter Costa *et al.* (2020) and Zhou *et al.* (2016). Based on Table 1, it can be concluded that no study has been performed worldwide regarding the examination, feasibility and simulation of ZEB in cold and semi-arid climates using the Meteonorm, PVsyst, Ecotect Analysis and DesignBuilder software packages. The study of the feasibility of using solar panels system in the cold and semi-arid climate of Iran and achieving a building with zero energy by considering the principles of passive design including optimal selection of direction, Trombe wall, shade and proper insulation has been the main focus of this research. For this purpose, a case study building has been adopted in the design phase to select the best case for construction and computer simulation in the cold and semi-arid region of Mashhad using Ecotect and DesignBuilder software,

Table 1. Previous studies on zero-energy buildings (ZEB)

Author(s)	Objective	Research methodology	Achievements	Year
Al-Saeed *et al.*	Investigating the potential of using nearly nZEB	Validating the simulation by comparing the simulated primary energy consumption of the case-study building	Significant annual energy reduction; 41% to 87% for current climatic conditions and 40% to 84% by 2080 Achieving nZEB standards	2020
Li and Wang	Coordinated robust optimal design of building envelope	Coordination of design optimization method of building envelope and energy system	Provide better services compared to current design methods at a lower cost	2020
Mahdavi Adeli *et al.*	Increasing thermal comfort of an nZEB	Using of computational fluid dynamics model to determine the temperature for thermal comfort	Using wind turbines for electricity generation in cold seasons as an appropriate substitute for the reduction in the electricity generated by photovoltaic panels	2020
Walter Costa *et al.*	Retrofit guidelines toward the achievement of nZEB	Investigation of the effect of an outer shell on energy consumption	Achieving the nZEB goal in the up to four-story office buildings	2020
Amani and Kiaee	Developing a two-criteria framework to rank thermal insulation materials	Using 12 typical insulation materials with different thicknesses, a four-layer insulation system was developed and applied to a Case study	more than 70% reduction in the energy demand and a global warming potential range of 192e1500 kgCo2 eq.	2020
Al-Saadi and Shaaban	ZEB in an extremely hot climate	Investigation of the data acquisition system for energy and thermal performance	ZEB is feasible in the extremely hot climate of Oman	2019
Salem *et al.*	Investigating the potential impact of energy-efficient measures for retrofitting existing UK hotels	Investigation of the effect of the building fabric and/or building envelope elements on energy consumption	Achieving the nZEB standard for older UK hotel buildings based on prioritizing improving the building fabric	2019
Sudhakar *et al.*	Net-zero building designs in hot and humid climates	Investigation of basic guidelines, natural ventilation systems, cooling and dehumidification, insulation and construction materials	Using the natural ventilation systems in places with high wind speeds Using different design strategies to achieve comfort performance in different seasons	2019
Liu *et al.*	Energy balance evaluation and optimization of photovoltaic systems for ZEB in different climate zones of China	Investigating the potential of PV systems for zero energy buildings in different areas of China Investigation of tilt angle, orientation, plot ratio, PV conversion efficiency and location Building simulation by RETScreen in combination with TRNSYS software	Southwest China was identified as the best place to develop zero energy buildings Low-rise and mid-rise residential buildings can realize zero energy in China when the PV conversion efficiency is higher than 20%	2019

(*continued*)

Table 1.

Author(s)	Objective	Research methodology	Achievements	Year
Danza *et al.*	The durability of technologies in the keeping of ZEB's performances	Definition of the reference building Definition of the refurbishment scenario The durability of the adopted technical solutions Analysis of the degradation of energy performance	ZEB performance in the building life cycle has decreased due to the instability of building materials	2018
Fonseca *et al.*	Achieving nZEB goals on the university campus	Using a wide range of technologies, systems and solutions	Achieving almost zero energy goals by the renovation with two main measures	2018
Albadry *et al.*	Achieving nZEBs through retrofitting existing residential buildings using PV panels	The use of polycrystalline solar cells in the optimization process	Increasing insulation surfaces to reduce energy consumption	2017
Charisi	The role of the building envelope in achieving nZEBs	Investigation of the effect of an outer shell, openings and shadows on energy consumption	Save up to 30% of energy and bring total annual energy demand to 50 kWh/m^2	2017
Ferrari and Beccali	Passive design strategies to complete a building aiming to approach a ZEB	Definition of frameworks for the formulation of statutory requirements	Primary energy demand and related CO_2 emissions can be reduced by up to 40%	2017
Lizana *et al.*	Advances in maintaining the thermal energy of materials	Review of recent advancements in the development of thermal energy storage materials for creating ZEB applications	Chemical and thermodynamic properties of materials for increasing the efficiency of maintaining the thermal energy were the most important factors	2017
Zhou *et al.*	Operational implementation of solar nZEB	Dynamic thermal simulation (DTS) with e-QUEST software	Development of new technologies (such as PV) and their generalization to diminish the initial cost of nZEBs	2016
Cellura *et al.*	Balancing various types of energy for redesigning nZEBs	Simulation of the study building called "Leaf Home" as the first nZEB	Proposing a framework to analyze different definitions and conventions for reaching the ZEB	2015
Li *et al.*	Simulation and comparison of the heating and cooling load	Developing the physical model of the building using the DeST software	Energy recovery can reduce over 72% of new loads	2015
Heravi and Qaemi	Building energy performance	Use of the mean score (MS) method to rank the design scales	Passive solar energy is the most applicable renewable energy system	2014

