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Article

Investigation of Photovoltaic Self-sufficiency for a Residential Building in Canada

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Abstract: — In this study, the self sufficiency of a photovoltaic (PV) system installed on roof of a single story home is investigated for the particularly severe weather conditions of Canada. Since the local climate presents large daily and yearly temperature fluctuations, in addition to the presence of snow, drizzle and freezing rain, the design of renewable energy systems is very challenging. This research presents the investigation of both passive and active solar designs for a Canadian house. Self and transfer admittances of all surfaces were calculated. Furthermore, the zone admittance matrix has been derived for three different harmonics of weather inputs. The explicit finite difference model is used to calculate the temperature of the all nodes which are considered. Further, the equations resulted from the finite difference model are solved by MathCAD. The passive response of the house shows around 20°C difference between room-air and ambient average temperature in a winter day. The second part of this study includes the simulation of the PV system and house’s energy consumption that was carried out by use of PVSOL. Consequently, by making a comparison between total consumption of the house and the electricity production by PV system, the self sufficiency of a PV system was evaluated. This system is theoretically self-sufficient since the designed PV system provides 70 kWh in a sunny winter day when the maximum required energy for the building is 30 kWh approximately.

Keywords: solar energy; photovoltaic (PV); passive design; active design; self-sufficiency.

1. Introduction

Nowadays, one of the most significant necessities in the world is energy. Due to limited fossil fuel resources, renewable energies have been become an appropriate solution. Solar energy has the largest potential among all renewable energy resources. The available solar energy available on Earth's surface is 36000 billion watts (3.6×10^4 TW_{ave}) when the wind energy resource base is $72TW_{ave}$, geothermal energy resource base is 9.7 TW_{ave}, and the human energy use is $58TW_{ave}$ [1].

Conversion of the solar irradiation on earth's surface with 100% efficiency, make possibility to provide energy for the world by using $1/1000^{th}$ of the earth's dry surface [2]. In recent years, solar energy has become an increasingly important source of renewable energy and it is expected to expand in the near future. Solar energy possess many advantages such as: no need for fossil fuels, has no moving parts to wear out, is not polluting in operation, is adaptable for on-site installation, is easy to maintain, and can be easily combined with other renewable energy sources. Photovoltaic (PV) technology plays a key role in producing electricity directly from the solar irradiation, with an efficiency of 10-20% approximately. Photovoltaic technology has advanced considerably in recent years. Several buildings that use only solar energy as their energy resource have been built and the two main technologies used were solar thermal collectors (STC) and PV.

In Canada, buildings account for about 31% (17% residential) of Canada's energy consumption, for about 50% of its electricity consumption, and produce 28% of its greenhouse gases (GHG) emissions [3]. High energy consumption of buildings increases the interest in passive design [4]. Passive solar building is a qualitative term describing a building which utilizes solar gains to reduce heating and cooling loads based on natural energy flows. Unlike the active design, the passive design doesn't involve the use of mechanical or electrical devices. Passive design helps to provide a comfortable internal environment by using the local climatic conditions. The annual solar energy incident on the roof of a house far exceeds its total energy consumption. The first principle of passive solar design is absorbing and transmitting the maximum amount of radiation to the interior space of the building in winter time. Reduction of heat losses, shading controls, and utilization of natural ventilation are other passive solar design principles. However, if passive and active solar designs are used together, building efficiencies would be improved.

In the active design part, designers use mechanical and electrical devices for heating, cooling and ventilating the building. PV systems, solar thermal collectors, and solar water heaters are main technologies to use solar energy in buildings. In this study, PV modules provide energy for an efficient residential building as the main source of energy for electric appliances.

This paper is organized as follows. Section 1 has already introduced the passive and active solar designs. Section 2 explains the building physical characteristics and orientations. Section 3 describes the thermal analysis of the building. Section 4 presents our active solar design and its analyses. Finally, Section 5 demonstrates the self-sufficiency of a PV system for an efficient residential building in Canada.

