Designing Zero Energy Building for Tehran

N.Mirkhani[1] and S. Sadoughi[2] and J. Eshraghi[3] and N. Narjabadi[4] and A. Nakhaei[5]

[1] Senior student at Faculty of Mechanical Engineering, University of Tehran, Iran
[2] Senior student at Faculty of Mechanical Engineering, University of Tehran, Iran
[3] Senior student at Faculty of Mechanical Engineering, University of Tehran, Iran
[4] Senior student at Faculty of Mechanical Engineering, University of Tehran, Iran
[5] Senior student at Faculty of Mechanical Engineering, University of Tehran, Iran

Email: s.n.mirkhani@ut.ac.ir

1. Abstract

In this paper, design of a zero energy building (ZEB), a case study for Tehran, in a moderately warm climate, for a typical single family has been introduced. It is important to develop solar energy resource potential in order to use it in construction of enhanced buildings. The benefits including reducing fossil fuel consumption, fading energy supply cost and lowering environmental pollutants, have created a growing tendency to these types of buildings. Calculating solar energy radiation and the house load are the basic steps to design a ZEB. Following steps are designing the heating, cooling and domestic hot water (DHW) systems and providing the electricity for appliances and lighting and designing the storage system. Economical features and environmental issues make ZEBs an appropriate solution for emerged problems of common houses and thus investments in large (state-wide) scales may be justified.

Keywords: Case Study for Tehran, Economical Features, Environmental Issues, Solar Energy, Zero Energy Building

2. Introduction

Energy is one of the most interesting topics for scientists to explore. Improving efficiency of energy consumption in buildings is a response to increased energy costs and lack of energy supplies. ZEB is one of the solutions to decrease greenhouse effect.

A zero energy building refers to a building with net zero energy consumption over a typical year. Such buildings can be dependent or independent on the electrical grid. A grid disconnected ZEB is difficult to implement, both from an economical and technical point of view due to the seasonal mismatch between energy demand and renewable energy supply. So approaching a Net ZEB (NZEB) is necessary: A grid connected ZEB does not require on site electrical energy storage, any surplus in electricity production is injected into the grid, conversely, when production is insufficient, the building draws from the grid.

The goal which is followed in this case study paper is not only to minimize the energy consumption of the building with passive design methods, but also to design a building that balances energy requirements with active techniques and renewable technologies (for example, solar photovoltaic panels and solar thermal). The further goal is to approach a zero energy building which does not need any input even though it can export electrical power to the grid when it has excess power generation. Another goal in this design is to the reduce carbon dioxide emissions in order to help scientists and environmental experts who are trying to find advanced technologies to diminish carbon dioxide emission.

In this 100 square meter home, solar energy is the main supply which provides thermal comfort, hot water and electricity needs, using combination of collectors and photovoltaic panels. Special insulations as a construction technique used in passive design cooperated with blind shading resulted in our goal, a super insulated home! HVAC requirement is met by both passive and active approaches with respect to moderately warm climate in Tehran. An absorption chiller as an active system has been utilized to support both heating and cooling. This system absorbs solar energy by making use of an optimized combination of flat-plate and evacuated collectors. And domestic hot water demand (DHW) is also supplied in part of our main absorption cycle to reduce the size of the equipment and consequently decrease the costs. In case of inadequate radiation, auxiliary system contributes the main system to meet the demands of this home. Several batteries are used to save extra energy from PV cells during the day for necessary conditions like night-time or cloudy days. To decrease energy consumption, LEDs and fiber optics used in lighting system. Fiber optics can transmit natural sunlight to the inner spaces of the house. Off-grid solar photovoltaic system has been chosen for energy storage. Stored energy utilized in appliances, lighting, HVAC auxiliary system and controllers. Biogas as an auxiliary system has been used to prevent usage from the stored energy in batteries.

The study presented in this paper, traces the following steps:

1. Describing the passive strategies used in the house.

2. Calculating maximum heating and cooling load for Tehran

3. Exploring the solar radiation data

4. Predict energy demand profiles:

    a. Thermal energy for ambient heating and cooling.

    b. Thermal energy for domestic hot water (DHW).

    c. Electrical energy needs for lighting and appliances.

5. Designing an active system for heating and cooling and domestic hot water (DHW).

6. Perform the lighting and energy storage system.

3. Passive Strategies

To use solar energy in natural lighting and thermal comfort, passive design strategies have key roles. Shading and thermal mass are also used to obtain the optimum solar energy.

To gain the maximum solar energy many different methods are available, three of which are used in this study:

a. 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 needs. Large amount of glazed south-facing windows can cause overheating. In this house, shading and thermal mass which are used in dining room and kitchen maintain the home from overheating. The area of south-facing window is about 9 percent of floor area. In addition, the windows used in other sides of the house have the minimum area.
b. Indirect gain. Trombe-wall which is used in the larger bedroom provides more than 40 percent of heating load required for this zone. In winter time, when the air located in the upper vent is nearer to the comfort condition more than room air, the vent would open and the air is circulated in the room until it reaches the comfort condition. Then, the vents would become closed again.
c. Isolated gain. In order to save the energy, there is a glazed room which is located at home entrance.

The orientation of different parts of home is based on passive design in order to use the day light and solar thermal energy. The kitchen, dining room and larger bedroom are located on the southern side of home and living room and the other bedroom are located on the northern side.

All the windows are shaded by different types of shadings based on their location. For example, all south-facing windows are shaded by roller-shading. An important goal followed in passive design is reduction in energy loss of home. This is where insulation plays a vital role. Creating super insulation conditions is followed in this project strongly by choosing materials with low overall heat transfer coefficient.