considering all the required frameworks. Most of the existing studies have used only one software tool to analyze energy efficiency in all stages of drawing, analysis and thermal simulation, which increases the probability of error. In the current study, one of the most powerful software tools has been used in each stage by examining the strengths and weaknesses of software. AutoCAD software has been used at the drawing stage to reduce the drawing and volumizing error. The *weather* tool was used in Ecotect software to analyze climatic data. Moreover, DesignBuilder software was used for dynamic thermal simulation (DTS) and analysis of the building, as well as was used the PVsyst software to design and evaluate the renewable energy yield. In general, the building was first designed and evaluated in Ecotect software in terms of optimum building orientation by considering parameters such as daylight, shade and wind. Then, the building energy consumption was evaluated in DesignBuilder software in two modes, with and without complying with the principles of sustainable design. Finally, based on the optimum annual tilt angle of Mashhad, the energy produced by the solar panels in PVsyst software was estimated and compared with the energy consumption of the building. The findings showed that complying with the principles of passive design in the building will significantly reduce energy consumption and achieving zero energy in the building at a lower cost will be more practical.

Problem statement

Given the rapid economic development of metropolitan cities in Iran, the construction industry has entered its critical phase. According to the latest information, about 260 million m^2 of buildings are constructed annually (Sheykhansari, 2016). The residential, commercial and office buildings have accounted for the highest energy consumption, about 40% of the total energy produced in the country (Amani and Reza Soroush, 2020). Therefore, supporting the use of environmental energy and the development of green and zero-energy buildings has become an important activity in Iran. The solution to the problem is to provide the energy needed by any energy-consuming system, including the building within the same set to overcome the energy crisis and reduce greenhouse gas emissions. A vision that changes the quality of life and prepares us for life in the new era. In this regard, to create the best conditions in the building is emphasized the study of the architecture of buildings with the minimum energy required and the maximum use of solar energy. This study was accomplished by focusing on the feasibility of constructing a ZEB using computer simulation and analysis, in the cold and semi-arid region of Iran. A case study was selected by choosing the best computer simulation in the cold and semi-arid region using Ecotect and DesignBuilder software, taking into account all the required frameworks. Table 2 shows the design of ZEB design.

Research methodology

The building energy consumption strategy in this study was conducted with the approach that the researchers were pursuing to develop a sustainable and environmentally friendly adaptive model. This study was performed in four stages. The first step involved collecting data and

ZEB design	Passive design methods	Choosing suitable orientation, choosing proper insulation, the position of windows, walls, porches, canopies and trees, using double-glazed windows with low emissivity coefficient, Trombe walls, green roof and canopy
	Active design methods and renewable technologies	Solar PVs, wind turbines, fuel cells, solar water heaters and heat pumps

Table 2. The design phases of the zero-energy building (ZEB)

analyzing the site during the hottest month of summer and the coldest month of winter in cold and semi-arid weather. The data collected were classified into two groups. The first category included a set of annual temperature data and the second one was a list of the building components, including the specification of materials and their implementation details. These data were used for computerized simulations to thermal analysis of the model, its energy performance and the design of an appropriate PV system in the software. The most important data analyzed were associated with the proper orientation of the structure for maximum use of the sun, the amount of annual energy required for building and the amount of energy derived from the solar system in cold and semi-arid climatic conditions. In the second stage, a computer model was simulated to validate the proposed design using the data calculated. DesignBuilder is a graphical software for simulation of energy consumption in the building, in which the problem solution is performed by the powerful "EnergyPlus" engine. The EnergyPlus simulation engine has been developed by the US Energy Department in 2011 and is recognized as one of the most prestigious energy modeling software. The reliability of the Energy Plus software has been confirmed, according to Building Energy Simulation Test (Bestest) and ASHRAE 14 standards (Zomorodian and Tahsildoost, 2015; Naghdalizadeh and Heybati, 2015). Energy simulation software such as eQuest, DesignBuilder and Ecotect are widely used to model the energy performance of buildings (Ham and Golparvar-Fard, 2013). PVsyst software is used to design a renewable energy system. This software is comprehensive and applied software in the field of solar systems, which includes a set of tools for examining, sizing, simulating and analyzing data of PV systems. This software, which is continually developed at the University of Geneva in Switzerland, is one of the most important and most widely used software tools in the design of solar systems. In the third stage, two buildings, one in accordance with the principles of sustainable design (Trombe wall, optimal orientation, canopy, proper insulation selection) and one without these principles, were designed and simulated under different conditions to compare their energy and environmental performance. Moreover, at this point, the solar photovoltaic system (PV) was designed to obtain as much renewable energy as possible. In the final stage, an adaptive comparison was made to specify the amount of energy reduction with respect to the principles of sustainable design, as well as the feasibility of building a ZEB in a cold and semi-arid climate. As the ZEB refers to its grid-connected type, if the energy obtained is less than the required amount of energy over a few consecutive cloudy days, the building will provide its energy from the power grid and in days when the system has surplus energy, this energy will be injected into the grid. Hence, the annual energy required for the building and energy yield of the renewable energy system can be compared with each other. Figure 1 shows the steps of the study method in the following flowchart format.