2. Building Characteristics

The analyzed building is a single story house with a basement and it is located in Montreal. This is a south facing house with a pitched roof. The aspect ratio (the ratio of length to width) of the building is 1.3, which is the optimal ratio to use solar radiation to heat the building. Walls are made up of gypsum board and insulation. The thermal mass (a concrete slab with 20 cm thickness) has been used in the floor to store the heat produced by solar radiation and also preventing overheating and decreasing the temperature fluctuations. Triple glazed windows with low emissivity coatings were utilized, since they have a high thermal resistance and solar heat gain coefficient. According to the literature, the yearly optimal angle to absorb the maximum amount of solar radiation by PV modules is equal to the local latitude at low latitude locations, and up to 14° less than latitude at high latitudes [5]. In our case, a 45° slope pitched roof has been selected for installing PV modules, since the Montréal's latitude is 45.5°. The main parameters of the house are shown in table 1.

Table 1. Main physical parameters of the building

Physical Parameter	value
Floor area, m^2	130
Total wall area, m^2	111.25
Internal height, m	3
South facing windows area, m^2 (10% of floor area)	14
Door area, m^2	3
Total west, north, and east facing windows area, m^2	9
Slope of the pitched roof, degrees	45
Roof area, m^2	2×91.91

The south facing windows have been selected with the optimum area (10% of floor area) to allow more solar radiation to enter the house in winter and to be stored in thermal mass. Two large area windows are used instead of many small area windows to minimize the heat loss through windows frames. The north facing windows have been used only to provide day lighting. This model has been studied for weather conditions of a typical winter day.

3. Thermal Analysis of the Building

The input parameters for thermal analyses of building are: building dimensions, location of the building (latitude of 45°), building orientation, thermal resistances, heat transfer coefficients, day number, ground reflectance, and basement temperature assumed 16°C. The calculations have been done by MathCAD.

Thermal resistances of all components of the house were calculated and the results are shown in table 2.

Table 2. R-value of house's components

R-value of the windows, m^2K/W	0.738
R-value of the door, m^2K/W	1.2
R-value of the walls, m^2K/W	3.482
R-value of the floor, m^2K/W	1.388

Then, the thermal network of the house was plotted and used for calculation of nodes temperatures by using an explicit finite difference model. The energy balance equation is applied at each node and solved repeatedly at each time step for the period of simulation to find the temperature fluctuations. The outside temperature was modeled by a Fourier series.

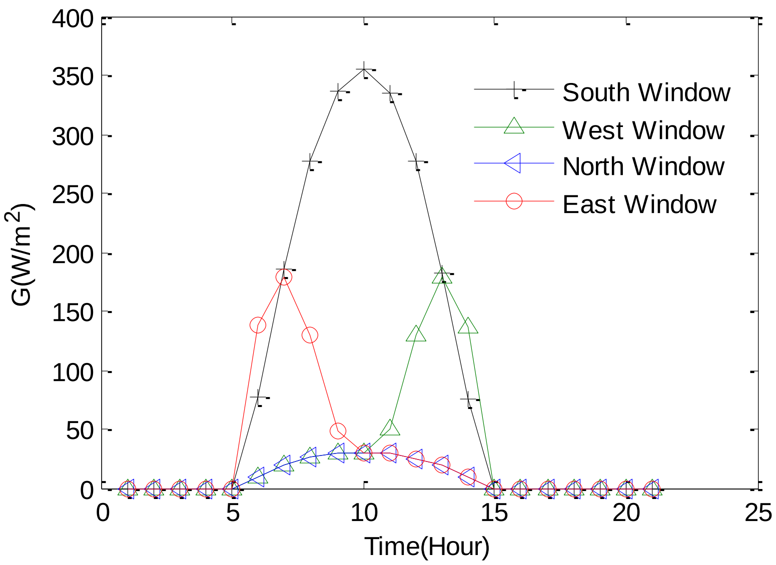
By using the admittance model, the admittances of all walls and windows were calculated and finally the total zone admittance matrix, shown as equation 1 analyzedfor the mean term and three different harmonics of the weather inputs were derived. Note that the first component of this matrix (Yz_0) is the total U-value of the house [6].

