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A comprehensive feasibility study of applying solar energy to design a zero energy building for a typical home in Tehran

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ABSTRACT

In this paper, a comprehensive feasibility study of solar zero energy building for a typical detached house in Tehran is investigated. This house is designed with respect to a moderately warm climate and a family of four members. Using meteorological data, house loads are calculated. Substantial part of total heating and cooling load is provided by applying Trombe-wall, roller shading and thermal mass as main passive strategies. A solar absorption heat pump is utilized to supply both heating and cooling demands. An optimization is done to determine the appropriate combination of flat-plate and evacuated collectors. Domestic hot water demand is also supplied through the common tank. Fiber optics provides the lighting by transmitting natural sunlight to the inner spaces of the house. DIALux 4.1 is used to model the lighting system. Photovoltaic panels are chosen to generate electricity that is stored in batteries. Remaining energy is sent to the grid. Regarding environmental features, rate of reduction of released CO_2 to the atmosphere is calculated per house. Finally, by exploiting present worth method, rate of return is discussed with respect to present energy cost. Sensitivity analysis shows that only with actual prices of energy and low interest rate, the investment is justified.

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1. Introduction

Today, world's energy resources are depleting fast and this issue has placed the world in the grip of energy crisis. In addition, increase in the amount of worldwide CO_2 emissions is damaging the ozone layer. In Iran, buildings are responsible for 25% of greenhouse gas emissions due to the use of natural gas and oil products. Also 36.25% of energy usage belongs to the buildings. This is equal to consumption of 432.4 million barrels of crude oil and 85% of this amount of energy is provided by natural gas and electricity [1]. Therefore, it is essential to take actions towards finding alternative sources of energy as well as conserving non-renewable energy resources. Solar energy is one of the solutions for the world's energy requirements and is the way of the future. Green and energy efficient buildings such as ZEBs[1] have attracted the governments' attention.

There are many definitions presented for the ZEBs. In the report written by Torcellini et al. [2], authors used the general definition for ZEB given by the U.S. Department of Energy (DOE), Building Technologies Program: "A net zero-energy building is a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies."

Charron [3] gave even a definition for zero energy solar homes: "Homes that utilize solar thermal and solar photovoltaic technologies to generate as much energy as their yearly load are referred to as net-zero energy solar homes."

Studies with clear definition for grid-connected ZEB belong to e.g., Gilijamse [4], Sartori [5], Iqbal [6], Laustsen [7] and the definition which indicates the best main features of this kind of ZEB formulated by Laustsen [7],: "Zero net energy buildings are buildings that over a year are neutral, meaning that they deliver as much energy to the supply grids as they use from the grids. Seen in these terms, they do not need any fossil fuel for heating, cooling, lighting or other energy uses although, they sometimes draw energy from the grid."

The definition given by Laustsen [7] for International Energy Agency (IEA) is among many definitions for the off-grid ZEB: "Zero stand alone buildings are buildings that do not require connection to the grid or only as a backup. Stand-alone buildings can autonomously supply themselves with energy, as they have the capacity to store energy for night-time or winter time use."

There are many different types of ZEBs and NZEBs studied all around the world [8–10]. Thus, every building has used a different

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[1] Zero Energy Buildings

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Table 1
Radiation data for different months on different slopes (MJ/m^2) [19].

Slope	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
80	14.24	16.09	14.39	12.87	12.34	12.00	12.33	14.01	16.36	17.08	15.08	12.27
65	14.47	16.64	15.99	15.64	15.71	16.04	16.37	17.85	19.50	19.02	16.11	12.74
60	14.41	16.69	16.40	16.45	16.76	17.34	17.65	18.99	20.35	19.45	16.27	12.77
55	14.29	16.67	16.74	17.19	17.75	18.59	18.87	20.05	21.08	19.77	16.33	12.72
40	13.54	16.18	17.33	18.96	20.30	21.92	22.08	22.64	22.57	20.03	15.92	12.20
35	13.18	15.96	17.46	19.40	20.97	22.86	23.01	23.42	23.15	20.27	15.81	11.93
30	12.74	15.52	17.36	19.71	21.58	23.70	23.76	23.80	22.93	19.62	15.18	11.54
20	11.73	14.62	17.09	20.08	22.49	25.06	25.00	24.46	22.77	18.75	14.08	10.66
15	11.15	14.09	16.85	20.12	22.79	25.58	25.45	24.60	22.50	18.15	13.41	10.14
10	10.54	13.51	16.53	20.07	22.98	25.98	25.78	24.61	22.09	17.45	12.66	9.573