Weather data

Stage one: The 1-h climate data of Mashhad was used based on the climatic data of 1991–2010, using the Meteonorm software database. Mashhad is located at the latitude of 36.2605° N, the longitude of 59.6168° E and an altitude of 985 m. The city is topographically composed of two types of terrains of mountainous and plain. Based on the climatic classification, Mashhad is located in a cold and semi-arid climate (Kasmaei, 2006). The average annual temperature and precipitation in Mashhad are 15.3°C and 217.38 mm, respectively. In addition, the hottest and coldest months are July and January, with an average temperature of, respectively, 27.4°C and 3.3°C (Climate, 2016). The 12-year-old weather data of Mashhad (2002–2014) was collected from the regional weather station as an annual indicator according to the recommendations of the same station. This collection of climatic information was used in thermal modeling to predict annual energy consumption and building optimal orientation under various

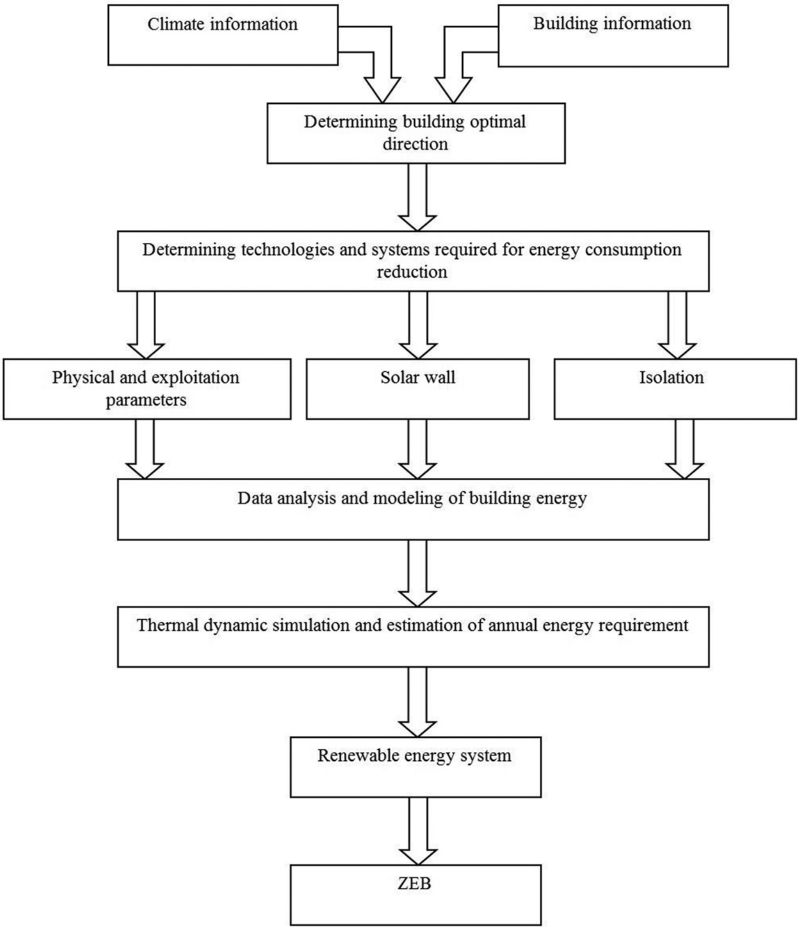

Figure 1.
Research method flowchart

atmospheric conditions. These data, while being compared with the output file from the Meteonorm software, were imported from the *Weather* tool of the Ecotect software and were displayed as the analytical results (Sabet Dizavandi, 2017). This tool is capable of calculating the amount of solar radiation received on a vertical plate with a surface area of 1 m^2 in warm and cold periods, as well as the whole year. It can also provide the most proper and the most improper orientations of the building in terms of obtaining radiation. The cold months of the year for the city of Mashhad included December, January and February, as well as the warm months, were June, July and August. Figure 2 displays the solar protractor to determine the radiation level in different directions.