$$Yz = \begin{pmatrix} 268.501 \\ 1.013 \times 10^3 + 487.883j \\ 1.169 \times 10^3 + 627.223j \\ 1.329 \times 10^3 + 777.162j \end{pmatrix} \text{WK}^{-1} \quad (1)$$

The incident solar radiation on each surface of the house was calculated. Direct, diffuse, and reflected radiations were considered. Hottel's clear sky model was employed to find the solar radiation on different surfaces of the house and also the ground reflected radiation. The correlation of Liu and Jordan was employed to find the diffuse component of radiation on different surfaces [7]. The hourly clearness index was employed for the assumed day (February 1st). The clearness index is the ratio of total horizontal solar radiation measured on the ground and the total horizontal solar radiation at the top of the atmosphere; it shows the cloudiness intensity of the sky [7]. After calculation of the incident solar radiation on exterior surfaces, transmitted solar radiation to the interior surfaces was calculated. It has been assumed that 70% of incoming solar radiation to the interior zone through windows is absorbed by the floor and the remainder by other surfaces in proportion to their areas.

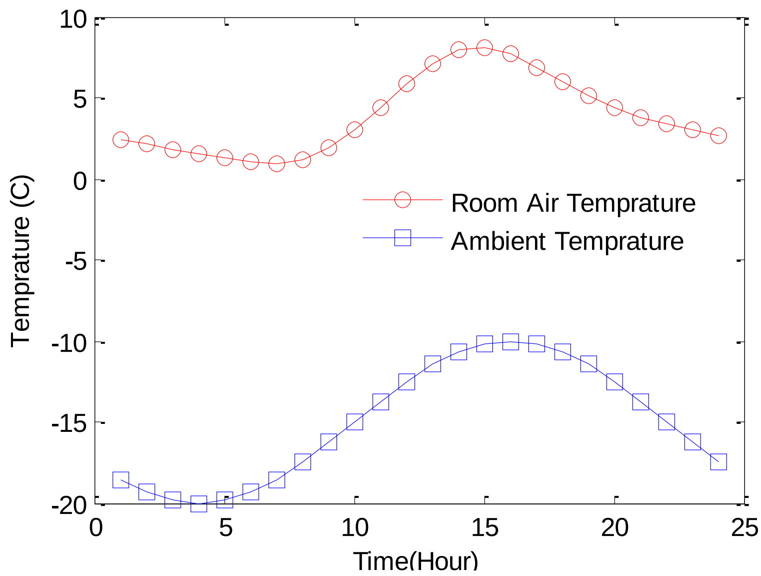
Figure 1 shows the transmitted solar radiation flux to the interior zone [8]. As it is shown, the main part of transmitted solar radiation comes from the south windows. The east windows transmit radiation only in the morning. In contrast, the west windows transmit radiation in the afternoon. The north windows transmit a negligible amount of radiation and only provide day lighting.

Figure 1. Transmitted solar radiation flux by different surfaces



Furthermore, the passive response of the building (without using auxiliary heating) was found as it is shown in graph 2. The room air temperature fluctuation chart has almost the same shape as the ambient temperature but with lower amplitude. In the afternoon, diminution of both ambient temperature and solar irradiance led to lower room air temperature; however, the reduction rate of the room air temperature is considerably less (only 63%) than the external temperature.

Figure 2. Passive response of the house



4. Active Solar Design

The second element of design studied is active solar design. The simulation was carried out by PVSOL. As the first step, the consumption of a regular Canadian house was estimated. High efficiency electrical appliances were utilized to maximize energy savings. Mechanical and electrical devices are used for heating, cooling, and ventilating the inside environment of the house. The electrical appliances and their consumptions are listed in table 3. The total load is about 30 kWh/day.