4. Architecture

This study builds on a 96m^2 (12^m×8^m), single-story house with two bedrooms. The plan of the house is shown in figure below. Table 1 show the construction material used in the house. The U-value of building elements are indicated in Table 2.

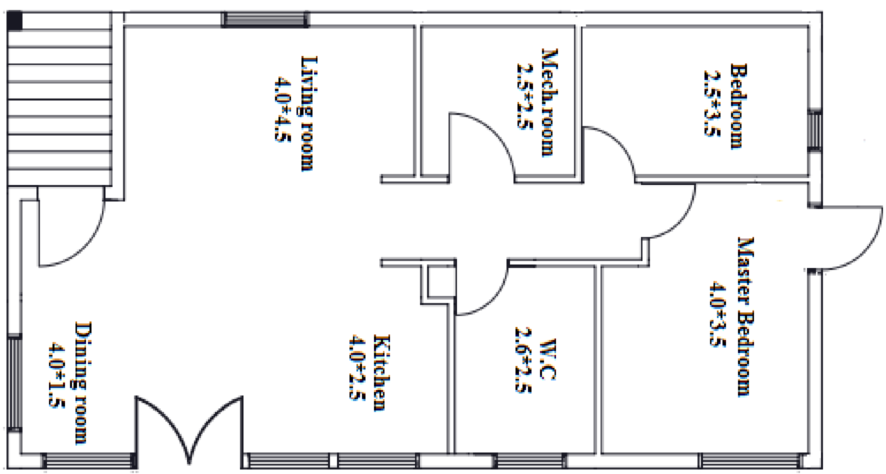

Fig.1. House plan

Table 1: Building construction materials

Building elements	Materials
External walls	Concrete block and brick
Glazing	Double insulating glass (suspended film and low-E)
Internal partitions	Plasterboard and insulation
Roof construction	Concrete tiles, felt/underlay
Doors	Metal Insulating (2” w/urethane)

Table 2: U-Value of different parts of house

Building elements	U-Values ($\boldsymbol{Btu/ft^2.hr}.$°F)
Exterior walls	0.02
Interior walls	0.038
Outside doors	0.067
Room doors	0.27
Glasses	0.247
Room ceiling	0.015
Tilted roof of bedrooms	0.083
Tilted roof of living room	0.015

5. Heating and Cooling and Hot Water Demand

In order to maintain thermal comfort for the house residents, several factors including temperature and humidity should be controlled to stay at a certain level. The designed system not only does meet these demands, but also supply the hot water need of the house. In this section, required steps for mentioned design are expressed.

5.1. Operating Cycle

In the case of zero energy buildings, space heating and cooling systems may run on either electricity produced by PVs or solar thermal energy absorbed by collectors. A comparative estimation of capital costs based on load peaks for a solar absorption chiller and a compression heat pump indicates the value of 30000$ for the former and 36000$ for the latter. Furthermore, environmental issues and intangible costs lead us to choose the absorption unit as mechanical system. The designed absorption heat pump has the capability of supplying heating and hot water demand as well as cooling; thus, this system contains collectors, storage, and auxiliary energy system as shown in Fig. 2.

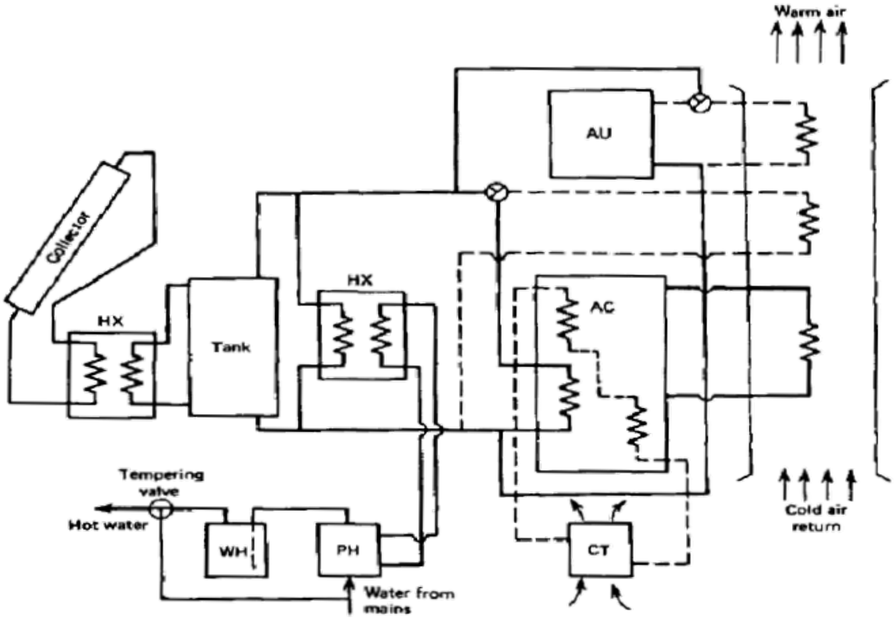

Fig.2. Schematic view of operating cycle

5.2. Hot water

In order to determine the amount of hot water which is required in a day, the data from engineering handbooks have been used and the demand rate calculated for a family with 4 members in Tehran is 233 gallons per hour, which leads to 0.00377 kilograms per second per day. The energy demand profile is obtained for Tehran according to the calculated hourly hot water use, as is presented in the red line of Fig. 5.

Mechanical system and its components are shown in Fig. 3. The DHW cycle is designed in a way that during day light, the cold supply enters the solar tank, becomes hot, returns to the storage tank and exits the path to supply daily need. In contrast, at nights, cold supply is led directly to the storage tank, gets warm and exits from the cycle to provide the house with its needs.