In Figure 2, the yellow-red spectra represent the most appropriate and most inappropriate orientations of the building in terms of solar radiation. Figure 3 shows the direction and amount of wind. This figure shows that the dominant winds of Mashhad are from east to west, so the length of the building sides should be as low as possible in the east to the west direction. Hence, the building will be exposed to the least effect of the adverse wind in the winter.

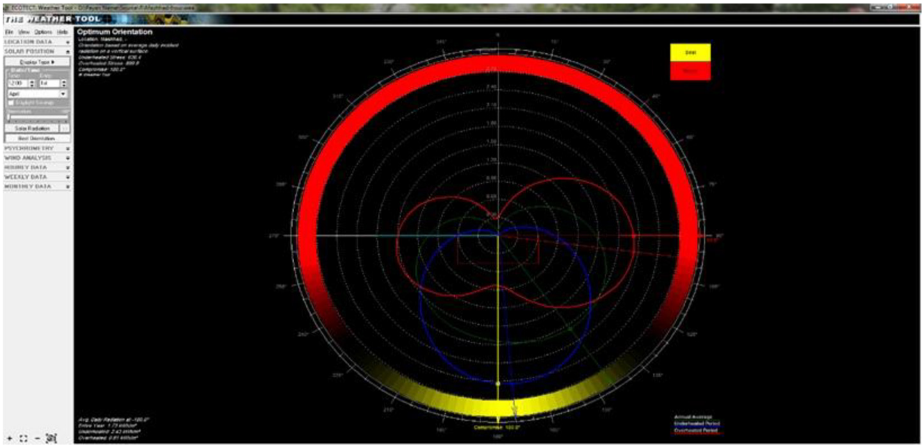

Figure 2.
Solar protractor, the most appropriate and most inappropriate orientations of the building

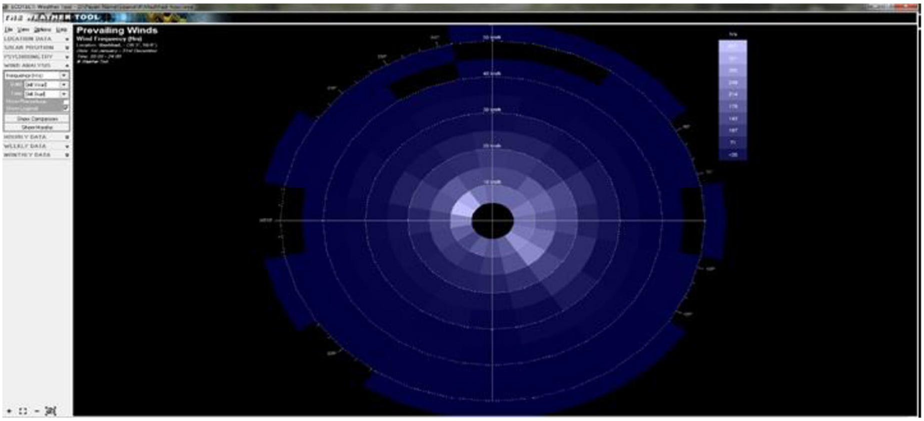

Figure 3.
Protractor of regional winds around the building

Given Figure 4, the building plan was designed in a direction that it was exposed to cool northern winds in the summer and is free from cold winds in the winter. Therefore, the building plan has an eastern-western extension for maximum use of solar heating and natural light, plus, the most commonly used and the unused spaces lay on the southern and northern sides, respectively.

Model specifications and software data

The second stage included the simulation of a residential building with an area of 100 m^2 and a height of 3 m. Table 3 indicates the specifications of the materials of the boundary elements.

Given the residential use, four individuals were considered to reside full-time on all days of the year. Also, natural light could be used in all directions of the building. Table 4 indicates the input data to the DesignBuilder software.

To examine and compare the annual energy consumption of the modeled building with a building in which the principles of sustainable design have not been met, the simulation