method for thermal energy collection and storage system. Some of them are described in the following. The seasonal heat storage system studied by Kroll and Ziegler [11] used 20–40 m^2 evacuated tube collectors for a single family detached house and a large thermally insulated soil based seasonal heat storage system. For this system, the larger solar panel area was able to achieve a space heating solar fraction above 80%. In the case of storage system, N. Soares et al. explored how and where phase change materials are used in passive latent heat thermal energy storage systems, and presented an overview of how these construction solutions are related to building's energy performance [12]. Another approach for thermal energy collection and storage was presented by Chen et al. [13]. In this system a geothermal heat pump was powered by integrated PV panels that collect thermal energy as well. Their system had the advantage of eliminating the need for conventional solar thermal panels, but it was comparatively less efficient (approximately 20%). Also, using air as the heat transport fluid made thermal storage very difficult. Another interesting energy system variation presented by Bojic′ et al. [14] was the combination of a PV system with a ground source/geothermal heat pump heating system.

There are several renewable energy systems that can be used in a ZEB: solar panels (thermal and electric), small wind [6,15] and hydro electrical generators, etc. Middle-east countries, especially Iran, have high solar irradiation, which makes the use of solar panels (both thermal and photovoltaic) an increasingly popular option [16]. This study will focus on solar energy as the only renewable energy source. The proposed renewable energy system will be based on solar thermal panels and a grid-connected PV array (the grid-connected PV is used only to sell excess electricity). The building uses an optimal combination of evacuated and flat plate collectors and PV panels to provide 100% of its net energy use. In addition, in emergency, an auxiliary system would help the collectors to supply the demand. This home harvests daylight to reduce electricity consumption by using large glazed south-facing windows and fiber optics. Also, it provides a high efficiency HVAC system and uses highly rated insulation and roller-shading. Besides, in winter time, Trombe-wall as a passive strategy, supplies a portion of heating load in one of the house zones. Also, external shading makes reduction in initial summer cooling load. The risk factor is defined for days without sunlight to guarantee the occupants' needs. One of the most important objectives pursued in this home is eliminating the natural gas consumption needed for cooking by using an electrical oven. The study presented in this paper traces the following steps:

(1) Studying the weather and solar radiation data.
(2) Calculating the house heating and cooling loads.
(3) Describing the passive strategies used in the house.
(4) Achieving energy demand profiles:
  (a) Thermal energy for ambient heating and cooling.
  (b) Thermal energy for domestic hot water (DHW).
  (c) Electrical energy for lighting and appliances.
(5) Designing an active system for heating and cooling and hot water demands.
(6) Modeling the lighting and energy storage system.
(7) Studying the economic features of the building.

2. Solar radiation data

Climate data analysis should be the primary step for each energy efficient building or zero energy building design. The meteorological data for Tehran is analyzed considering some factors such as cloudy days, solar radiation and ambient temperature. These radiations are verified by the theoretical calculations based on methods that are introduced in Duffie [17] text and data given by Saghafi [18] for Tehran.

Table 1 demonstrates the amounts of monthly average solar radiation on different slopes. It is found that the amount of solar radiation is generally high from March to October. Based on reports, Tehran has approximately 4397 h sunshine in a year. The annually highest statistics dry bulb temperature is 36.8 °C and lowest statistics dry bulb temperature is −4 °C [19–21].

The bold values in Table 1 show the optimized slope in each month, which has the maximum radiation. It can be found from Table 1 that in summer months the optimum slope is about 20 degrees below the location latitude and in winter months is around 20° above the location latitude [18].

3. Passive strategies

To use solar energy in natural lighting and thermal comfort, passive design strategies have key roles. To gain the maximum solar energy, many different methods are available. Two common methods used in this study are discussed below:

Direct gain. In this method, large glazed south-facing windows are used in order to gain the direct solar energy for natural lighting and thermal energy. Shading and thermal mass used in dining room and kitchen prevent the home from being overheated. 18 m^2 concrete slabs with 25 cm height are used in this zone to appoint thermal comfort as a material with high thermal capacity. The area of glazed south-facing windows is about 14% of floor area. Moreover, the windows used in other sides of the house have the minimum area.

Indirect gain. Trombe-wall provides 42 percent of heating load that is required for the larger bedroom. This 5.5 m^2 wall has a canal with capacity of 0.825 m^3 air with two vents, one in top and the other 2.5 m downer. In a day in January with ambient temperature of −4 °C this wall provides 360 W of heating load for the larger bedroom.

The orientation of different parts of the home is based on passive design in order to use the daylight and solar thermal energy. The kitchen, dining room and larger bedroom are located on the southern side of the home. Living room and the other bedroom are located on the northern side. All the windows are shaded by

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