A specific characteristic of the designed system is the use of tempering valve which enables us to stratify the exit water according to its temperature. In the cases water with less temperature is needed, tempering valve in open to reduce the temperature.

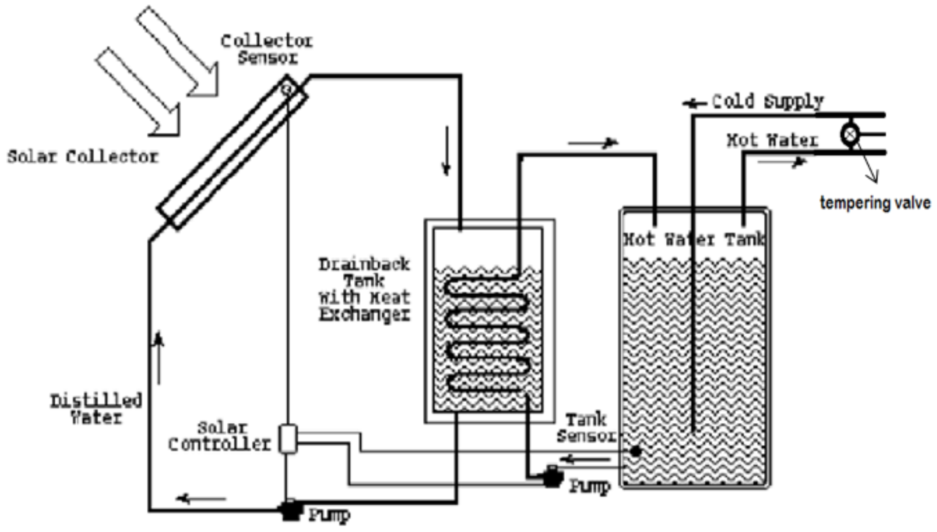

Fig.3. DHW system

5.3. Design of Solar Thermal Power System

Heating and cooling demands of a detached residential house should be met with respect to some important criteria such as human comfort and regional climatic conditions which mainly impose some limitations on the design process. So as the first step, hourly total solar radiation on the tilted surface is calculated. The results shown in Fig. 4 represent the effect of the surface orientation.

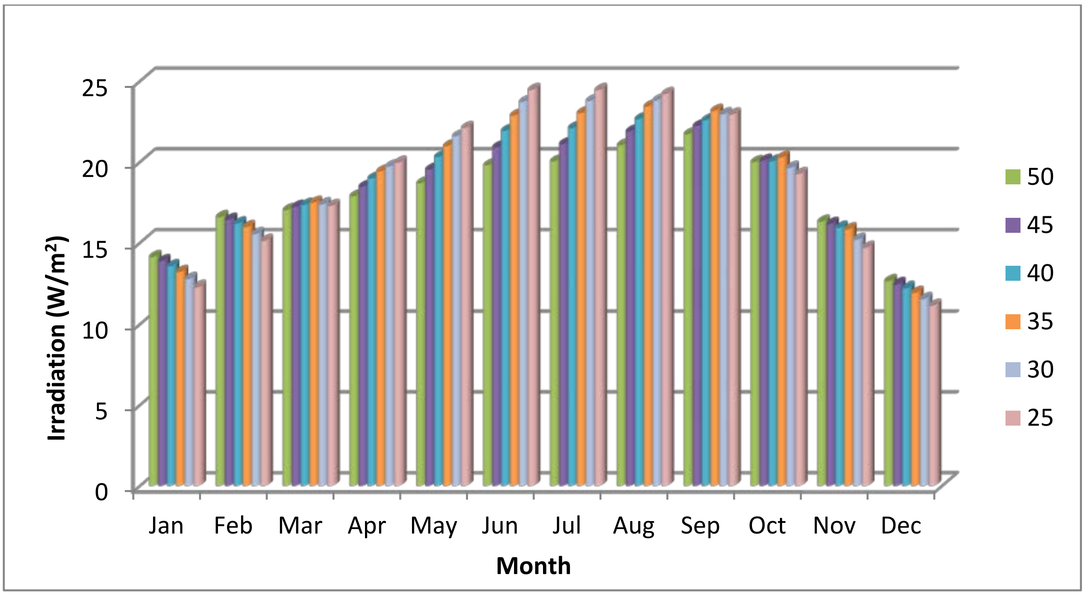

Fig.4. Incident radiation for some slopes

Using mechanical lever enables us to alter the collector orientation each month and achieve the maximum input; however, in order to obtain a safe design, following calculations are conducted based on the slope of $30°$ for collectors.

In this typical home in Tehran, concept of utilizability has been used. Utilizability is defined as a radiation statistic that represents the fraction of the total radiation which is received at an intensity higher than a critical level. As a result, total utilizable energy in Tehran is calculated in order to assign the absorption chiller capacity and type of the collectors. It is important to note that the design procedure in this way is quite iterative since the absorbed and utilizable energy depend on the collector type and characteristics; however, the collector itself is selected according to evaluated demand and incident irradiation.

Table 3 summarizes the results for the calculated monthly average hourly utilizable energy in the daylight hours for Tehran which represents a cold and a warm month. Note that the data is symmetrical after the solar noon.