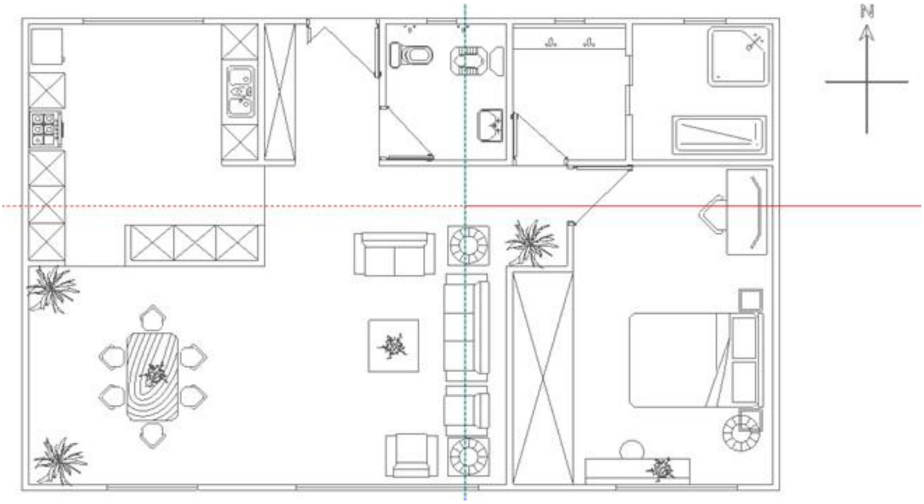

Figure 4.
Plan of the building modeled

Elements	Specifications of materials	Heat transfer coefficient (W/m^{2}K)
Outer walls	100 mm Brickwork outer + 79 mm Extruded polystyrene + 100 mm Concrete block	0.35
Ceiling	19 mm Asphalt + 13 mm fiberboard + 122 mm Extruded polystyrene	0.25
Floor	30 mm Timber flooring + 70 mm Floor screed + 100 mm Cast concrete + 59.6 mm Formaldehyde foam	0.46
Windows	Triple layers + Argon 13 mm (Window gas type)	1.635
Entrance door	35 mm Wooden door	2.823

Table 3.
Specifications of materials of elements in the DesignBuilder software

No. of residents	4 persons	Coefficient of performance (Cop) of the cooling system	0.45
Use	Residential	Cop of the heating system	0.85
Building dimensions (m)	8*12.5*3	External wall heat transfer coefficient	0.35 (W/m^{2}K)
Plan elongation	East-West	Ceiling heat transfer coefficient	0.25 (W/m^{2}K)
The building orientation, panels and collectors	South	Floor heat transfer coefficient	0.46 (W/m^{2}K)
WWR (window to wall ratio)	20%	Window heat transfer coefficient	1.635 (W/m^{2}K)
Lighting rate	300 Lux	Door heat transfer coefficient	2.823 (W/m^{2}K)
Heating set temperature	20°C	Air penetration rate	1.8 AC/H
Cooling set temperature	26°C	Heater set temperature	65 °C

Table 4.
Input data to the DesignBuilder software

process was performed again in a similar building in terms of the number of inhabitants and the area, as well as the thermal zones, without considering the appropriate angle and other passive design principles and systems. The input data of this conventional building were in accordance with Tables 5 and 6.

Table 7 shows the input data to the PVsyst software for the design of the PV solar system. The optimum tilt angle for panels in Mashhad is 30° (Taheri *et al.*, 2013).

Figure 5 shows the simulation steps in the DesignBuilder software. These steps include calling the two-dimensional (2D) output file from AutoCAD with the "dxf" extension, defining the thermal regions and boundary elements, assigning materials of elements (walls, floor, ceiling, door and windows), as well as calling the climate file with the "epw" extension, defining the geographic coordinates and designing cooling, heating and lighting systems.

To design a solar system in PVsyst software, a climate file with the "dat" extension was first called from the output of the Meteonorm software database. Figure 6 shows the input information for designing the PV system in PVsyst software. This information included the type of solar cells, the type of solar cell array, the type of solar module, the pitch for shadow overlap, the tilt angle of the panels, the width of the panels and the number and the nominal power of the panels.

Table 5.
Specifications of materials of elements in the DesignBuilder software for the conventional building

Elements	Specifications of materials	Heat transfer coefficient (W/m^{2}K)
Outer walls	100 mm Brickwork outer + 200 mm Concrete block	1.80
Ceiling	20 mm Asphalt + 80 mm Slab Concrete	2.25
Floor	200 mm Cast concrete	2.12
Windows	Double layers + Argon 7 mm (Window gas type)	2.412
Entrance door	35 mm Wooden door	2.823

Table 6.
Input data to the DesignBuilder software for the conventional building

Number of residents	4 persons	Cop of the cooling system	0.45
Use	Residential	Cop of the heating system	0.85
Building dimensions (m)	8*12.5*3	External wall heat transfer coefficient	1.80 (W/m^{2}K)
Plan extension	North-South	Ceiling heat transfer coefficient	2.25 (W/m^{2}K)
The building orientation, panels and collectors	North-East	Floor heat transfer coefficient	2.12 (W/m^{2}K)
WWR (window to wall ratio)	30%	Window heat transfer coefficient	2.412 (W/m^{2}K)
Lighting rate	300 Lux	Door heat transfer coefficient	2.823 (W/m^{2}K)
Heating set temperature	20°C	Air penetration rate	1.8 AC/H
Cooling set temperature	26°C	Heater set temperature	65 °C

Table 7.
Input data in PVsyst software

Panel type	Monocrystalline	Short circuit current	5.65 A
Width of the PV array	2 m	Open circuit voltage	52.3 V
Nominal power of panels	16 kW	Panel efficiency	17.45%
Number of panels	12	Pitch	6.6 m
Rated power	220 W	Tilt angle	30°