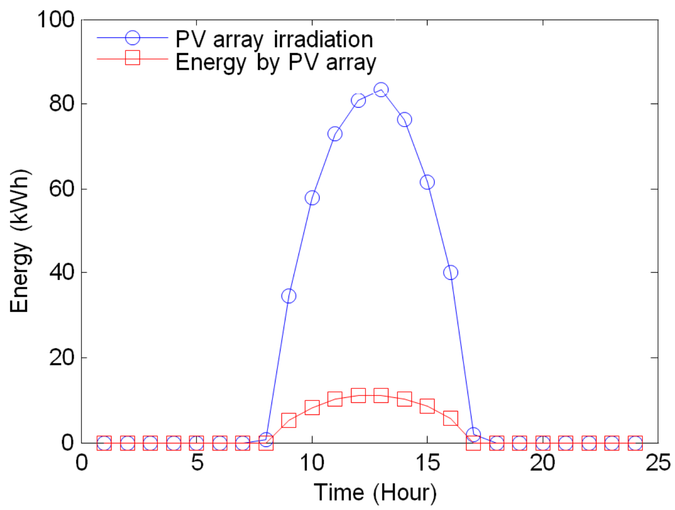
Table 3. Appliances used in proposed house

appliance	quantity	power (W)	Hours of use (h)	Total load(Wh/day)
LED lights	12	10	4	480
Refrigerator & Freezer	1	800	8	6400
TV	1	150	3	450
Kitchen stove	1	1200	3	3600
CD player	1	20	1	20
Dish washer	1	1000	1	1000
Computer	1	200	4	800
Clothes washer & drier	1	2500	0.1	250
HVAC	1	1000	6	6000
Water pump	1	1000	3	3000
Water heater	1	1000	6	6000
other appliances	...	...	...	2000
Total				30,000

Forty two Si Monocrystalline PV panels with efficiency of 16.2% and output power of 310 W from Canadian solar Inc. were utilized. Panels were installed on the roof tilted at 45°. The output power of PV system is 13 kWp. There are many possible conditions to connect PV panels to each other. In this proposed design, the optimal condition has been selected according to the I-V characteristics of modules and inverters and to create more efficient system. The optimal configuration for the panels connections was selected: seven panels were connected in series and the two series connected in parallel. The same was done for the other two inverters. Furthermore, inverters best matched with the system were selected. Three 4.60 kW inverters were proposed for this system. Using a smaller number of inverters with high power is more efficient than using more inverters with low power.

Simulation predicts 13.2% PV array efficiency, 94.5% inverter efficiency, and 12.5% overall efficiency of the system. The assumed day (February 1st) is completely clear. The PV array irradiation and energy produced by PV array are shown in figure 3. The total PV array irradiation on a clear day is 510 kWh and the total electricity produced by PV array is 70 kWh.

Figure 3. PV array irradiation and energy production



Heat dissipated by the electric appliance will suffice to heat the house to a confortable temperature. If needed, the HVAC system can provide additional heating.

5. Conclusions

Passive and active solar designs optimizations are performed in this study. Passive solar design principles were employed and the following analyses show that the average room air temperature of the designed building without using auxiliary heating is 4°C when the average of ambient temperature is -15°C on a winter day. High level insulation, using thermal mass, and applying the passive solar design principles allow this difference between ambient and room air temperature.

The total consumption from electrical appliances in the house is a 30 kWh/day. A total of 42 PV modules installed on the house's roof provide the electricity. The total power of the designed PV system is 13 kWp. Results from simulation predict an electricity production of 70 kWh on February 1st. Therefore, this production is enough to fulfill 30 kW.hr consumed by electrical appliances. Surplus could be stored in batteries or feed into the grid. Surpluses are large enough to insure that the house would have a net zero consumption over a year. However, autonomous operation is not granted as the energy storage needed for a long sequence of cloudy days in winter would be quite large.

This raises this important question: Is this environmentally sound? The study demonstrates that Net Zero Energy operation could be achieved under Canadian winter conditions. However, a large amount of resources is used for the additional insulation and the fabrication of the solar panels and associated electrical system. Maybe, these would have been used better in the production of energy from other renewable sources (ex: wind, hydro), than trying to save the same amount of energy.

Conflict of Interest

Authors have no conflict of interest to declare.

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