Table 3: Utilizable energy in daylight hours

	6-7	**7-8**	**8-9**	**9-10**	**10-11**	**11-12**
January	0	0.2649	0.7041	0.7959	0.8317	0.8456
July	0.6348	0.7553	0.8096	0.8382	0.8536	0.8604

With assumed collector characteristics, useful gain per unit surface area is calculated. These values in conjunction with heat pump coefficient of performance (COP) constitute the available energy which should satisfy cooling and heating loads during the year. Monthly energy demand for space heating and cooling is obtained by curve fitting according to total annual heating and cooling load and measured load peak. Note that the heating load is calculated in a day in January with ambient temperature of $-4℃$ and comfort temperature of $24.5℃$ and cooling load is also calculated in a day in July with ambient temperature of $36.6℃$ and comfort temperature of $25.5℃$. The achieved results are $1.5ton$ for heating and $1.8ton$ for cooling. Furthermore it should be mentioned that total annual space heating load is $0.824GJ$ and annual cooling load is $1.008GJ$ and in order to obtain the hourly demand profile, the curve fitting is carried out in concern with the assumption of negligible load in March and October.

Fig. 5 shows the results for three different collector surface areas. The available energy from collectors is a design parameter which has to meet the average demand for all of months.

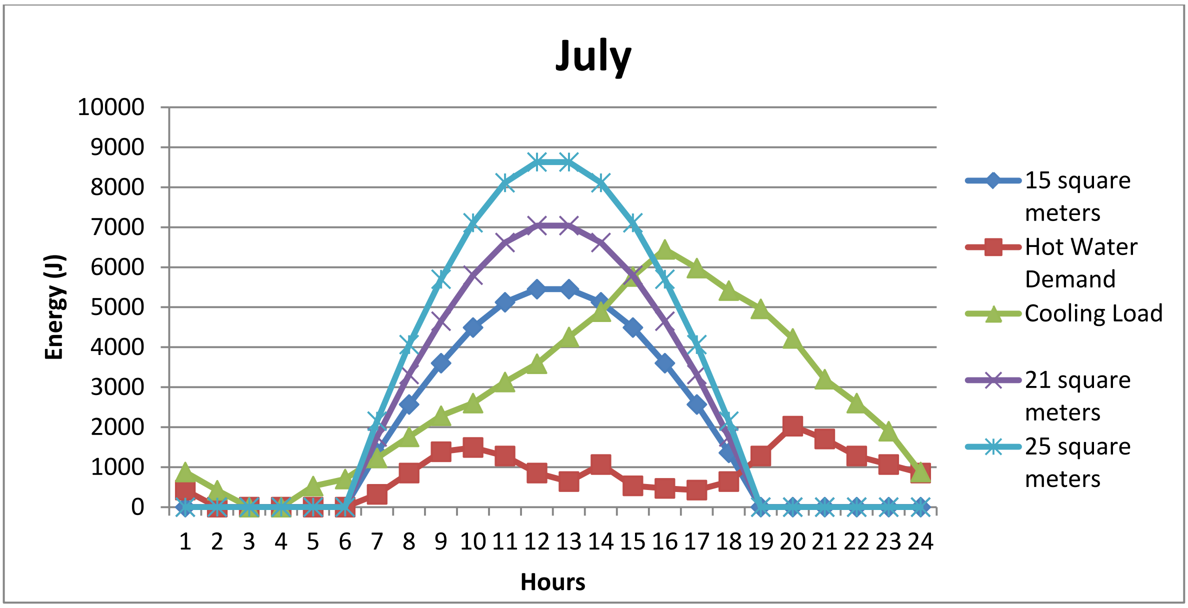

Fig.5. Useful Energy for three surface area and needs

Note that the auxiliary system using PV cells compensates the shortage during one day. Comparing the results for several collector areas, it can be concluded that $21m^2$ is sufficient to meet the average cooling and heating needs.

Table 4: Collector efficiency in daylight hours

	6-7	7-8	8-9	9-10	10-11	11-12
January	-	0.178	0.474	0.516	0.540	0.550
July	0.428	0.509	0.546	0.565	0.575	0.580

An innovative work for this home is choosing set of collectors to verify the achieved results for useful gain in Tehran. From the achieved collector efficiencies that summarized in Table 2 we find out that due to critical conditions at heating seasons, flat-plate collectors cannot be a logical choice because of the remarkable drop in efficiency in these seasons (blue curve at the right side of the diagram in Fig. 6). So in this case we increase efficiency in winters by making use of some evacuated collectors –the red curve- with the expense of a drop in cooling seasons. So the light green curve is the result and the final calculations are based on the light green curve discretized to two constant values for warm and cold seasons.