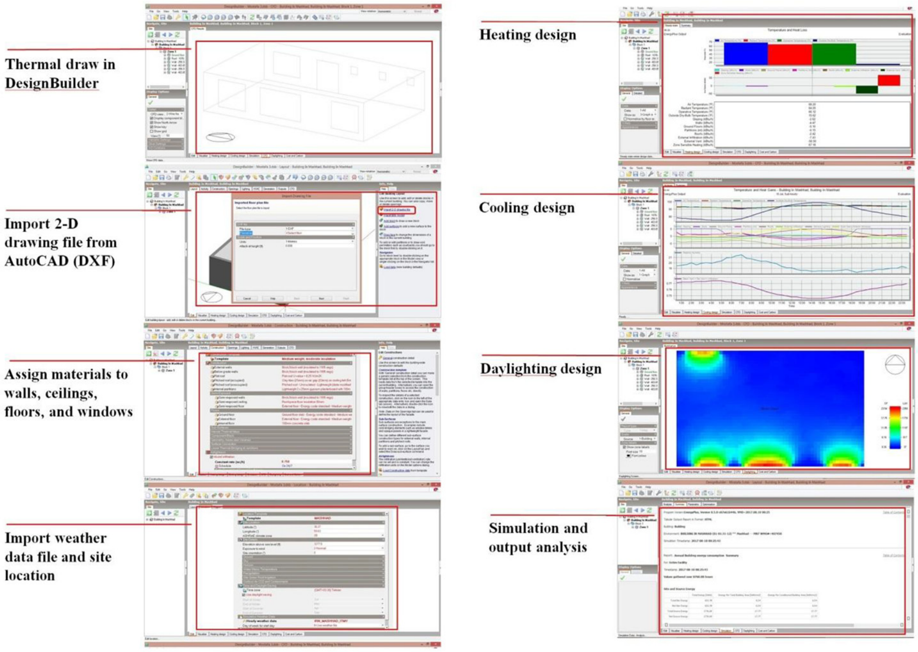

Figure 5.
Simulation steps in the DesignBuilder software

Software simulation

In this study, building energy simulation was performed in DesignBuilder software. This software is capable of calculating energy consumption in less than 1-h intervals and can simulate the space of a building that is composed of several thermal zones with different ventilation conditions, and hence is suitable to calculate the amount of energy consumed in the building (Zomorodian and Tahsildoost, 2015). Accordingly, DesignBuilder was chosen as the simulation software in the present study and the PVsyst software was used to design the renewable energy system.

Third stage: the simulation results using the DesignBuilder Results View tool were provided in a table including the amount of annual energy required for the structure, the energy required by the structure per square meter, the structure carbon use during the structure life cycle, the rate of the annual production of greenhouse gases, estimation of recycling rate and structural waste in the useful life of the structure in the form of an HTML file. Table 8 shows the amount of energy required for a model simulated, taking into account the principles of sustainable design and passive architecture (optimal selection of direction, Trombe wall, canopy, selection of proper insulation).

Based on Table 8, the amount of energy required of the building was 65.38 kWh/m^2 and the total annual energy required of the building was equal to 17,767 kWh; considering the electrical devices including an LED lighting system, a computer, a pump, a chiller and common types of kitchen and administrative equipment for the four residents of the building.

Table 9 shows the amount of energy required for a model simulated without respecting the principles of sustainable design and passive architecture (optimal selection of direction, Trombe wall, canopy, proper insulation selection). As shown in Table 9, the annual energy required by a conventional building without respect to the principles of the passive architecture, taking into