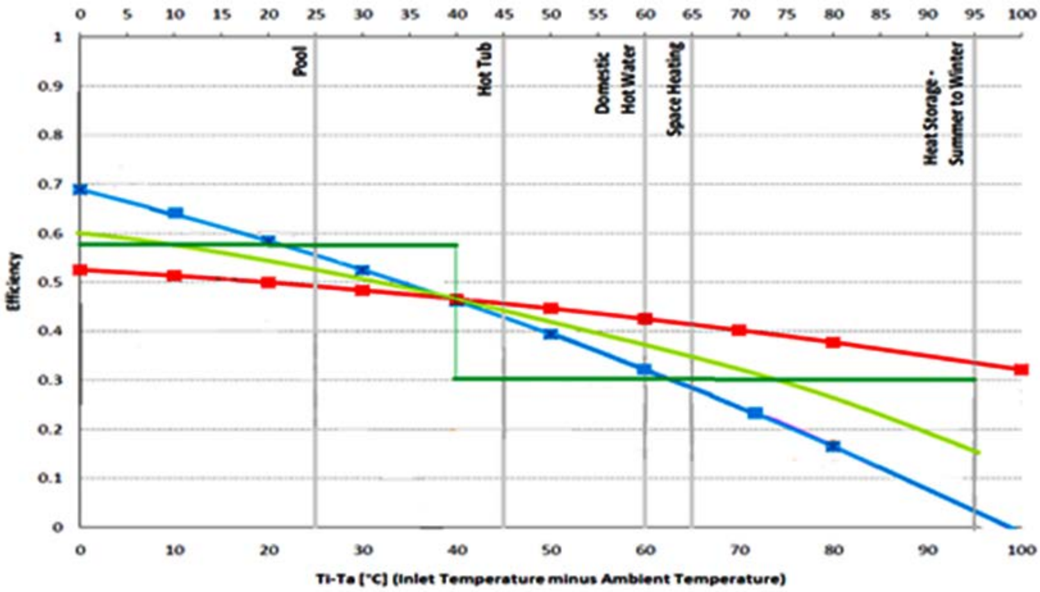

Fig.6. Operating curve of collectors

In conclusion, three evacuated collectors with each area of $3m^2$ has been utilized along with four flat-plate collectors with $4m^2$ surface area to supply the space heating and cooling and DHW needs simultaneously.

5.4. Auxiliary system

The existence of an auxiliary system is essential in the days in which the amount of sunlight is not sufficient or the duration is so short that the storage tank is not able to supply the whole day's need. Consequently, there should be another system which is run with electricity power. Fig. 7 shows the difference between gain and demand. In the hours in which this amount is negative, auxiliary system has to be used along with storage to meet the demand.

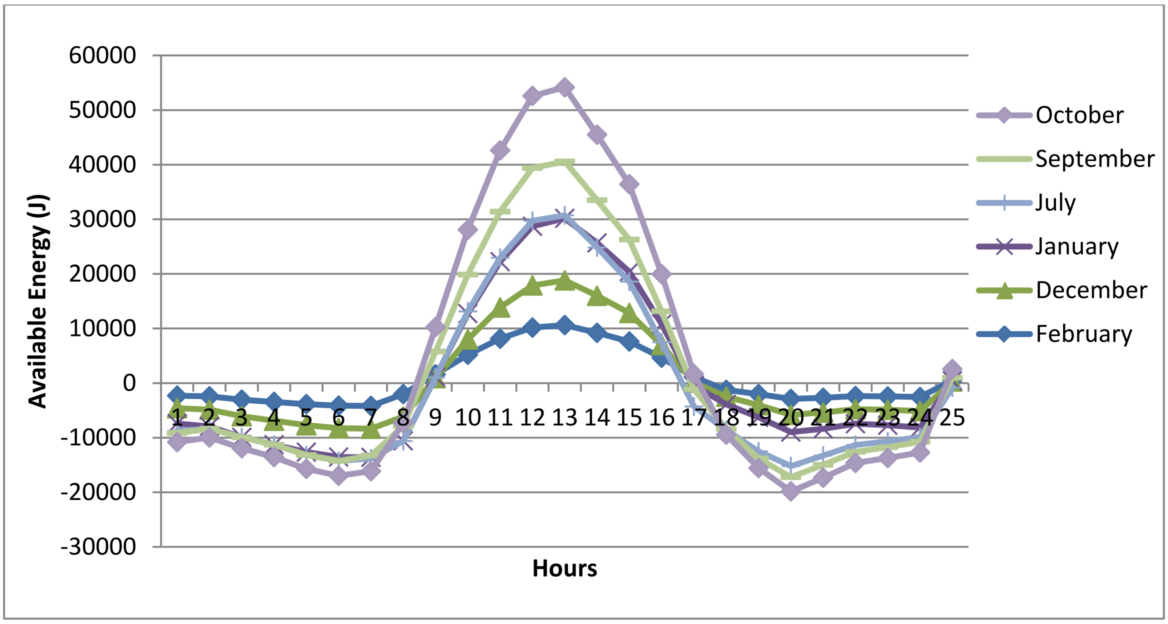

Fig.7. Difference of useful energy and demands in some months

Among various types of auxiliary systems shown in Fig. 8, type B is chosen to provide the house with its needs due to its prior functions. Auxiliary energy is supplied to the water leaving the tank and is controlled to maintain the outlet temperature from the auxiliary heater at a desired level. This method has the advantage of using the maximum possible solar energy from the tank without driving up the collector temperature, but additional heat loss will occur from the auxiliary heater if it has storage capacity.

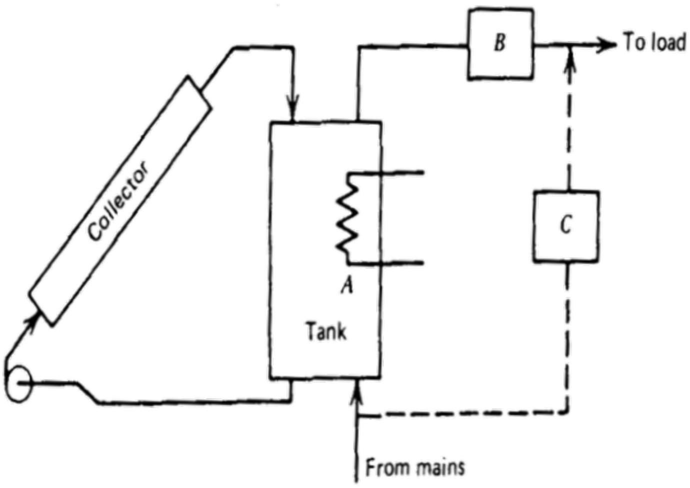

Fig.8. Different types of auxiliary system

6. Lighting

Lighting system is designed to decrease destructive environmental effects and minimize the energy consumption. For this case study, lighting system uses fiber optics and LEDs instead of other common lighting tools. Not containing any toxic materials, fiber optics are suitable to be used at homes especially ZEBs. Also fiber optics can transmit daylight to different zones of home and use an illuminator to deliver light at night without any dazing. “DIALux” 4.1 is utilized for modeling this lighting system. The lighting model for the master bedroom obtained by “DIALux” software is shown in Fig.9 and the wattage and lighting tools used in different zones are summarized in Table 5.

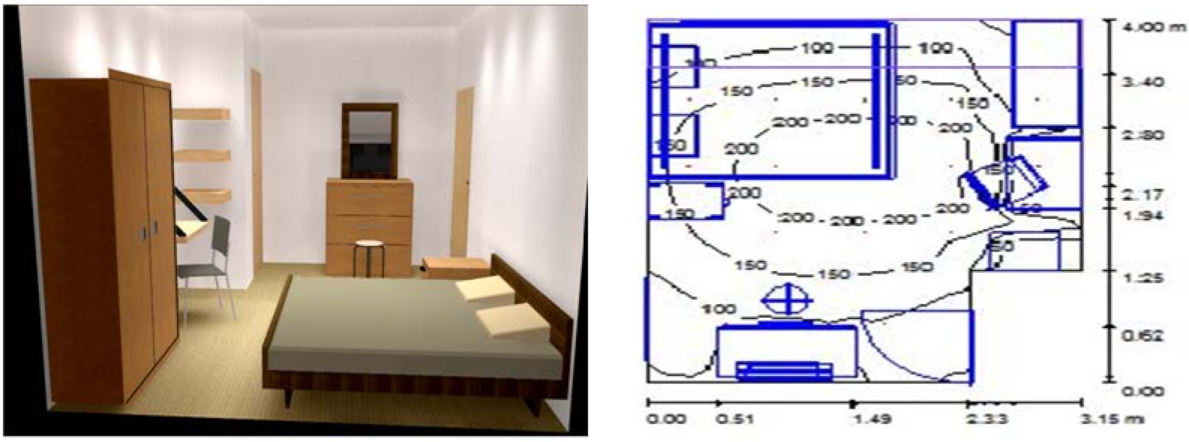

Fig.9. Master bedroom lighting model (left), light distribution in big bedroom (right)

Table 5: Wattage and lighting tools in different zones

Zone	Lighting Tool	Wattage (W)
Living room and kitchen	LED	112
Master bedroom	Fiber optic	17
Small bedroom	Fiber optic	12
Restroom and bathroom	Fiber optic	8
Vestibule	Fiber optic	10
Total	---	163

7. Electricity storage

Systems designed to supply a renewable source of electricity devices are indispensable in the delivery of zero energy building designs. It is comprised of photovoltaic panels, batteries, an inverter-charger unit and electricity loads. Annual electric demand for electrical appliances, lighting, controllers and HVAC auxiliary systems are shown in Table 6.

Table 6: Annual electrical power usage

Annual electricity	kWh
Lighting	310.23
Appliances	2079.72
Controller	240.00
HVAC	2043.59
Total	**4673.54**

The designed PV array is composed of 32 modules to provide electrical demand of the house. The array slope has been set to 30°. The PV parameters are listed in Table 7.

Table 7: PV parameters in the electricity system

Parameters	
Rated power	220W
Open circuit voltage	52.3V
Short circuit current	5.65A
Cell efficiency	19.8%
Module efficiency	17.4%
Area	1.26m^2
Cell number	72 cells
Ambient temperature	$-20℃$ to $+46℃$

Table 8 is an estimate on how much power the PVs could produce each month through the year in Tehran. Also Fig.10 shows the PV monthly output power.

Table 8: Monthly PV power output

Month	Power (kWh)
January	734.86
February	897.26
March	1004.56
April	1099.68
May	1200.02
June	1352.56
July	1322.4
August	1249.32

September	1210.46
October	973.24
November	834.04
December	716.3
Total	**12594.7**

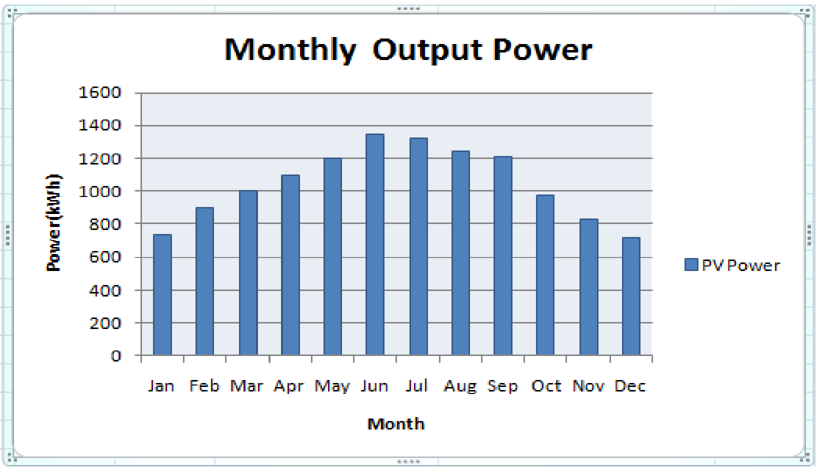

Fig.10. Monthly PV power output

By obtaining these results, we are able to compare the total output power with the total electric loads to come to a conclusion on whether we have a net zero system or not. Fig.11 compares the total output power with the total house loads.