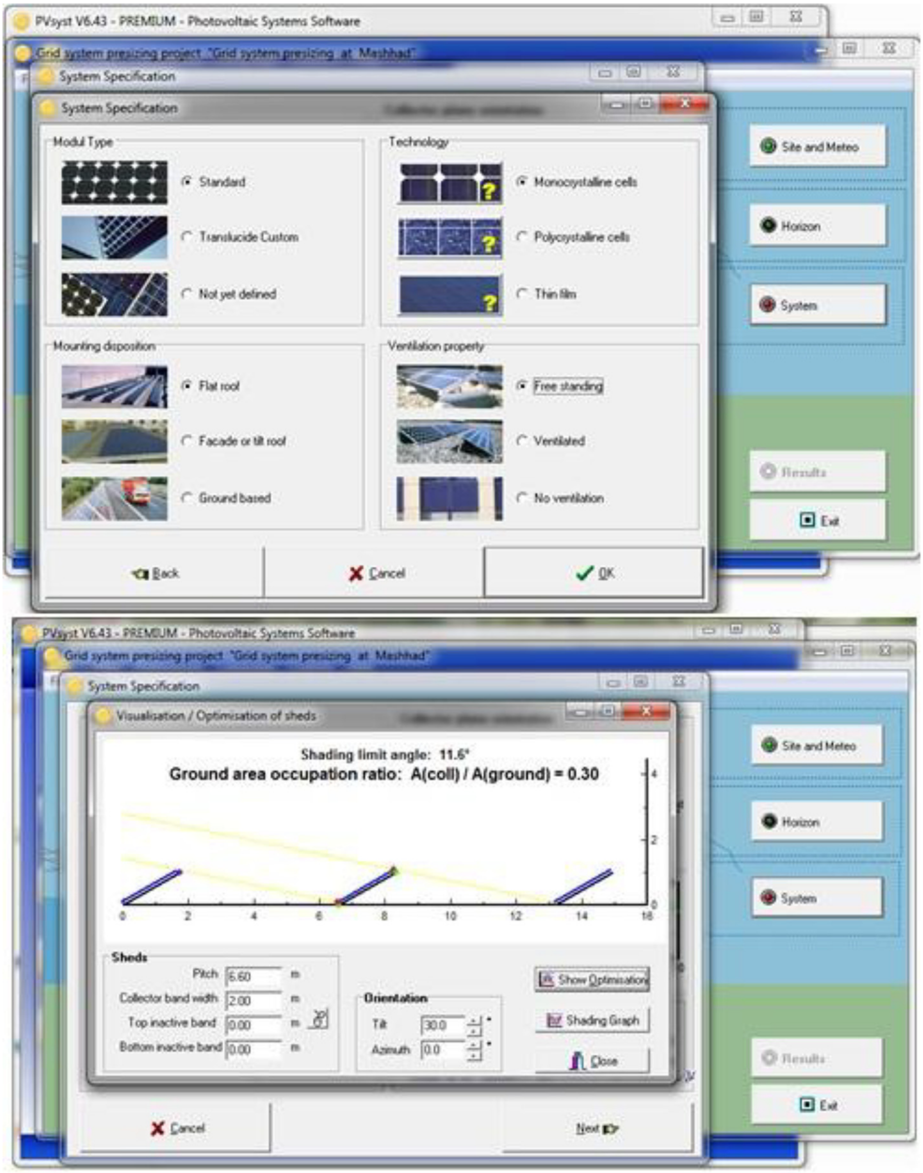

Figure 6.
Input data for the photovoltaic system design in PVsyst software

account electrical equipment including a lighting system, a computer, a pump, a chiller and various common kitchen and administrative equipment for four residents of the building is equal to 25,443 kWh, and hence the amount of energy needed of the building is 98.5 kWh/m^2.

In Figure 7, the horizontal and vertical axes represent, respectively, the year and the average amount of energy obtained per month in kWh/day. Given this figure, the highest rate of energy has been produced in June, July, August and September and its lowest levels have been produced in November, December, January and February. A comparison of this amount of energy with the average monthly energy demand indicated that there was an energy surplus in July and August that was injected into the electricity distribution grid. However, there was an energy shortage in December and January, which had to be provided from the grid. The results have shown that the annual energy yield of the PV solar system is equal to 26,291 kWh/year.

Comparative analysis

Final stage: One of the causes of heat dissipation in buildings is the incorrect behavior and habits of some users. Opening the window to regain thermal comfort due to overheating in

	Total energy (kWh)	Energy per total building area (kWh/m^2)	Energy per conditioned building area (kWh/m^2)
Total site energy	6,537.9	65.38	65.38
Net site energy	6,537.9	65.38	65.38
Total source energy	17,767	177.7	177.7
Net source energy	17,767	177.7	177.7

Table 8. Annual building energy consumption in DesignBuilder software

	Total energy (kWh)	Energy per total building area (kWh/m^2)	Energy per conditioned building area (kWh/m^2)
Total site energy	9,854	98.5	98.5
Net site energy	9,854	98.5	98.5
Total source energy	25,442.7	254.4	254.4
Net source energy	25,442.7	254.4	254.4

Table 9. Annual energy consumption of the building in DesignBuilder software without passive architecture