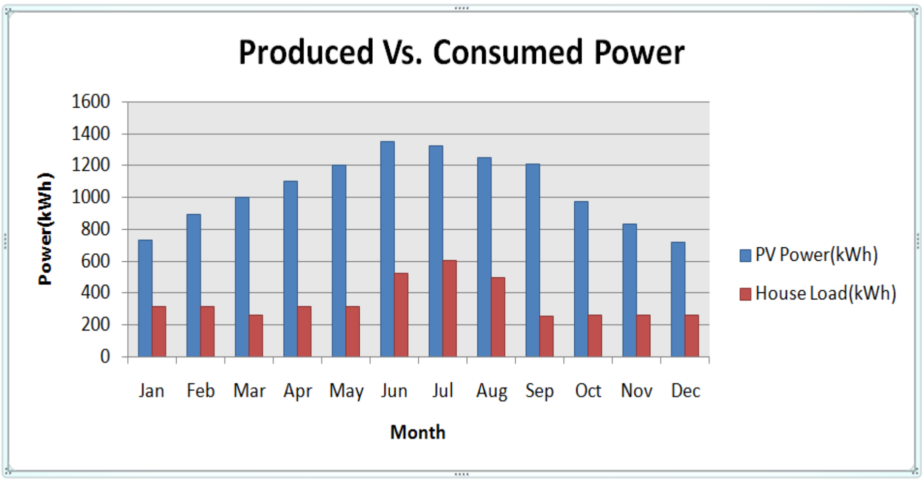

Fig.11. Monthly PV power output vs. house load

Fig.12 helps us to choose the battery size required to provide the need for specific days in which there is no sun. These determined days refer to the climate of Tehran through the year. Relief factor for energy consumption in months is assumed.

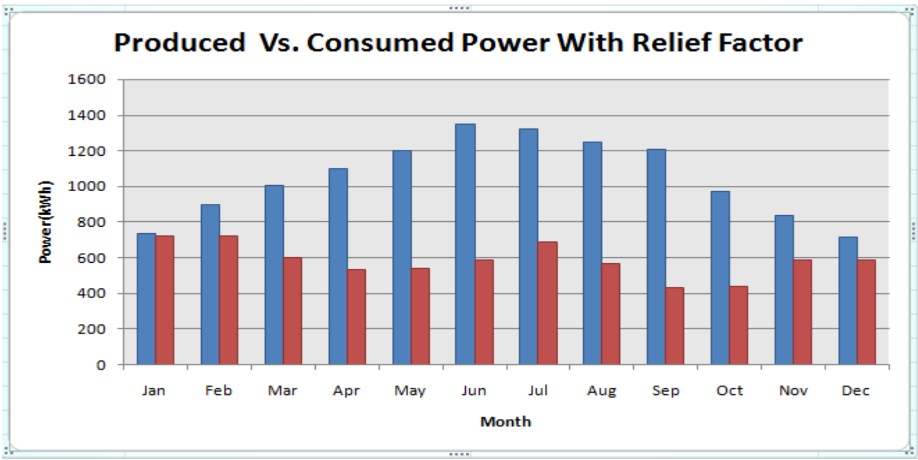

Fig.12. Monthly PV power output vs. house load with relief factor

Considering the results, we used 4 batteries to store produced energy and provide electrical load, and a charger is needed to control charge current and voltage. The battery parameters are shown in Table 9.

Table 9: Battery parameters in the electricity system

Parameters	
Nominal voltage	24VDC
Capacity	400Ah
Battery number	4
Total capacity	1600Ah
Maximum rated energy per month	1152kWh

System designed uses an inverter to convert the direct current (DC) electricity emanates from battery into current electricity (AC) typically required for light and appliance loads with the efficiency of 0.95.In the study, annual house load with relief factor is 7009.97 kWh (Fig. 12) and annual output power from the inverter is 11919.94 kWh.

Monitoring batteries status is an important issue. The monitoring system used in this home is able to calculate consumed electricity in ampere-hours and the state of charge (SoC) of batteries; consequently, we can keep batteries away from over discharging, overcharging and so forth. If the SoC of batteries become less than 30 percent, the control system alarms to decrease energy consumption, and if the SoC becomes less than 10 percent, the control system turns off nonessential appliances and lighting with precedence.

8. Feasibility Study

In each engineering design, the economic study is indispensable. For this typical home, the rate of return is calculated based on two approaches, the present cost of energy and the actual cost with no subsidies from the government. The vast capital and zero running cost for this typical home is treated as though it was interested during the time. Fig. 13 shows the cash flow diagram with the present value of energy in Iran. As it was predictable, it is not economically justified for a private entrepreneur to invest in such a project unless the investment is supported with the government.