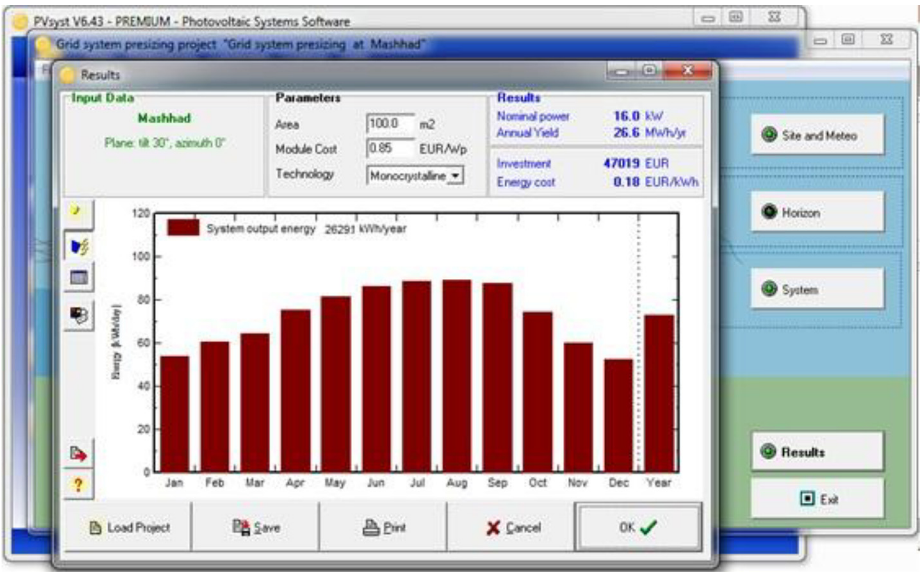

Figure 7. PV system energy production graph by month in PVsyst software

the cold season and rising humidity in the hot season, as well as the use of artificial lighting, despite the presence of sufficient natural light, due to improper design of space are among these habits. Due to the lack of sufficient information to achieve a comfort level such as consumer exploitation pattern, modeling and operational errors, material quality, accurate determination of cloudy days and building occupancy conditions (comfort temperature and type of occupant coverage), was considered a safety factor with a coefficient of 1.4. Table 10 shows the results of the thermal analysis of the building with and without observing the principles of sustainability and the annual energy yield of the photovoltaic system.

As previously mentioned, the Ecotect analysis specified the appropriate orientation of the structure as the north-south direction to the south in the area. Observing the principles of sustainable and passive architecture, including the use of Trombe wall, canopy and needle-leaved trees in the wind-catching side of the plan and selection of the optimal design orientation for maximum use of the sun with respect to the surrounding winds, decreased the amount of energy by 30% in the building studied, reducing this amount from 25,443 kWh/year to 17,767 kWh/year. The capacity of the photovoltaic system was determined based on default items in PVsyst software (as shown in Table 7 and Figure 6). As a ZEB is of the grid-connected type, the energy storage system was not considered in this study. Hence, if the energy obtained is less than the required amount of energy over a few consecutive cloudy days, the building will provide its energy from the power grid and in days when the system has surplus energy, this energy will be injected into the grid. Thus, the annual energy required of the building and energy yield of the renewable energy system can be compared with each other. As explained, the energy required for the building by complying with the principles of sustainable design is 17,767 kWh/year. Also, the energy produced by the photovoltaic system will be equal to 26,291 kWh per year, which is about 48% more than the energy required by the building. Hence, considering the 30% reduction in energy requirements of the building and the monthly energy produced by the photovoltaic system, as shown in Figure 7, it can be met that achieving the zero-energy building goals is possible, albeit the need for economic analysis.

Conclusion

A review of past studies shows that 50% of the world's raw materials are used in buildings. In Iran, the construction sector, with an average consumption of 41.42%, has a high share of energy consumption in the country. Meanwhile, according to published statistics, Iran is ranked 11th among the countries with the highest rates of energy consumption. As many Iranian cities have a cold and semi-arid climate, the energy consumption rate is significant in these areas. In this study, aiming to examine the feasibility and simulate the ZEB in the cold and semi-arid climate of Mashhad, Meteonorm software was used to obtain meteorological data of the study area. AutoCAD and Ecotect software were used to create, volumizing and analyze climatic data in the case study building. Also, DesignBuilder and PVsyst software were used for thermal simulation and renewable energy system design,

Table 10. Comparison of software results

Energy	Total annual energy (kWh)
Amount of energy required for building without observing the principles of sustainability	25,443
Amount of energy required for building with observing the principles of sustainability	17,767
Amount of energy required for building taking into account a safety factor of 1.4	24,874
The energy yield of the PV system	26,291

respectively. The simulation results show that the annual energy requirement of the case study building based on the principles of sustainable design and passive architecture (Trombe wall, optimum direction, shading and proper insulation) was equal to 17,767 kWh/year. As mentioned, taking into account the safety factor of 1.4, energy consumption was estimated to be 24,874 kWh/year and proportionally, a renewable energy system using solar panels was designed for the building with a production capacity of 26,291 kWh/year. By adaptive comparison of these values, it can be concluded that constructing a ZEB in the cold and semi-arid climate of Mashhad is feasible. Observing the principles of sustained and passive architecture reduced energy consumption by 30% in the building under study. Decreasing this rate was from 25,443 kWh/year to 17,767 kWh/year, which is considered an effective step to achieve sustainable and environmentally-friendly construction. A summary of the key findings of this study is provided below:

- Optimization of building orientation.
- Significant reduction of building energy consumption by complying with the principles of sustainable design.
- Achieving ZEB at a minimum cost by considering the principles of passive design.
- Possibility of using the ZEB in the cold and semi-arid climate.

In designing buildings with zero energy, in addition to environmental aspects such as reducing energy consumption, economic and socio-cultural aspects should also be considered. The high potential of solar energy in Iran to diversify the energy basket and create a platform for the development and promotion of renewable energy provides the possibility of exploiting this endless resource.

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