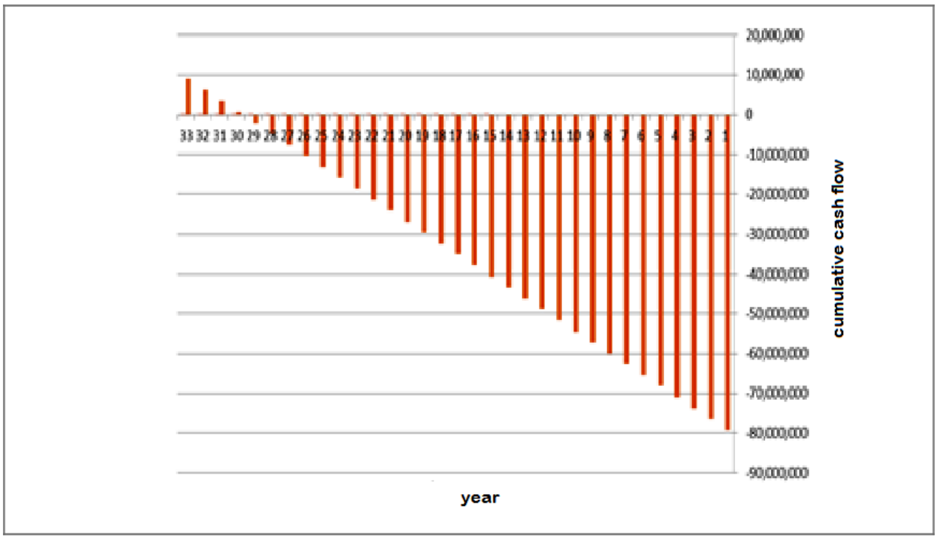

Fig.13. Cash flow diagram with respect to energy subsidies

On the other hand, Fig. 14 indicates that considering the actual costs of energies would result in tangibly less return span and after less than 9 years these homes make profit comparing with conventional ones.

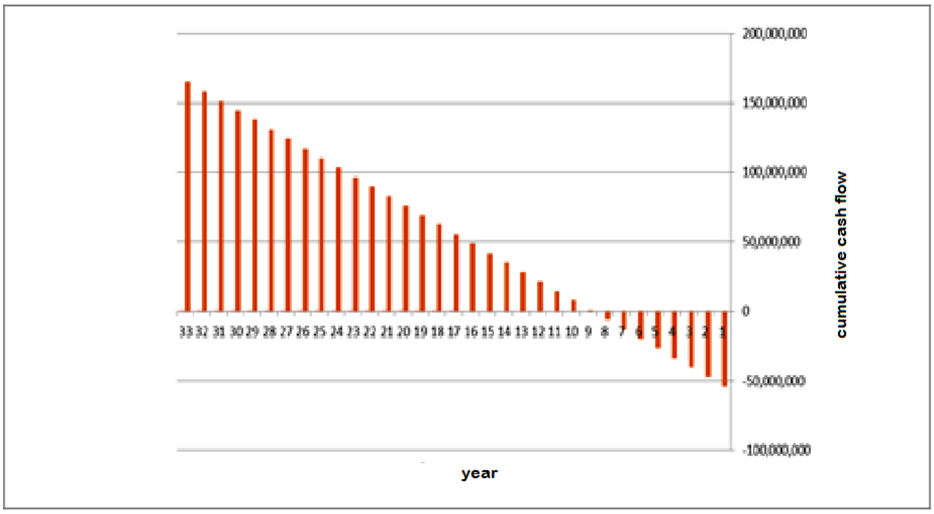

Fig.14. Cash flow diagram with actual costs

Finally it is worth noting that in this calculation the environmental costs and subsequent social costs is ignored and they can solely justify the construction of zero energy buildings regardless of savings in energy. Thus, for a comprehensive study these parameters should be taken into account.

9. Conclusion

In this study the feasibility of solar net zero energy building (ZEB) systems for a typical family of four members in Tehran is investigated. In the first place, solar radiation data and house load are calculated through the designed software and accurate data from local meteorological organization. Applying trombe-wall as a passive strategies results in 40 percents reduction in the house load of master bedroom. A combination of collectors and photovoltaic panels is chosen to supply thermal comfort, hot water and electricity needs. HVAC requirement is met by both passive and active approaches. A solar absorption chiller is utilized to support both heating and cooling need. This system absorbs solar energy through combination of $12m^2$ flat-plate and $9m^2$ evacuated collectors. Furthermore, domestic hot water demand (DHW) is also supplied in part of the designed absorption cycle in order to reduce the size of the equipment and consequently decreases the costs. Results indicate that July is the most critical month which assigns the amount of needed auxiliary energy. Several batteries are used to save extra energy from PV cells during the day for critical conditions such as night-time or cloudy days in which sunlight is not available. To decrease energy consumption and entry of toxic materials to the environment, LEDs and fiber optics are used in lighting system. Fiber optics can transmit natural sunlight to the inner spaces of the house. Off-grid solar photovoltaic system has been chosen for energy storage. It was concluded that it is theoretically possible to achieve the zero energy homes in Tehran. The annual electricity generation is almost 12594.7 kWh while the annual electricity consumption from lighting, appliances, controllers and HVAC is 4673.54 kWh. The remaining electricity can be used to gain financial profit by selling back to the grid.

Acknowledgments
The authors would like to acknowledge the support of professor Ashjaee and help of colleagues Amin Khalaf Rezayi and Zahra Aghayi.

References:

Wang, L., Gwilliam, J., Jones, Ph. (2009), *Case study of zero energy house design in UK*, Energy- and Buildings, N.41, pp.1215-1222, 13 July.

da Grac, G..G.,. Augusto, A., Lerer, M.M. (2011), *Solar powered net zero energy houses for southern Europe: Feasibility study*, Solar Energy 86 (2012) 634–646, December

Saqafi, M.J., Asadi, M.K., Pooyandeh, R. (2011), *The optimized tilt of solar collectors and comparison with installed ones on the south surface in Tehran*, Beautiful arts, Architecture and urbanize, N.44, pp. 57-63, 8 January.

Bula, A.J., Herrera,D.L., Navaroo, L.F., Corredor, L.A., Thermodynamic simulation of a solar absorption refrigeration system, generator-heat exchanger, Department of Mechanical Engineering, Universidad del Norte Barranquilla, Colombia

Duffie, J.A., Beckman, W.A., Solar engineering of thermal processes, Second Ed., Willy, 2005

Çengel, Y.A. and Boles, M.A. *Thermodynamics: An Engineering Approach*, 5th Ed, McGraw-Hill, 2006.